Soil evolution and plant communities in coastal dunes near Veracruz, Mexico

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ABSTRACT

At the Ecological Research Station of La Mancha, north of Veracruz, a study on different dune soils linked to different plant communities confirms the coastal origin of the sandy substratum and explains the diversity of soil and vegetation in the zone. The environmental variations are particularly caused by recent tectonic movements as well as anthropic actions. Two types of dune development are observed. One, subject to permanent hydromorphism, is oriented towards carbonate accumulation and a limited clay formation under a perennial shrub vegetation with coriaceous leaves. The other, in areas of good drainage under a semi-deciduous tropical forest, is oriented towards carbonate elimination and formation of smectite clays. The latter evolution is mainly induced by the tropical forest ecosystem itself and leads to the formation of deep red-brown sandy-clay soils appropriate for sustaining an important biomass.

KEY WORDS: Coastal dunes – Soil development – Mexico.

RÉSUMÉ

ÉVOLUTION DU SOL ET COMMUNAUTÉS FLORISTIQUES SUR LES DUNES CÔTIÈRES DE VERACRUZ, MEXIQUE.

En climat tropical les dunes côtières peuvent, dans certaines situations protégées des vents dominants, se fixer et évoluer rapidement (PARKER-NANCE *et al.*, 1991 ; AMUNDSON et TEMBLACK, 1981). Dans ces conditions se forment des sols profonds sablo-argileux brun-rouge sur lesquels croît une forêt tropicale.

Sur la station biologique de La Mancha, Veracruz, des recherches furent entreprises afin de vérifier si les paramètres qui influencent le développement de la forêt sur les dunes sont liés aux sols et à leurs réserves minérales (KELLMAN et ROULET, 1990 ; KELLMAN, 1990). Mais la grande variété des groupements végétaux de cette zone ne semble pas se calquer sur la répartition des sols. Une étude intégrée de la géomorphologie (fig. 2), de la pédologie (fig. 4) et des groupements végétaux (tabl. II) confirme que le sable a partout la même origine, à la fois marine et continentale volcanique, mais la lithologie des dépôts a été bouleversée par des mouvements tectoniques récents (fig. 10). Les sols présentent, côte à côte ou en superposition, des horizons anciens de sable très altéré avec des horizons de sable peu évolué. La végétation a elle aussi subi des bouleversements, mais d'origine anthropique. Actuellement les espèces se concentrent en îlots qui colonisent à nouveau les sites favorables. Cette colonisation suit deux orientations distinctes qui se calquent sur les conditions actuelles d'évolution du sol. La première tend à former un bush arbustif d'espèces à couvert permanent de feuilles coriacées, la seconde tend à former des îlots de forêt tropicale avec des arbres à port élevé et un grand nombre d'espèces associées.

L'étude minéralogique des sols montre que les deux types de colonisation se répartissent sur des milieux totalement différents. Le premier est hydromorphe. Le substrat sableux est soumis à une calcitisation prononcée (fig. 4) sous un pH élevé et de fortes concentrations en Ca et Mg. La formation d'argile, un mélange smectite et chlorite (fig. 5 et 6), reste très limitée. Le second milieu est bien drainé, les carbonates tendent à disparaître du profil et un horizon B sablo-argileux bien structuré (fig. 7), à smectite (Beidellite) associée à de faibles quantités d'illite (fig. 9) et à des oxydes de fer, se développe. Les situations des horizons brun-rouge, en relation avec la présence passée ou actuelle de la forêt, tendent à montrer que cette évolution est dépendante du couvert végétal et de l'activité biologique liés à la forêt. En effet elle ne s'observe pas en dehors des foyers de régénération forestière.

MOTS CLÉS : Dunes côtières – Évolution du sol – Mexique.

INTRODUCTION

Different stages of plant colonization are observed in the majority of coastal sand dune environments. They constitute vegetational zonation in relation with contrasted local variations in physical and climatic conditions, such as wind velocity (PLUIS, 1992), topography and grain size distribution (NARUSE *et al.*, 1992).

In cold to temperate climates plant colonization and soil evolution of coastal dunes remain only at low grades of development (CARTER and WILSON, 1990). In contrast, under warmer to tropical climates and during long periods of time some protected areas of dunes can reach high grades of evolution towards stabilization, as described in South Africa (PARKER-NANCE *et al.*, 1991) and California (AMUNDSON and TREMBACK, 1989). In these conditions dunes develop deep red sandy-clay soils where tropical forest grow. Nevertheless, conditions prevailing on the evolution of a loose sand into a structured soil are not actually completely clear.

