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Holocene Mangrove Swamps of West Africa Sedimentology and Soils

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Abstract - The mangrove swamps of West African Coast belong to the Atlantic type which is characterized by a small number of species. They colonize tidal environments which are dissected by numerous meandering tidal channels and are presently subject to a low rate of sediment accumulation.

The mangrove vegetation exhibits a characteristic zonation pattern that basically reflects the adaptation of the various species to saline conditions. The typical zonation sequence is: *Rhizophora racemosa* (or Rh. mangle), Rh. mangle + *Avicennia africana, Avicennia*, flooded tanne, barren tanne, herbaceous tanne. The tannes are generated by aridic climatic conditions, heavy soil and water salt content, and are, in a way a peculiar feature of mangrove swamps in West Africa.

The sediment colonized by the mangroves is relatively homogeneous. Mineralogically, they are dominated by quartz and clay to which are associated halite, pyrite and jarosite. The clay suite is mainly composed of smectite and kaolinite. Smectite is predominant in the inlet areas and is replaced inland by kaolinite.

Chemically, the sediments contain very low amounts of Ca, bases and trace elements. The mangrove swamp floodwaters have a chemical composition similar to that of seawater. It is dominated by sodium and chloride.

Morphologically, the ripening of the soils appears with a chestnut mash colour horizon and buttery consistency in relation with the decomposition of fibrous roots of Rhizophora and also with pale yellow jarosite mottles in the top horizons of the tanne profiles due to the oxidation of pyrite.

The two main properties of the mangrove soils of West Africa are acidity and salinity; the first is related to the high content of sulphur and the second to the sea influence.

The acidity has to be connected mainly to the Rhizophora vegetation whose the root system is a real trap for catching the pyrites resulting from the reduction of the sulphates of sea water by the sulphate reducing bacteria, in a reduced environment rich in organic matter and iron.

The salinity is mainly related to the sea water which is flooding the mangrove or which flows through the water table up to the tanne. It is mainly sodic chloride.

From the geochemical point of view, the disequilibrium between mangrove and tanne is appearing by a high increase in the tanne area of silica in one hand due to the dissolution, partly of the quartz, but mainly of diatomaceous frustules, and increase of magnesium, on the other hand, due to the clay mineral weathering.

Résumé - Les mangroves sont présentes sur tout le littoral ouest africain, et plus particulièrement, du Sénégal à la Siérra Léone où elles couvrent une superficie d'environ 3 millions d'hectares. Elle font partie de la mangrove de type atlantique représentée par un petit nombre d'espèces de palétuviers dont *Rhizophora racemosa, Rh. mangle, Rb. harrissonii, Avicennia africana et Laguncularia racemosa.*

Le caractère commun à toutes ces mangroves est la présence, à l'arrière des palétuviers de zones nues, les «tannes», résultant de la sursalure des eaux et des sols, malgré des différences de pluviométrie importantes (500 mm au Sénégal, 3000 mm en Guinée).

Ceci est essentiellement dû à une saison sèche longue (6 mois et plus).

L'installation des mangroves sur le littoral ouest africain date de la transgression nouakchottienne, (5500 B.P.) et depuis, elles ont évolué sous l'influence de la sécheresse climatique.

Le sédiment colonisé par les mangroves est relativement homogène et a dominance de quartz et d'argile auxquels sont associés la halite, la pyrite, la jarosite et le gypse. La fraction argileuse est représentée par la kaolinite et la smectite, l'une étant fournie par le continent et l'autre étant apportée par la mer.

Du point de vue chimique, le sédiment de mangrove est caractérisé par ses très faibles teneurs en Ca et en éléments traces et les nappes phréatiques ont une composition chimique proche de celle de l'eau de mer.

La pédogenèse des sols de mangroves est liée à 2 facteurs, d'une part à la *pyrite*, provenant de la réduction des sulfates de l'eau de mer en sulfures, sous l'action des bactéries sulfato-réductrices et dont l'oxydation conduit à la formation de jarosite et à l'acidité de ces sols, d'autre part aux *sels solubles* liés à l'action de la marée et principalement au chlorure de sodium. Les sols sont tous sulfatés acides et salés.

Du point de vue géochimique, le déséquilibre entre la mangrove et le tanne se manifeste par une augmentation importante de la silice dans le tanne, resultant, en partie de la dissolution du quartz, mais aussi des frustules de diatomées. L'acidité de la nappe phréatique dans le tanne est aussi a l'origine de l'altération de certains minéraux argileux et de la néogenèse d'autres.

DEFINITION

Mangroves are evergreen forests between the land and sea, found essentially in the intertropical zone and occupying large areas along sheltered coasts, estuaries and in deltas where they are influenced by tides and widely differing conditions of salinity and rainfall regimes.

They are also found around coastal lagoons communicating with the sea and where the effect of tides may be very weak and the salinity very low. Substrata are mostly composed of fine recent clay or silt sediments, but also of sand and peat.

In West Africa, mangroves occupy large areas from Saloum Estuary, in Senegal, to Sherbro bay in Sierra Leone. Their extension are restricted along the coast from Liberia to Niger Delta, and again they occupy large areas on the coastal zone from Niger Delta to Gabon (Fig. 1).

The studies concerning geomorphology, sedimentation, geochemistry and mineralogy of the mangrove swamps sediments are relatively recent and date from the last twenty years. Most of the works are related to Senegal: Diop (1986), Kalck (1978), Marius (1985), Marius and Lucas (1986), Pimmel (1984), Viellefon (1974) and as said Rollet (1981) in the bibliography on mangrove research "Senegal is the most important research center on pedogenesis". In other countries, like Sierra Leone, Guinea, Benin, Gabon, etc., research works are related mainly to geomorphology or sedimentology of surface sediments. The main works are due to Pons-Ghitulescu (1986) for Bissau; Aubrun and Marius (1986) and Diop (1986) for Guinea; Anthony (1983, 1988) for Sierra Leone; Lang *et al.* (1983, 1986) for Benin; Lebigre and Marius (1984, 1986) for Gabon.

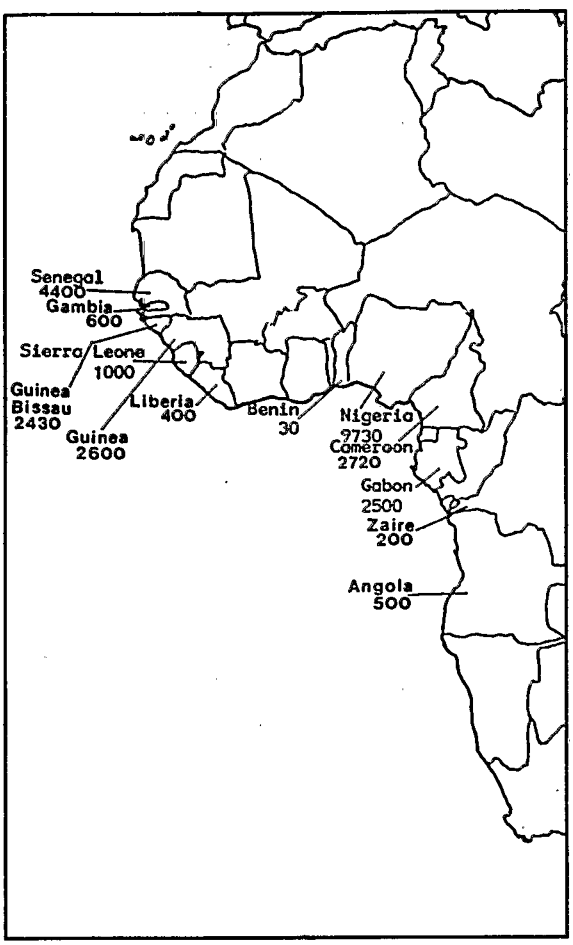

Fig. 1. Geographical distribution of mangroves in West Coast of Africa. (Saenger *et al.*, 1983).

