VI Simpósio Nacional de Geomorfologia / Regional Conference on Geomorphology
Geomorfologia Tropical e Subtropical: processos, métodos e técnicas / Tropical and Subtropical Geomorphology: processes, methods and techniques
Goiânia, 6 a 10 de setembro de 2006 / Brazil, Goiânia-GO, September 6-10, 2006

INTERACTIONS BETWEEN BIOLOGICAL, SOIL-FORMING, HYDRODYNAMICAL, GEOMORPHOLOGICAL AND GEOCHEMICAL PROCESSES IN THE SENEGAL VALLEY.

FURIAN, S. [1,2]

[1] Department of Geography, University of Sao Paulo, Sao Paulo State, Brazil, phone/fax +55 11 30913794. E-mail laboped@usp.br; [2] IFCWS, Dep. of Civil Engineering, Indian Institute of Science, 560 012, Bangalore, India, phone +91 80 22933127.

BARBIÉRO, L. [2,3]

[2] IFCWS, Dep. of Civil Engineering, Indian Institute of Science, 560 012, Bangalore, India, phone +91 80 22933127.; [3] IRD, UR 154, Laboratoire des Mécanismes de Transfert en Géologie, 14 Avenue E. Belin, F-31400 Toulouse, France.

OULD MOHAMEDOU, A. [4]

[4] Faculté des Sciences et Techniques de Nouakchott, B.P. 56, Nouakchott, Mauritanie.

RESUMO

In this paper, we gather several studies in order to highlight how the sedimentation (Gac and Kane, 1986), soil forming processes (Mohamedou 2000, Barbiéro et al., 2005), soil hydrodynamic regime (Wade, 2000), aeolian deflation (Barbiéro et al., 1998) and geochemistry (Mohamedou et al., 1999, Barbiéro et al., 2004) have interacted and led to the present day geomorphology of the Senegal valley. The development and buffering of soil acidity and aeolian deposition have been identified as major factors in the formation of soil profiles and distribution of the present day salinity. Acid Sulfate Soils (ASS) have formed from the river deposits and result from the expression of a potential acidity due to oxidation of biologically accumulated pyrite. The buffering of acidity through transformation of shells into gypsum layer, protonation and acid hydrolysis of clay, and eventually the precipitation of kaolinite and subsequently smectite at the topsoil lead to Vertisols (VTS). The lateral and abrupt change in the topsoil texture modifies the hydrodynamic properties of the soil. As a consequence, at loamy places, the salt precipitates at topsoil favouring the formation of a soft powder, whereas most of the salt precipitates at about 3 cm deep at more clayey places, provoking the formation of centimetric platelets. Therefore, the aeolian deflation and the formation of saline clay dunes occurring on ASS are blocked on VTS area. The transformation of ASS into VTS has accompanied the last sea regression along the Senegal valley. Although VTS soil types are dominant upriver, they are former ASS, which have suffered aeolian deflation and clay dune accumulation. Clay dunes have protected the gypsum layers located below from dissolution and leaching. Therefore, former clay dunes evolved into saline area, which salinity results from that of the clay dune itself (Na-Cl, secondarily Ca-SO_4) and of the several gypsum layers (only Ca-SO_4). These studies carried out at the Senegal valley highlight the interconnections between biological processes, soil formation, landscape evolution and geochemistry. It is not necessary to resort to changes in the environmental conditions to explain a stop in the aeolian deflation and clay dune formation.

Keywords: aeolian deflation, clay dune, Acid Sulfate Soil, Vertisol, Senegal.

INTRODUCTION

The aim of this contribution is to consider the successive biological, pedological, hydrodynamical, geomorphological and geochemical processes that have occurred in the Senegal valley, and to describe how they have interacted and conditioned the formation of the soil cover and the evolution of the landscape. The problem will be tackled through a chronological order, by considering successively the initial sedimentation, the formation of Acid Sulfate Soils, their transformation into Vertisols, the consequences on aeolian deflation and clay dune formation and eventually the influence on the chemistry of present-day saline areas.

SITE:

During the Quaternary, the sea transgressed and regressed several times into the Senegal River valley (Faure et al., 1980). About 2000 BP, a final transgression formed a large gulf, as far inland as Boghé, which is now 380 km from the coast. The sea regressed from Boghé to the present Senegal delta in the medieval period accompanied by the mangrove vegetation, and the remains of this vegetation still occur along creeks in the delta.

INITIAL SEDIMENTATION:

The composition of the sediment at the river mouth has been studied by Gac and Kane (1986). The clay fraction consists in kaolinite, secondarily smectite and some traces of illite. This composition is in agreement with that of the unripe mud observed today in the lower delta, which was therefore supposed to be the original river sediment. Additional analysis carried out on the clay fraction suggests that the smectite has two possible origins, i.e., a smectite of neoformation, and a smectite of transformation from mica (Ould Mohamedou, 2000). Because only well-crystallized mica was observed and because of the absence of interstratified minerals in spite of some slightly weathered illite, we concluded that the transformation of the mica into smectite did not occur in the mud, but was inherited from the source area Barbiéro et al. (2005).

POTENTIAL ACIDITY:

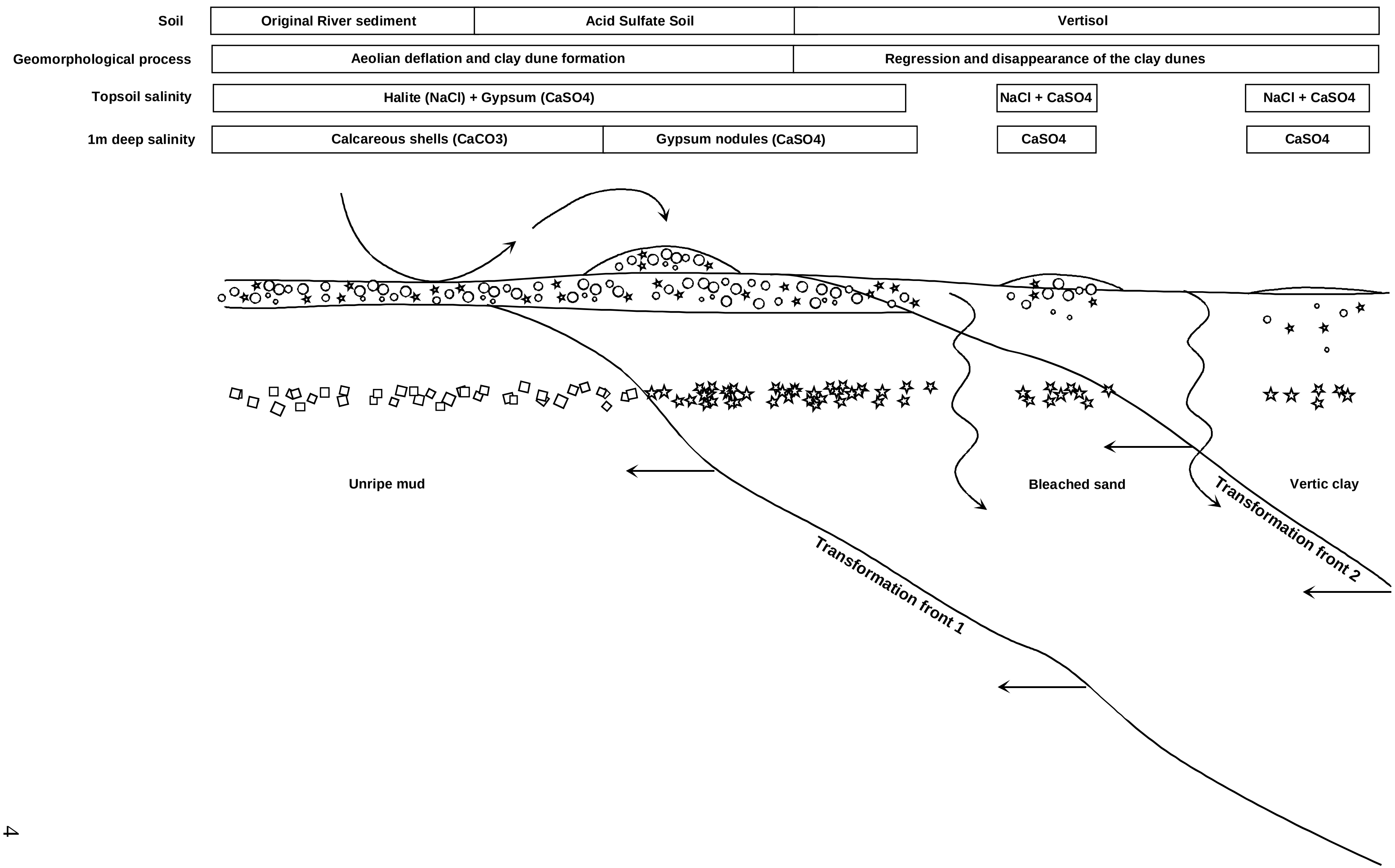
The sequence of transgression–regression cycles had a great influence on soil formation through the development of a potential acidity. Accumulation of pyrite by sulphur-fixing bacteria in the roots of the mangrove vegetation occurred in the waterlogged environment supplied with seawater sulfate under a tidal influence. Pyrite is still observed at many place of the lower delta, where it appears as black mottles in the unripe mud of the soil profile.