MANGROVE ENVIRONMENT

1. Factors of mangrove development

Three main factors are governing the development of mangroves: climate, ocean influence and fresh water influence.

a) Climate - From Senegal to Sierra Leone the climate is tropical with two contrasted seasons: one rainy season from May or July up to October and one dry season from November to May or July. The mean annual rainfall varies from 900 mm in Senegal which is semi-arid to 4000 mm in Sierra Leone which is typically humid tropical. A climatic change toward aridity has taken place from 1968 in Senegal and Guinea-Bissau due to the drought and mainly to the contraction of the wet season. Table 1 shows the mean annual rainfall for six stations.

From Liberia to Gabon, the climate is typically equatorial with two wet seasons and two dry seasons. The mean annual rainfall is generally higher than 2000 mm and in Gabon it is close to 3000 mm.

b) Oceanographical factors - These factors are conditioning the development of the intertidal area and so, they have a big effect on the hydrodynamical regime of the estuaries.

Among these factors, two are very important. The extent of Continental shelf and the influence of surges from which two areas may be differentiated:

From Senegal to Sierra Leone, the surge is weak and the tidal range is relatively high, up to 4 m. It is typically a "ria shoreline" in the estuaries of which the tide penetrates very far.

On the other hand, on the shoreline from Liberia to Gabon, the Continental shelf is very short and the surge is very strong giving sand ridges and lagoons.

c) Hydrological factors - Mangrove trees possess a common ability to survive and

Table 1. Mean annual rainfall (mm).

	Kaolak	Banjul	Zinguichor	Bissau	Conakry	Forecariah
1960-1970	775,5	1086,8	1465,9	1953,7	4209,3	3009,5
1971-1983	449,5	860,3	1046,9	1521,1	3686,8	2907

perpetuate themselves along sheltered tropical coastlines in saline environments under tidal influence. So, mangrove swamps are tidal swamps influenced by the daily or the twice-daily tides. The distance to which tidal fluctuations are observed in rivers of West Africa depends on the elevation of the river bed, the river discharge and the tidal range and period. In the Casamance River (Senegal) saline tidewater intrudes more than 200 km upstream in the dry season; in the Gambia River, more than 500 km (Marius, 1985). During the wet season, high river discharge and seasonal inundation cause higher water levels.

But the main characteristic of the west African estuaries is the presence of numerous anastomosed tidal creeks. The mangrove trees - *Rhizophora* mainly -occupy only a thin strip back of which are developing large areas of barren hyper- saline flats, locally called "tannes".

2. Vegetation. Mangrove species zonation

West African mangrove is a part of Atlantic mangrove, characterized by six species of trees: *Rhizophora racemosa, Rhizophora mangle, Rhizophora harrissonii, Avicennia africana, Laguncularia racemosa, Conocarpus erectus.* These mangrove forest trees are often associated with salt water, brackish water and freshwater swamps of numerous species: *Sesuvium portulacastrum, Philoxerus vermicularis, Paspalum vaginatum, Scirpus littoralis, Eleocharis mutata, Typha sp., Cyperus sp., Achrosticum aureum.*

The distribution of these species and their zonation are strictly related to the soil evolution. It is the "chronosequence".

In estuaries and lagoons which are protected from the surge and the winds and characterized by a low sedimentation and a lot of tidal channels the tidal range is lower than 1 m. In this case, *Rhizophora* is the pioneer species. Then, along the shorelines, tidal range is high and *Avicennia* is the pioneer species.

In humid tropic areas (Guinea, Sierra Leone ...) the typical chronosequence is:

- mangrove forest with *Rhizophora* or *Avicennia*;
- brackish water swamps with *Eleocharis*;
- freshwater swamps with *Cyperus, Phragmites*;
- swamp forest with *Achrosticum aureum, Echinocloa, Montricardia arborescens.*

In some parts (Guinea-Bissau) we can observe some spots of "tannes".

In dry tropic areas (Senegal), *Avicennia* is scarce and the "tanne" areas are larger and more frequently characterized by hyper salinity and the occurrence of bare flats with salt crusts.

A typical sequence of vegetation is as follows:

- a thin strip of *Rhizophora racemosa*;
- *Rhizophora mangle* forest;
- *Avicennia africana* mixed with *Rh. mangle*;
- a bare flat: "tanne vif";
- a herbaceous marshy flat: "tanne herbacé".

Due to the drought which began in 1972, the changes in vegetation were very spectacular and the general trend was for the forest to disappear and for the bare flats, especially the salt crusted bare tannes to expand at the cost of the herbaceous tanne (Fig. 2). In Bissau, the vegetation of the northern part is similar to Casamance vegetation, in the southern part it is similar to Guinea vegetation .

In conclusion, the plant species zonation in mangrove swamps of West Africa is mainly related to the salinity of soils and water and, they are thus characterized by the presence of saline or hyper-saline bare flats: the "tannes".

GEOLOGY

1. Morphology

Mangrove swamps, marshes and tannes (bare flats) develop in four tidal zones.

a) The lower intertidal zone is exposed only at low tide and corresponds to the lower slikke of

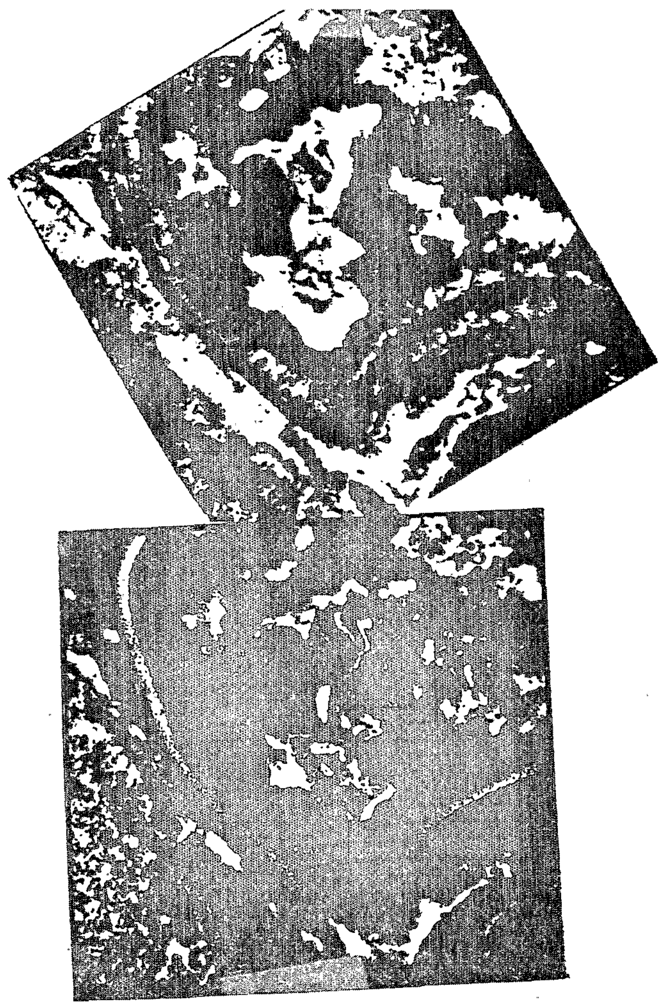

Fig. 2. Aerial photograph of mangrove-tanne association in Casamance. 1) 1969. 2) 1978.

temperate regions. This zone consists of bare mud-flats.

b) The middle intertidal zone lies between mean high and low water. It corresponds to the lower schorre of temperate regions and is colonized by mangroves. Since the onset of the Sahelian drought, there has been a considerable die-back of mangrove and the attendant development of tannes characterized by important crab populations.

c) The higher intertidal zone is flooded only during exceptional spring tides. This zone is either characterized by bare tannes or by *Eleocharis* marshes.

d) The non-tidal zone is flooted only during storm surges and consists of grass-herb swamps and low sandy terraces.