FORMATION OF ACID SULFATE SOIL:

The sea regression provoked an oxidation of the soil profile, making possible the expression of the potential acidity. Two main pedological processes transformed the initial deposit into an Acid Sulfate Soil: ripening of the mud involving principally an irreversible loss of water, and the oxidation of iron minerals. A typical soil morphology has developed including, from the bottom to the top of the profile the following sequence: Gr, Gj, Bj, Bg and A horizons (criteria used in the ILRI classification; Dent, 1986). The pyrite in the Gr horizon was produced by the activity of the sulfate-reducing bacteria in waterlogged sediments rich in organic matter. The pale yellow colour in the Gj and Bj horizons results from jarosite, which is generally observed when pH is < 3.7 and Eh >400 mV (Dent, 1986). At higher pH values, jarosite is metastable with respect to goethite and ultimately, it is hydrolysed to iron oxide, predominantly geothite and sometimes hematite (Van Breemen, 1976), as observed at the top of the Bj horizon. All these chemical reactions generate acidity and pH can reach value below 3.

FROM ACID SULFATE SOIL TO VERTISOL:

The strong acidity of the soil solution, following oxidation of pyrite, will induce a series of chemical reactions related to acid neutralization by the soil alkalinity. The alkalinity is mainly provided by carbonates, exchangeable bases and easily weatherable silicates. The first control of acidity is the progressive dissolution of the shells, leading to disappearance of the calcareous layers. The calcium released in the saline and sulfate-rich environment precipitates as centimetric gypsum nodules, highlighting the former presence of the shell beds in the soil. After dissolution of the carbonates, acid neutralization is provided by protonation of clay minerals (Van Breemen, 1976). The resulting protonated clays are not stable and their crystalline structure is attacked by H^+ at pH < 4 (Van Breemen, 1976), liberating silica and metal ions, principally aluminium, iron, magnesium and potassium into the soil solution. The acid hydrolysis of aluminosilicate clays can contribute 10% of the buffering of the acid produced by oxidation of pyrite (Dent and Raiswell, 1982). The direct consequence of the acid hydrolysis of aluminosilicate clays is the relative accumulation of quartz, leading to formation of a sandy bleached horizon. It produces a first pedological front in the soil profiles. During the rainy season, the Senegal River overflows and neutral or slightly alkaline freshwater infiltrates into the soil profile.



Soil
Original River sediment
Acid Sulfate Soil
Vertisol
Geomorphological process
Aeolian deflation and clay dune formation
Regression and disappearance of the clay dunes
Topsoil salinity
Halite (NaCl) + Gypsum (CaSO4)
NaCl + CaSO4
NaCl + CaSO4
1m deep salinity
Calcareous shells (CaCO3)
Gypsum nodules (CaSO4)
CaSO4
CaSO4
Unripe mud
Bleached sand
Vertic clay
Transformation front 1
Transformation front 2