The last three zones correspond to the schorres of temperate regions.

2. Geological evolution during the Recent Quaternary

The infilling of all valleys along the coast of West Africa is generally attributed to the terminal phase of the Post-Glacial Marine Transgression whose peak is referred to as the Nouakchottian (Michel, 1973; Kalck, 1978; Tastet, 1975; Anthony, 1988; Oyede, 1983). Stages of the geomorphic evolution of these bays and inlets since the Middle Holocene have been schematically presented by these authors.

a) Senegal (Kalck, 1978) (Fig. 3)

- At the height of the transgression, towards 5500 B.P. the sea invaded the lower Casamance valley which then became a wide gulf.

- By 4000 B.P. (Fig. 3b), N-S longshore drift, attributed to a strengthening of northwesterly swell at around 4500 B.P., resulted in the formation of a series of beach ridges that progressively sheltered the gulf. In the vicinity of Diouloulou, basal beach ridge sands have yielded a ^{14}C age of 4310 B.P.

- By 3000 B.P., the Casamance gulf had developed into a vast lagoon characterized by intensive development of mangrove swamps (Fig. 3c).

- The Casamance finally attained its present morphology 1500 years ago (Fig. 3d). Closure of the gulf by beach ridges has led to a diminution of sediment inputs of marine origin and a considerable slow-down of the geomorphic evolution of the gulf. The low terraces identified by Vieillefon (1974) probably emerged at this time.

Infilling of the Casamance Gulf has thus involved two progradational sys tems: beach ridges and mangrove flats. The most important beach ridge sets are oriented N-S. Mangrove flats have progressively prograded over open areas of the lagoon (Fig. 4).

b) Guinea Bissau (Pons, 1985) - The estuarine sediments of Guinea Bissau were deposited during the Holocene. During the Nouakchottian, the sea invaded all the estuaries in this region. Sea level dropped slightly in the Middle Holocene, resulting in the formation of the terraces which border the Continental Terminal. These terraces are essentially clayey, in contrast with those of Senegal which are sandy.

Sediments deposited during the rise in sea level following the negative Middle Holocene pulsation are essentially clayey and are designated by Pons *et al.*, (1985) as recent estuarine sediments (ER). These deposits of Upper Holocene age involve two phases of predominantly detrital sedimentation separated by a phase of organic sedimentation associated with mangroves. The older of the two inorganic phases, dated by Michel (1973) at between 4000 and 1800 B.P., is characterized by pyrite-rich clays with traces of Rhizophora mangroves (ERr). The younger phase exhibits pyrite-poor clays associated with Avicennia mangroves (ERa). It is probably no older than 500 B.P. The style of sedimentation identified in Guinea Bissau is applicable to the entire Guinean coast which is subject to a high tide range.

c) Sierra Leone (Anthony, 1988) - The Holocene coastal sedimentary environments of Sierra Leone have been analysed by Anthony (1988) in a global study of the geomorphology of this coast. The southern sector, from Sherbro Island to Liberia, is characterized by prograded beach-ridge plains behind which have accumulated freshwater fluvio-lagoonal deposits. North of Sherbro Island, open-coast mangrove-colonized tidal flats alternate with major estuarine complexes and headlands of hard rocks (Freetown Peninsula) and soft, locally cliffed and retreating sedimentary out-crops (Bullom Peninsula) (Fig. 5).

Phases of the late Pleistocene and Holocene development of this coast were also studied by Anthony (1988). Coastal translation during the Post-Glacial Marine Transgression has varied markedly between the northern sector, adjacent to a wide shelf, and the southern sector which borders a narrow shelf. In the north, from 18 000 B.P. to 5500 B.P., the transgression led to rapid coastal translation under low energy conditions that allowed for the preservation of various drowned coastal forms on the shelf. Since 5500 B.P., coastal progradation, in the form of mangrove-colonized tidal flats, essentially has been limited to areas adjacent to major estuarine complexes, notably Sherbro and Yawri Bays and the Scarcies estuary. This coast experiences a mesotidal tide-range and is fronted by a 150 km-wide, low-gradient shelf which dampens wave energy, and amplifieg tide range, thus allowing for

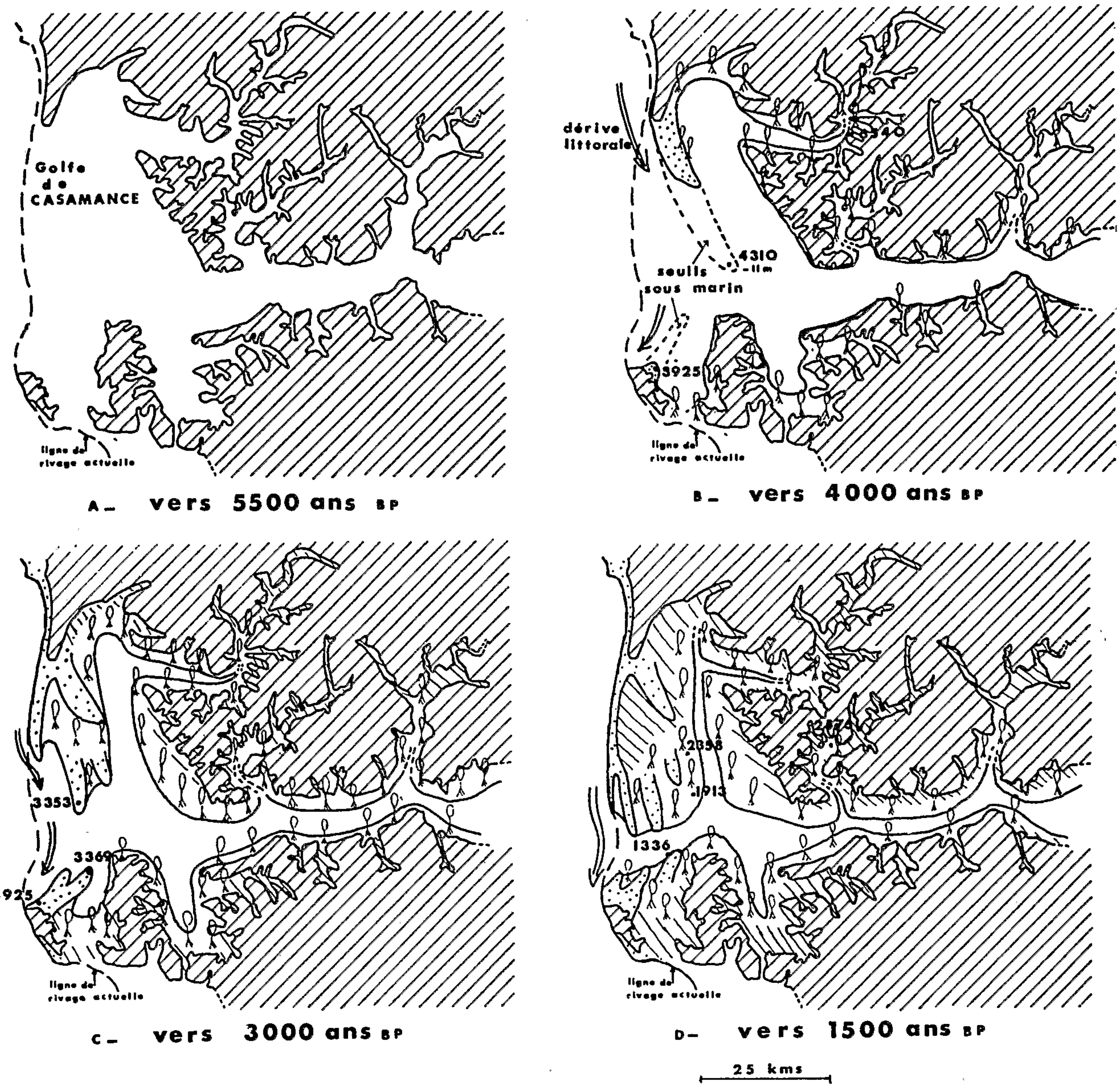

Fig. 3. Late Quaternary evolution of the Casamance Gulf. (Kalck, 1978).

Continental Terminal | Cordons littoraux | Zones de mangrove | Terrasses abandonnées et tannes

A. ca. 5 500 B.P. Casamance gulf; present shoreline — C. ca. 3 000 B.P.
B. ca. 4 000 B.P. longshore drift; submarine shoals — D. ca. 1 500 B.P.
- Continental Terminal - Mangroves - Beach ridges - Abandoned terraces and tannes

deposition of fluvially-supplied muds. In the extreme north of Sierra Leone, where tidal flat progradation has been most pronounced, chenier ridges of quartz sand also occur. They probably reflect phases of climatically-induced decreasing of mud supply since the Middle Holocene as well as the effects of internal geomorphic changes proper to the coastal plain as progradation proceeded.

In the south, where the continental shelf is deep and less than 50 km-wide, a slow, moderate to high-energy transgression resulted in reworking and regularization of the shelf surface. At the end of the transgression, towards 5500 B.P., a high influx of sand from accreted equilibrium estuaries, coupled with a shallow shoreface, led to rapid progradation of a 180 km-long and 5-18 km-wide beach-ridge plain.

Anthony (1988) has shown that the change in coastal progradational type in Sierra Leone, from sandy in the south to muddy in the north, represents a major geologically and dynamically controlled change in the coastal geomorphology of West Africa. The coast of Sierra Leone thus

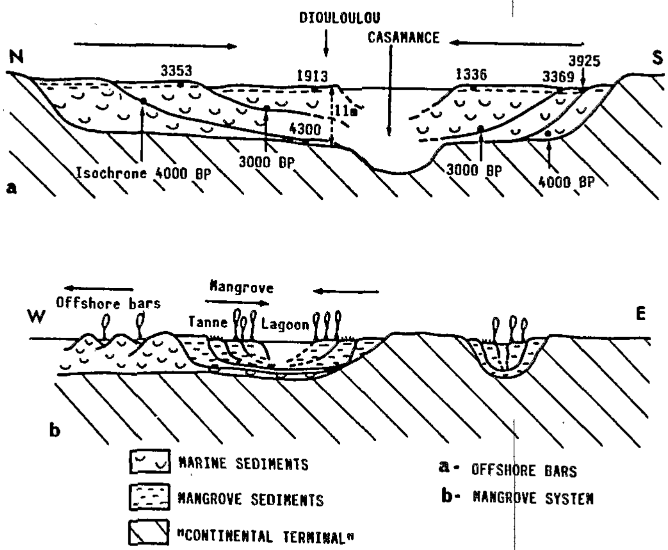

Fig. 4. Progradational systems in the Casamance (Kalck, 1978)
a) beach ridges; b) mangrove flats; lagune = lagoon.
- Marine sediments
- Mangrove sediments
- Continental Terminal

constitutes a major morphodynamic junction in west Africa.

d) Côte d'Ivoire (Tastet, 1979) - Studies on the Recent Quaternary in the Côte d'Ivoire are very few. Tastet (1979) has presented the following interpretation:

- The last high sea level stand during the late Pleistocene was higher than the present. Wave action resulted in cliffing of the Continental Terminal. No other evidence for this transgression has been identified.

- During the regression that followed, sea level may have attained a low stand of -100 m. The climate, drier than the present, was marked by a seasonal rainfall regime. Fluvial and sheetwash sedimentation of material derived from the Continental Terminal resulted in the elaboration of a sandy-clayey glacis at the foot of the Continental Terminal cliffs.

- Between 23000 and 11000 B.P., the change from a dry to a humid climate, attended by a lag in the establishment of the corresponding vegetation, led to the incision of deep valleys in the poorly consolidated glacis sediments. The north-south ant east-west orientation of this drainage network was probably controlled by the local tectonic framework.

- During the last transgression, the sea invaded the lower reaches of this drainage network, creating a vast system of rias. Fluvial sedimentation resulted in the formation of deltaic complexes while strong west-east longshore drift resulted in the formation of beach ridges which closed off the rias into discrete lakes and lagoons. Beach ridge formation has been most important west of Vridi.

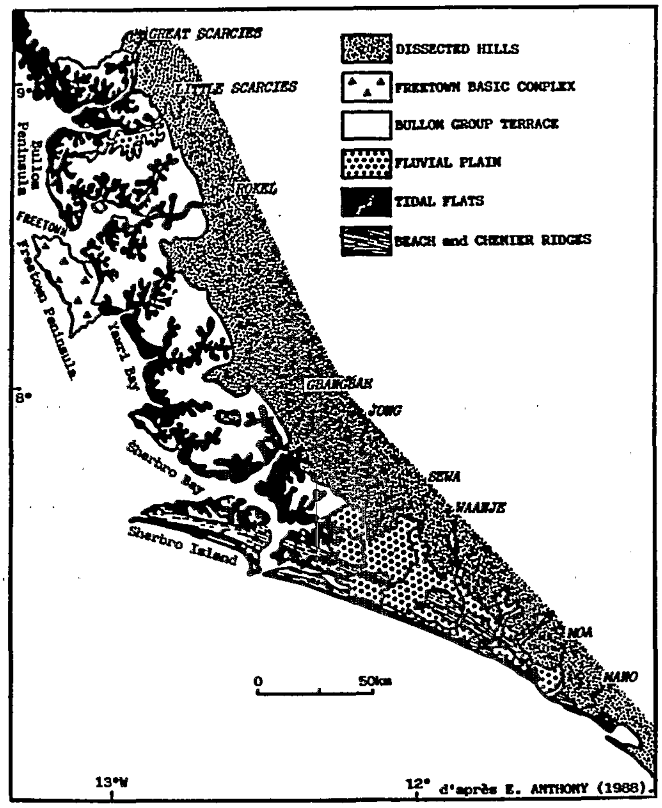

Fig. 5. Geomorphic units of the coast of Sierra Leone.