At the contact between the fresh Senegal water and the acidic water rich in Al, Fe and Si, kaolinite precipitates forming clay laminae in the sandy horizon. In acid sulfate waters, high Al contents occur as a result of aluminosilicate dissolution, but the geochemistry of Al is significantly modified by sulfate, so that gibbsite and kaolinite are not the most stable phases (Bigham and Nordstrom, 2000). In some parts of the Senegal delta where the acid soil solution concentrates, Le Brusq et al. (1987) observed soluble aluminium sulfate minerals. However, during overflow of the Senegal River, a neutral or slightly alkaline water with lower ionic concentrations easily infiltrates the sandy or loamy horizons of the acid soil. After dilution and partial control of the acidity by the Senegal freshwater, kaolinite can form. Mohamedou (2000) observed that the kaolinite in the clay laminae differs from that observed in the original river sediments, because it is slightly heat-resistant at the treatment at 500 degrees. Therefore, we concluded that the kaolinite was precipitated in the laminae (Barbiéro et al., 2005). Progressively, the acid conditions are sufficiently buffered to allow smectite precipitation. By studying four successive laminae, Mohamedou (2000) have shown the progressive appearance of the smectite in the profiles, which first appears as a plateau, and then a peak becomes clearly apparent on XRD diagrams. Clay precipitation results in the formation of a superficial clay horizon, which acquires a vertic structure and produces the second pedological front between the sandy horizon and the vertic clay horizon. Towards upriver, the whole ensemble (vertic horizon and sandy horizon) get progressively thicker ranging from about 1m in the delta, to more than 6 m near Podor, at about 200 km from the sea. Favre et al. (2002) identified large proportions of Fe on octahedral position on the smectite sampled at the Podor region. It shows that the smectite is of iron-beidellite type, whose formation has possibly been favoured by the high Fe and Al concentrations in the soil solution.

INFLUENCE ON TOPSOIL:

An abrupt change in the topsoil structure is locally observed, shifting from soft powder to centimetric platelets. Mohamedou (1998) suspected that it was due to lateral changes in the soil salinity, but no relationship between the topsoil structure and the electromagnetic conductivity was observed. In compensation, this author shows that the change in the topsoil structure is strongly related to the appearance of the clay horizon with a clay content shifting laterally and abruptly from 19 % (associated with the soft powder and referred as SP) to 29 % (associated with centimetric platelets and referred as CP). A Wind experiment was carried out at the laboratory on two contrasted soil blocks sampled on both side of the topsoil changes between SP and CP (Wade, 2000). The objective was to test if the different behaviour of the samples could be related to a difference in the soil unsaturated flow. Results indicate that the saturated hydraulic conductivity (Ks) was higher in CP than in SP. However, during the drying of the samples, the author observed that the hydraulic conductivity decrease faster in CP than in SP, and that K_{CP} becomes rapidly much lower than K_{SP}. The direct consequence is the following. During evaporation, in SP the saline soil solution reached the topsoil and favoured the formation of a soft powder vulnerable to the deflation, whereas in CP, the salt precipitated below the topsoil at about 3 cm deep provoking the individualisation of centimetric platelets not vulnerable to erosion.

CONSEQUENCES ON AEOLIAN DEFLATION AND SALINITY:

Aeolian deflation and clay dune formation occurred on ASS and is blocked on VTS because of the change in the topsoil structure. However, because the transformation front from ASS to VTS is developing towards downriver and is today observed in the delta, former clay dunes can be observed upriver, although these places are today occupied by VTS. Because these clay dunes are saline, with a certain proportion of gypsum, the percolating soil solution reached saturation with gypsum and is not aggressive with respect to the gypsum layers occurring in the soil. Therefore, former clay dunes are today detected as saline area with a double origin of the salt (Barbiéro et al., 2004). One is aeolian salt (Na-Cl, secondarily Ca-SO4), whereas the other arises from former transformation of shell beds into gypsum layers (Ca-SO4).