A recent small regression has led to the emergence of white sands along the edges of the lagoons. These sands have been subject to leaching, a phenomenon accentuated by water table fluctuations. Moreover, the deltaic formations of the Bandama and Komoe have gradually emerged, isolating several lagoons.

e) Benin (Oyede, 1983) - In a study of biodetrital Quaternary sedimentation in Lake Ahémé, Oyede (1983) has proposed the following interpretation of the Recent Quaternary in Benin.

At the height of the Nouakchottian trangression between 6000 and 5000 B.P., the sea invaded the lower reaches of the Onémé, Couffo and Mons rivers (Fig. 6). North of the present Lake Ahémé, a mangrove cover, denser than the present one, led to the accumulation of close to one metre of peat dated by Germain (1975). This vegetation was established at a time when sea level was slightly higher than at present.

The Post-Nouakchottian negative pulsation has been marked by a succession of beach ridges, the oldest of which have been dated from 5000 B.P. (Paradis, 1977; Lang and Paradis, 1982). Coastal progradation has thus led to progressive isolation of Lake Ahémé from the sea. The upper 3-4 m of lacustine sediments consist of muddy sands and muds, indicating conditions of Post-Nouakchottian sedimentation similar to those of today. The phases described by Oyede are in

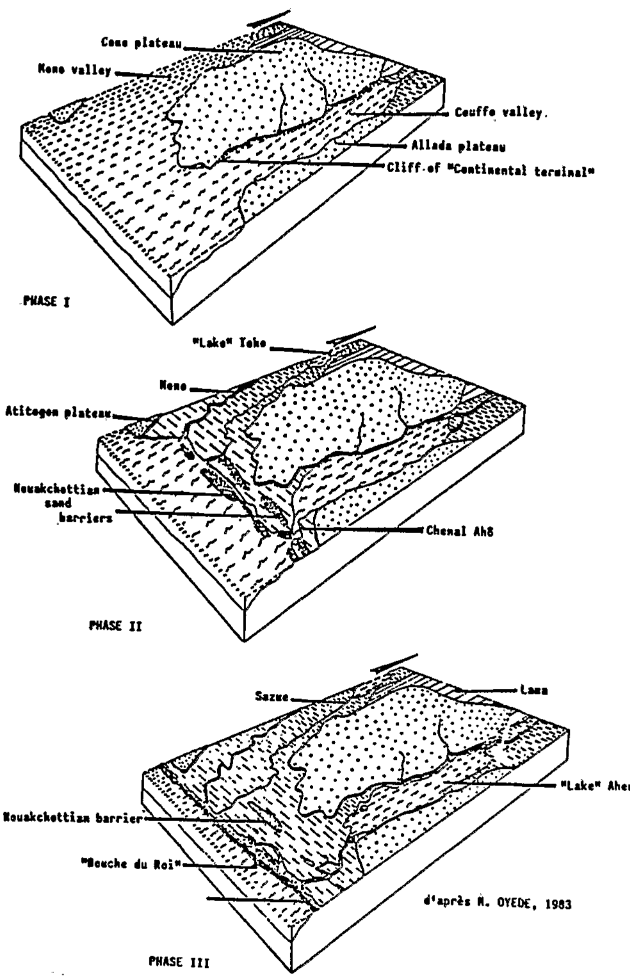

Fig. 6. Recent palaeogeographic evolution of Lake Ahémé. (Oyede, 1983).

accordance with those proposed by Sall and Diop (1977) and Faure and Hebrard (1977) and Faure and Williams (1977) for the Casamance estuary in Senegal. To summarize, the lower Couffo valley was invaded by the Nouakchottian transgression between 6000 and 5000 B.P. Sediments derived from Mio-Pliocene and Quaternary plateaux of the coastal basin were deposited on older sediments. As sea level started to fall after the Nouakchottian, a wide beach ridge plain was built south of Guezin. These beach ridges presently isolate the water body of water referred to as the Ahémé.

f) Gabon (Lebigre and Marius, 1986) - The knowledge on Quaternary marine sedimentation in Gabon is still rather rudimentary. No traces of former shorelines above present sea level have been identified. Lebigre and Marius (1986) propose four major phases associated with sea level fluctuations.

- The Inchirian transgression presumably attained a level close to present zero 40000 to 30000 years ago. Mangroves may have become established during this humid Intra-Wurm phase but no evidence to this effect has been found.
- The Ogolian regression (22000 to 16000 B.P.) associated with a drier climate than present, resulted in a sea level drop of 120 m. The beach ridges bordering the Bay of Mondah were probably built as sea level progressively started falling.
- The Holocene transgressive phase (8000 to 5000 B.P.) was followed by submergence of the bay. Succession of fluviatile and marine sediments deposited during this phase have progressively filled in part of the bay, allowing for the establishement of mangroves. In the Gabon estuary, several minor climatic oscillations (Weydert and Rosso, 1981) resulted in alternations between marine and fluviatile conditions. It is doubtful whether fluviatile influences have at any time been predominant in the Bay of Mondah where most of the sediments appear to be of marine origin. Confirmation of this tendency would necessitate drilling of bay sediments.
- The minor Taffolian regression (3000 B.P.) has had very little impact and has heralded present conditions.

g) Conclusion - Establishment of mangroves along the West African coast dates back to the Nouakchottian transgression, i.e. from 5500 B.P. to ca. 1500 B.P. Mangrove evolution has since been considerably influenced by drought conditions, as will be seen below in a discussion of mangrove soils.

3. Sedimentology

a) Grain size characteristics - The only detailed grain size study of mangrove formations has been carried out in the Casamance and Saloum areas of Senegal where several deep (up to 20 m) boreholes were sunk using a stationary piston corer.

Seven cores covering the Casamance estuary from the mouth to upstream of the tidal limits have been studied by Pimmel (1984) who showed the existence of a major vertical and lateral discontinuity. This discontinuity is characterized by:

- a sharp change in facies, from sands at the base to clay deposits;
- a change in grain size curves from current or compound type parabolic curves to hyperbolic curves;
- variations in flow competence and energy under equilibrium conditions (Fig. 7a);
- variations in transport rate (Fig. 7b).

The depth of this major discontinuity increases upstream, from less than 1 m at Diouloulou to 3, 4 and 5 m respectively at Oussouye, Baila and Balingore.

Lateral evolution is marked by a change from heterogeneous sandy clays down-stream at Diouloulou, Oussouye, Baila and Balingore to essentially clayey and homogeneous facies at Tobor, Ndieba, and Bona. The upstream zone has thus

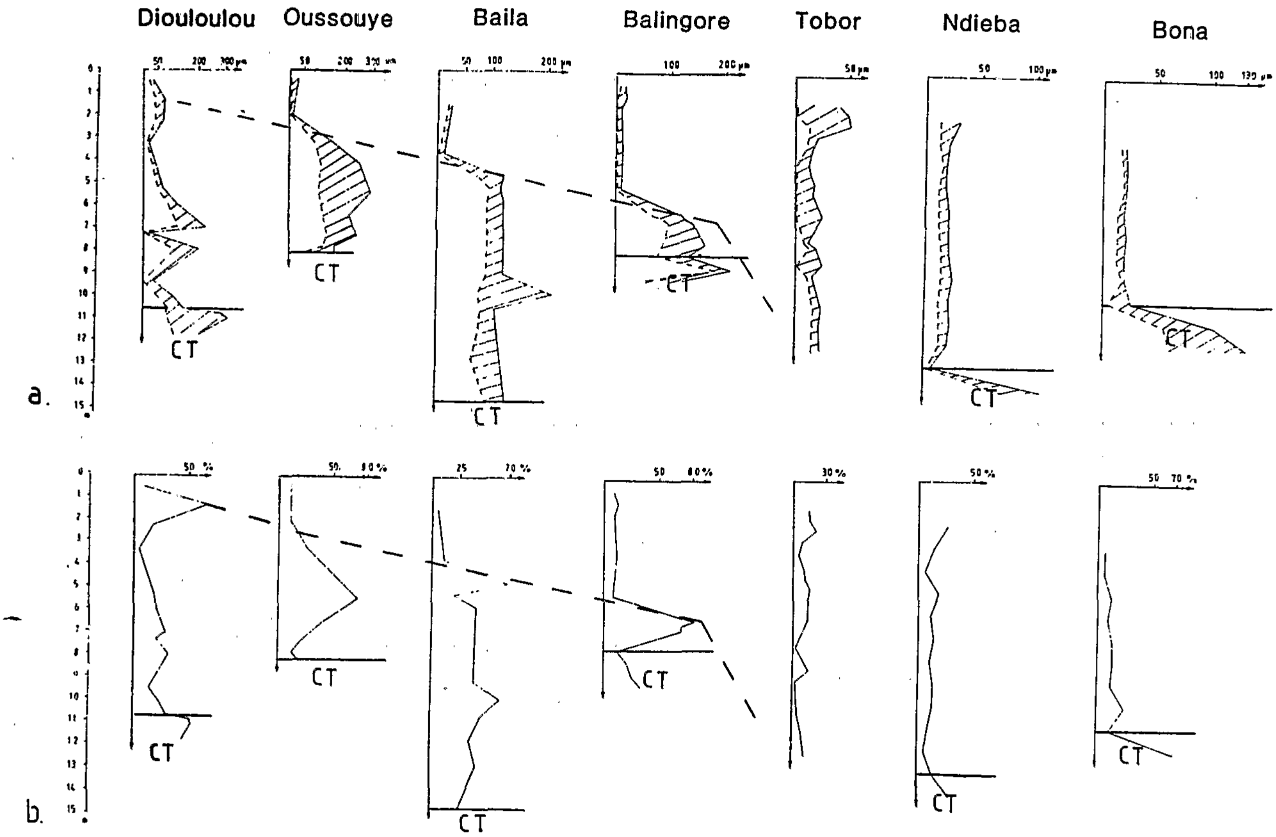

Fig. 7. The sedimentary discontinuity in cores from downstream to upstream. The discontinuity is expressed by: a) variations in flow competence; b) transport rate under equilibrium conditions (Pimmel, 1984) C.T.: Reworked or non-reworked Continental Terminal.

been characterized by flow conditions of low energy and low competence. The sandy facies is absent upstream.

The sands are essentially medium to very fine in size and were deposited from excess transport loads («current» or «compound» parabolic facies).

Clays exhibit constant hydrodynamic characteristics. Two modes of sedimentation predominate:

- the first reflects settling processes that were slightly modified by low energy and low competence flow under equilibrium conditions;

- the second results from excess suspended load after transport over a short distance, followed by settling out of particles.

In the downstream part of the estuary, analysis of the clayey deposits overlying the basal sands at Diouloulou, Oussouye, Baila and Balingore show that settling out is the dominant mode of sedimentation. Upstream, at Tobor, Ndieba and Bona, sedimentation from excess loads dominates, especially in the last two cores. These two facies were associated with specific environments:

- hyperbolic curve clay facies represent settling out after floods over low marshes limited by levees or by the sand facies. Vegetation, especially *Rhizophora*, may have played a role in the trapping of muds;

- compound type curves correspond to clays undergoing discontinuous transport in the upstream part of the Casamance river where marine influence was less important. These channel deposits accumulated from excess suspended loads.

In comparison, the Saloum estuary is characterized essentially by sands of marine origin, with little or no sediment inflow from upstream zone.

On the Guinean coast, sediments are predominantly clayey or silty-clayey deposits reworked from older coastal clays.

In Benin, Gaillard *et al.* (1982) and Oyede (1983) have clearly demonstrated the complex nature of mangrove sediments through the analysis of several cores. They have also shown that mangroves play a role in the accumulation of these sediments (Fig. 8). Grain size curves show that the lowest median values occur in the upper part of the profiles where the very dense network of mangrove roots leads to active sedimentation of the finest particles. The resulting curves are of the hyperbolic type. 35 to 60% of the clays have a diameter of less than 0,1 μ. The multiple origin of detrital material (Mons river, Continental Terminal and Atlantic Ocean) and current activity result in very poorly sorted (several sediment stocks) and immature (absence of plurimodal curves)

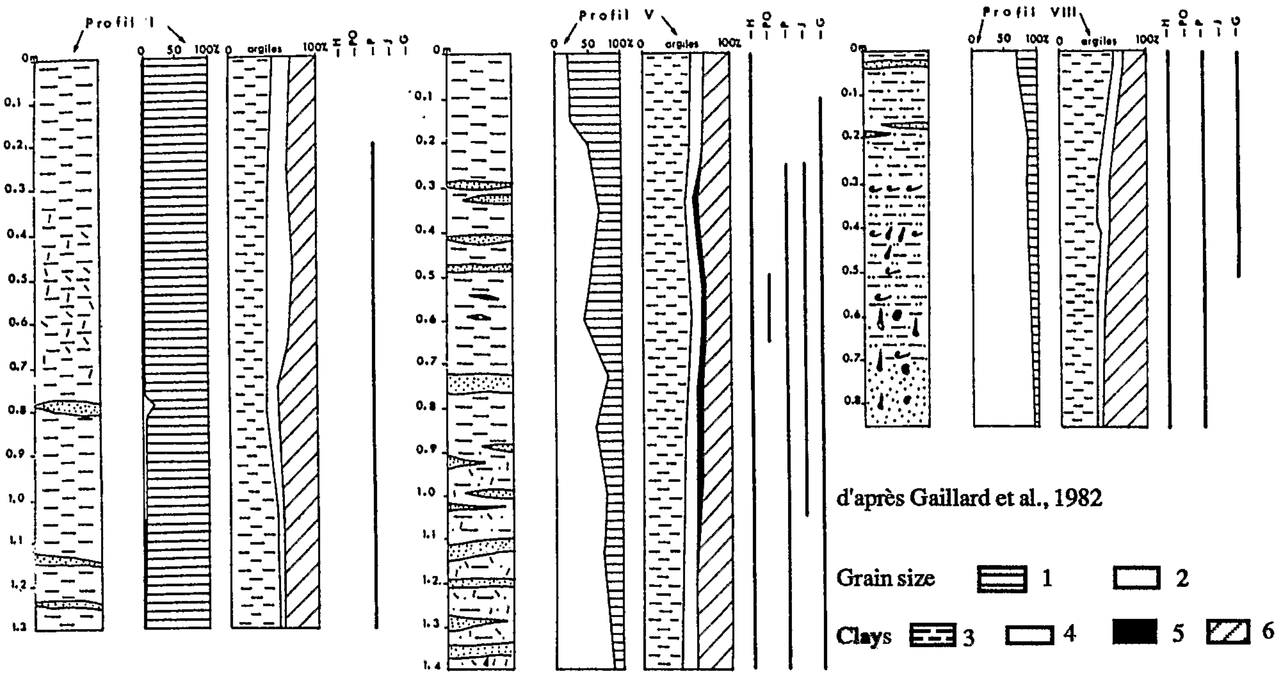

Fig. 8. Grain size analysis of some typical drilled cores of Benin (Gaillard *et al.*, 1982).
Analysis of some typical drilled cores:
- Grain size analysis: 1. Fraction finer than 80 µ; 2. Fraction coarser than 80 µ.
- Clays: 3. Kaolinite; 4. Illite; 5. Interstratified minerals illite-smectites; 6. Smectites.
- Mineralogy: H. Halite; Po. Polyhalite; P. Pyrite; J. Jarosite; G. Gypsum.