CONCLUSION:

The recent evolution of the sediments in the Senegal valley is a perfect example to illustrate the interconnections between biological (pyrite accumulation), hydrological (expression of acidity) pedological (development of Acid Sulfate Soil and transformation into Vertisol), geomorphological (aeolian deflation and clay dune formation) and geochemical (salt accumulations) processes. The study highlight how powerful could be a pedological process under extreme geochemical conditions (in this case, very acidic), which are here the driving forces behind the soil formation from unripe mud to Vertisol. Because the conditions for clay dune formation are very restrictive, they are frequently used for the reconstruction of palaeoenvironments. A stop in the sedimentation of clay dune is generally attributed to changes in the climatic or hydrological conditions. This study shows that transformations in the topsoil can result in a stop of the aeolian deflation without changes in the environmental conditions.

REFERENCES

Barbiero L., Ould Mohamedou A., Laperrousaz C., Furian S., Cunnac S., 2004. Polyphasic origin of salinity in the Senegal delta and middle valley. Catena 58, 101-124.

Barbiero L., Ould Mohamedou A., Roger L., Furian S., Aventurier A., Rémy J.C., Marlet S., 2005. The origin of vertisols and their relationship to Acid Sulfate Soils in the Senegal Valley. Catena 59, 93-116.

Bigham, J.M., Nordstrom, D.K., 2000. Iron and aluminium hydroxysulfate minerals. In: Alpers, C.N., Jambor, J.L., Nordstrom, D.K. (Eds.), Sulfate Minerals. Crystallography, Geochemistry, and Environmental Significance. Reviews in Mineralogy and Geochemistry, vol. 40, pp. 351–403.

Dent, D., 1986. Acid sulphate soils : a baseline for research and development. ILRI Publication 39. Wageningen, The Netherlands.

Dent, D.L., Raiswell, R.W., 1982. Quantitative model to predict the rate and severity of acid sulfate development: a case study, the Gambia. In: Dost, H., Van Breemen, N. (Eds.), Proceedings of the Bangkok symposium on Acid Sulfate Soils. ILRI Publication 31. ILRI, Wageningen, The Netherlands, pp. 73– 95.

Faure, H., Fontes, J.C., Hebrard, L., Monteillet, J., Pirazzoli, P.A., 1980. Geoidal changes and shore-level tilts along Holocene estuaries: Sénégal river area, West Africa. Science 210, 421-423.

Favre, F., Tessier, D., Abdelmoula, M., Génin, J.M., Gates, W.P., Boivin, P., 2002. Iron reduction and changes in cation exchange capacity in intermittently waterlogged soil. European Journal of Soil Science 53, 175-193.

Gac, J.Y., Kane, A., 1986. Le fleuve Sénégal : I. Bilan hydrologique et flux continentaux de matières particulaires à l'embouchure. Sciences Géologiques Bulletin 39, 99-130.

Le Brusq, J.Y., Loyer, J.Y., Mougenot, B., Carn, M., 1987. Nouvelles paragenèses à sulfates d'aluminium, de fer, et de magnésium, et leur distribution dans les sols sulfatés acides du Sénégal. Science du Sol 25, 173-184.

Michel, P., 1973. Les bassins des fleuves Sénégal et Gambie. Etude géomorphologique. Mémoire ORSTOM 63. Paris, France.

Mohamedou, A.O., 1998. Contribution à l’étude de l’environnement du Parc National du Diawling (Mauritanie). Eaux-Sols-Végétation. PhD thesis, Univ. Nice-Sophia Antipolis.
Mohamedou, A. O., 2000. Evolution pédogénétique des sols de mangrove de la vallée du fleuve Sénégal et phénomènes associés. Rapport Post-Doctoral, Univ. Nouakchott, Mauritania.
Mohamedou, A.O., Aventurier, A., Barbiéro, L., Caruba, R., Valles, V., 1999. Geochemistry of clay dunes and associated pan in the Senegal delta (Mauritania). Arid Soil Research and Rehabilitation 13, 265-280.
Van Breemen, N., 1976. Genesis and solution chemistry of acid sulfate soils in Thailand. Agricultural Research Report 848, Pudoc, Wageningen, The Netherlands.
Wade, M.A., 2000. Détermination des paramètres hydrodynamiques de deux types de sol du delta du fleuve Sénégal, simulation des transferts hydrosalins : application au phénomène de déflation éolienne. Mémoire d’ingénieur Institut des Sciences de la Terre UCAD, Dakar.