sediments. However, these mangrove sediments do constitute a distinct grain size facies: similarity of grain size curves, high proportion of very fine particles, rather similar plurimodal distributions for the sand fraction dominated by a median diameter of about 300 µm; curves also exhibiting better sorting towards the coarser fractions probably as a result of winnowing of fine particles.

b) Mineralogy of sediments - From Senegal to Gabon, mangrove sediments are characterized by remarkable mineralogical homogeneity. The mineral suite consists essentially of quartz, clays, feldspars, halite, pyrite, jarosite and gypsum. Halite is related to the salinity of interstitial water while pyrites result from bacterial reduction of sulphates of marine origin under anaerobic conditions and in environments rich in organic matter. Jarosite results from bacterial oxidation of pyrites. Gypsum occurs mainly in dry or arid regions such as Senegal and Benin.

In Guinea and Sierra Leone, gibbsite, derived from weathered bauxitic material, is also present in the clay fraction.

The clay fraction is essentially dominated (80-90%) by a kaolinite-smectite association, the rest consisting of illites and interstratified clays of the illite-smectite type.

Kaolinite is of the fire-clay type and its constance probably reflects a unique origin, from the Continental Terminal. Kalck (1978) has shown that smectites in the Casamance estuary are essentially of marine origin. Smectites are basically ferriferous beidellites (Kalck, 1978; Oyede, 1983) and, at least as far south as Sierra Leone, may be transported from the Senegal-Mauritania area by the surface Guinea current that flows from North to South off the West African coast (Anthony, 1988).

c) Geochemistry of the sediment - The chemical composition of the mangrove swamp sediment studied from very numerous samples from Senegal, Guinea, Sierra Leone and Gabon shows a great homogeneity and stability. The common characteristic is the relatively large lack of calcium, and partly, of magnesium. The clay content plays a leading part in that environment to fix the sediment mineralogy by controlling organic matter and pyrite content. Mangrove sediment is rich in carbon and sulphur. Trace element contents are constant.

SOILS

1. Morphological features of mangrove soils

The morphological evolution of soil profiles is expressed by the following features: sediment colour, colour of mottles and consistency of horizons; these features are related to the degree of physical and chemical ripening of the profile.

Examination of a homogeneous profile, under *Rhizophora*, generally rich in poorly decomposed organic matter made up essentially of dark coloured fibres and rootlets, without mottles and having a fluid unripe consistency brings out the following differences (Fig. 9):

a) at the bottom, fibrous matter, in a reduced state, occurs in all the sequences at a depth of less than one metre;

b) above, the development of subsurface horizons is expressed by the occurrence of a brown horizon ("chestnut mash") having a butter-like semi-developed consistency with fibres undergoing decomposition. This horizon sometimes exhibits jarosite mottles which are localized in *Rhizophora* root "pipes". These features are especially associated with most profiles under flooded tannes or dying mangrove swamps;

c) at the surface can be observed:

- on the one hand, profiles under *Avicennia* characterized by a light coloured horizon with no mottles and a well-developed consistency;
- on the other hand, profiles under tannes characterized either by numerous jarosite mottles and a well-developed consistency or by a semi-fluid consistency and a light grey or brown colour.

It can therefore be said that the morphological observation of profiles under mangroves or bare flats brings out clearly the transformation of sulphur compounds into jarosite.

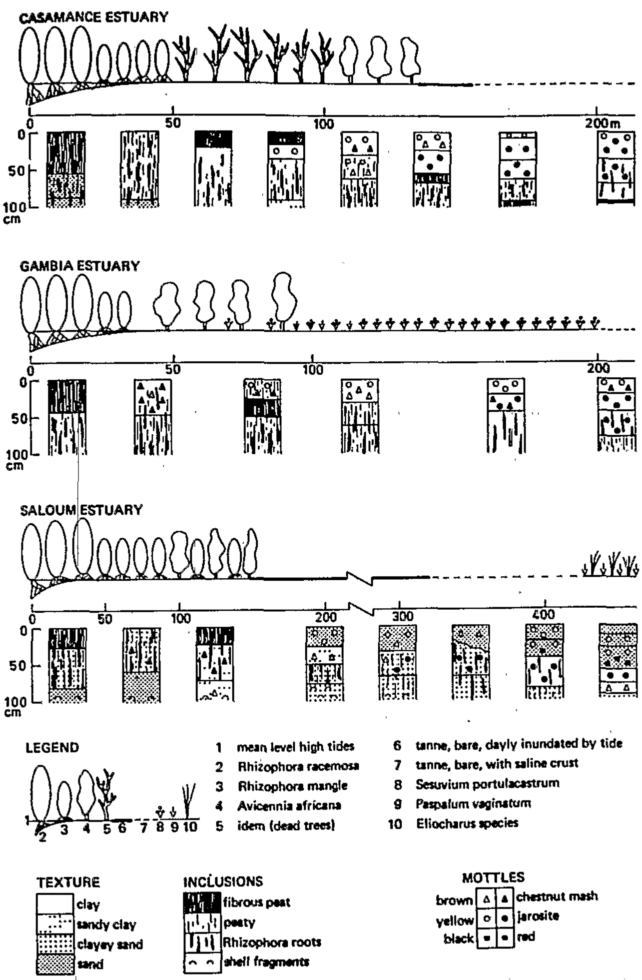

Fig. 9. Soils and vegetation in estuaries of Senegal and Gambia.

2) Physical characteristics

The bulk of the soil material of mangrove soils is made up of heavy clay with many inclusions of fibrous *Rhizophora* roots. Bulk densities of 0.3 to 0.6 are common and water contents are normally above 100%.

But the main physical characteristic of the mangrove soils is the consistency which is related to the physical ripening and which can be measured by a index "N" related to the water content, to the clay fraction and to the organic matter content:

$$N = \frac{A - 0{,}2(100\text{-}L\text{-}H)}{L + 3H}$$

in which A = water content in grams per 100 g of dry soil

L = clay content

H = organic matter content

The consistency can be estimated satisfactorily by squeezing the soil in the hand.

Pons (1965) has defined six types of consistency in relation with N index (Table 2). Most of the mangrove soils of West Africa are unripe or half-ripe. As a result of a high macroporosity, lateral and vertical permeability are high and tidal influence pervades soil bodies up to several hundreds of meters from the creek banks.

3. Chemical characteristics

The two main chemical characteristics of the mangrove soils of West Africa are: the **acidity** related to sulphur and their compounds and the **salinity**, related to soluble salts of the seawater.

a) Acidity - pH is the main data of all the mangrove soils. Measured in the field, the pH is generally cloge to 6-6.5 under *Rhizophora* and close to 7 under *Aricennia*. It is the "in situ" pH. Measured in the air dried sample, the pH decreases to the values often lower than 4-3.5. The difference between the field pH and the dry pH is the "potential acidity". This is why these soils are called "Potential acid sulphate soils".

In West Africa, most of the "tanne" soils have a very acid pH. In the same way, when the *Rhizophora* mangrove soils are reclaimed for rice cultivation, using deep drainage system, the pH can decrease to the values close to 2. This acidity is due to the high content in sulphur compounds

Table 2. Classification of soil material according to physical ripening (Pons, 1965).

N-value	Designation	Suffix to horizon symbol	Description of consistency (valid for average clay content)
< 0.7	ripe	r	firm, does not stick to the hands, or only slightly, and cannot be squeezed through the fingers
0.7-1.0	nearly ripe	$w\alpha$	fairly firm, tends to stick to the hand, and cannot be easily squeezed through the fingers
1.0-1.4	half-ripe	$w\beta$	fairly soft, sticks to the hand, and can be easily squeezed through the fingers
1.4-2.0	pratically unripe	$w\gamma$	soft, sticks fast to the hand, and can be easily squeezed through the fingers
> 2.0	pratically unripe	$w\delta$	liquid mud, non kneadable

-mainly pyrite- of these soils. Indeed, the natural environment of the mangroves, groups together all the factors responsible for pyrite formation:

- sulphates which are continually brought in by sea water;
- ferric minerals contained in the sedimentary formations of the "Continental Terminal" which constitutes the inland drainage basins;
- metabolizable organic matter representing accumulations of *Rhizophora* roots and fibres;
- permanently present sulphate - reducing bacteria;
- an anaerobic environment;
- limited aeration (as a result of tidal action) necessary for the oxidation of sulphur into disulphides.

Under these combined conditions, pyrites are formed by:

- the reduction of sulphates into sulphides by sulphate-reducing bacteria;
- the partial oxidation of sulphur into poly-sulphides or into basic S accompanied by: either the formation of FeS (from iron oxides or ferri-ferous smectites) followed by the combining of FeS and S to give FeS_2; or direct precipitation of FeS_2 from ferrous iron and polysulphides.

When oxidized, either by natural way, either by artificial reclamation, pyrite turns into jarosite -a iron sulphate- characterized by its pale yellow colour, and there is a formation of sulphuric acid and a drop of the pH.

In very dry conditions like in Senegal, oxidation of pyrite can produce other sulphates like tamarugite, alunite... In aridic conditions, conspicuous gypsum cristals are found in the powdery saline crusts of bare tannes.

Most of the mangrove soils of West Africa countain significant amounts of sulphur up to 10% of total sulphur, generally trapped in the roots of *Rhizophora*, even though under *Avicennia*, the sulphur content is very low. So, the pioneer and dominant mangrove species is responsible for the future evolution of the soils to the acidity or not.

b) Salinity - All soils of the mangrove area of West Africa are more or less saline in natural conditions. Indeed, the waters which flood the mangrove swamps daily and the tannes occasionally are saline and are mainly composed of sodium chloride. Groundwater table circulation occurs laterally from the bounding tidal channels to the mangrove-tanne contact zone and its salinity evolution closely follows the tidal channel and the river which undergoes seasonal variations. In the tanne, on the other hand, water table movement occurs vertically and seems to be largely independent of the mangrove water table. Its salinity, which is very high compared to that of the mangrove zones hardly varies throughout the year. This marked difference between the mangrove water table salinity and that of the tanne is responsible for the formation of the latter zone and for its subsequent development. In mangrove swamps temporary water table desalinization favours the growth of certain halophytic plant species while permanently hyper-saline tanne conditions, associated with strong acidity indefinitely inhibit plant growth.

Even in Gabon and in Guinea, where the annual rainfall is higher than 3 m, salinity of waters and soils is often higher than sea water salinity.

Tables 3 and 4 give some salinity data for phreatic waters and soils, and show that the salinity everywhere is very high. This is due either to the contrasted seasons or to the location of these mangroves in lagoons.

The study of the chemical evolution of groundwater tables and interstitial water (soil solutions) confirms the existence of two disequilibrium zones (Marius, 1985):

- at the mangrove swamp/tidal creek contact area, SO_4 = and SiO_2 are trapped and respectively from pyrite and diatoms, while Ca^{++} and Mg^{++} are rapidly precipitated as calcite, talc and magnesite;
- in passing from the mangrove swamp to the tanne, there is an enrichment in SiO_2, Mg^{++} and SO_4 = and a K^+ and Ca^{++} deficit due to mineralogical transformations: dissolution of quartz and no doubt clay also; precipitation of gypsum and amorphous silica.

The effects of the climatic drought which has been affecting the sahelian zone for more than two decades now were studied in a mangrove-tanne sequence in Casamance. The drought has generated an important increase in water table and soil salinity and this has significantly modified plant zonation, with in particular, the disappearance of certain species *(Rhizophora, Scirpus, Paspalum)* and their replacement by species that are more adapted to highly saline conditions *(Aricennia, Sesuvium)*. Tannes have considerably expanded at the expense of mangrove swamp zones while soil morphological and geochemical features have undergone dramatic changes (appearance of brown mottles and acidification of subsurface horizons, development of a butter-like consistence, silicification of roots, formation of gypsum...).

CONCLUSION

Mangrove swamps of West Africa, were mainly, developed on recent Holocene sediments in estuaries, rias or bay areas.

Notwithstanding their large extent in latitude and in longitude, they have many common points.

- They are Atlantic type mangroves, characterized by a very small number of species and ecologically, by a distribution of the vegetation in which appear everywhere hypersaline areas: the tannes, which are, either bare-flots, either covered by halophytic plants.
- Except for the regions where the tidal range is high (South Bissau and Guinea) and where *Avicennia africana* is the pioneer species, everywhere else, *Rhizophora* is the predominant species.
- The sediment colonized by mangroves is relatively homogeneous. It is dominated by quartz and clay to which are associated halite, pyrite and jarosite. The clay suite is mainly composed of smectite and kaolinite. Smectite is predominant in the seaside and is replaced inland by kaolinite.

Chemically the two main properties of the mangrove soils of West Africa are acidity and salinity, the first property being in relation with the high content of sulphur and the second, to the sea influence.

Table 3. Phreatic Mater salinity, in mS/cm.

VÉGÉTATION	RHIZOPHORA RACEMOSA	RHIZOPHORA MANGLE	AVICENNIA	MANGROVE DÉCADENTE	TANNE INONDÉ	TANNE HERBACÉ	TANNE	RIZIÈRE
Saloum	104	111	137		148	283	115	
Casamance	21.5	21.8	41.7	21.5		148.5	115.3	
Gambia	46		54		65	130		
Guinea	19		55.4				62.5	34.8
Sierra Leone								
Gabon	71.6	55.9	35.7					

Table 4. Soil extract salinity in mS/cm.

VÉGÉTATION	RHIZOPHORA RACEMOSA	RHIZOPHORA MANGLE	AVICENNIA	MANGROVE DÉCADENTE	TANNE INONDÉ	TANNE HERBACÉ	TANNE	RIZIÈRE
Saloum	15	10.5	11.7	8.1	18.6	12.2	7.1	
Casamance	13	23	3.7			20	15	
Gambia	6.6	9.5	6.1	11.3		13.2		
Guinea	6.7		12.7				7.5	3.9
Sierra Leone	6					3.2	6.16	
Gabon	10.6		14		6.9	4.2	0.6	

Meanwhile, it is important to note that if the acidity is a non-reversing characteristic of these soils, the salinity, on the other hand, is only a temporary characteristic which can be reduced or eliminated by a climatic change or an appropriate reclamation.

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