In order to verify the influence of soil nutrients on the vegetational zonation in coastal dunes under tropical conditions, preliminary investigations were carried out at the biological station of La Mancha, Veracruz. The various dune soils demonstrated two different groups of responses to nutrient retention. One group is related to recent sand which does not support a forest. The other group is related to the intensely weathered sand forming a deep sandy-clay soil and supporting a semi-deciduous tropical forest. In this group a notable retention of cations as well as anions such as nitrates was observed in the soil. Furthermore, other results on dune soil leaching and absorption capability were obtained from experiments using titrated solutions (KELLMAN and ROULET, 1990). In the apparently non-weathered sand dune where no forest has developed a large variety of results were obtained. This variability signifies that dunes are probably edificated from various sandy materials of different ages and rates of weathering resulting in a wide diversity of soils in the zone, from loose sandy soils to deep red-brown and structured soils. This diversity is not only existing in soils but also in vegetation. Various communities ranging from the pioneer shrubbery to the medium subperennial tropical forest (RZEDOWSKI, 1978) are observed along short distances. They correspond to different plant successions following the colonization stages of dunes (MORENO-CASASOLA, 1982), leading finally to stabilization.

In the stabilization process root development plays a very important role. Each plant community shows its own development dynamics of fine root system and soil occupation in regard to the absorption of the available nutrients (KELLMAN, 1990). Among the various communities, subperennial tropical forest seems to be the most adapted to surficial nutrient absorption in having a highly developed superficial radicular system (KELLMAN, 1990). In this dune environment, subperennial tropical forest appears to be the most complex plant association with a high number of species and a high grade of development in comparison with the other plant communities.

These first results about vegetation and soil response to nutrient solutions show that highly developed plant communities, such as subperennial tropical forest, grow upon intensely weathered dune soils. These results suggest a relation between soil development and plant growth and, more particularly, suggest that the specific capabilities of the subperennial tropical forest to cycle nutrients and grow into an important biomass have an effect on dune soil evolution. However, to verify the impact of the subperennial tropical forest on soil evolution, a detailed study of dune soils and parent materials appears to be necessary. The purposes of this study are, first, to assess the various degrees of weathering occurring in the sand dune and then, to profile the processes prevailing on soil and vegetation distribution as they are currently observed in the zone. Then, relations between red-brown soils and actual or past semi-deciduous tropical forests will be presented.

MATERIALS AND METHODS

Site description

The study was conducted in the ecological reserve of La Mancha, located on the shore to the north of Veracruz, 19°30' northern latitude and 96°30' western longitude (Fig. 1). The average annual rainfall in the region is 1, 300 mm distributed in two well-defined seasons, a dry season with a temperature decrease due to the strong winds from the north, from December to May, and a rainy and warmer season from June to November (MORENO-CASASOLA, 1982).

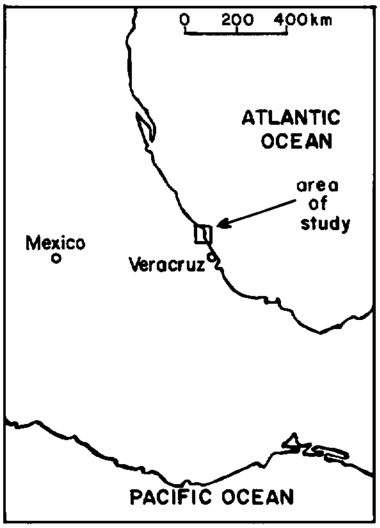

FIG. 1. – Location map
Carte de localisation

Methods

Geomorphology of the area was reconstructed from field observations of natural cuts along the shore and interpretation of aerial photographs at scale 1/50,000 enlarged to 1/20,000.

A plant inventory was carried out of the entire area. Four sites were selected as representative of the plant communities, from arboreal bush to a dense forest relic of the primary subperennial tropical forest. In each site we grouped the tree species in relation with their origin and their actual distribution.

By means of several drillings and four pits dug at depth 2.5 m in the four previously selected sites, soils were observed beneath the most representative plant communities in the zone.

Sampling and Analysis

Eleven non-disturbed and oriented soil samples from depth 10 cm to 200 cm were collected to get thin soil sections after polyester resin impregnation. Observations were carried out using optical microscope with polarized and natural light device.

Seventeen mineralogical analyses by XR diffraction, using a Siemens D 500 diffractometer with Cu anticathode, were carried out in Orstom laboratories in France. Two samples were separated for total soil analysis and fifteen for clay fraction (particle size<2 µm) analysis.

The chemical (pH, cation exchange capacity, exchangeable cations) and physical (particle size) analyses from the seventeen soil samples were carried out at the Instituto de Ecologia A.C. soil laboratory in Mexico. Dry soil less than 2 mm has been previously ground. Cation exchange capacity and exchangeable cations were obtained using NH4OAc. Carbonate quantity was calculated separately using HCl N/10 in pH4 conditions.

RESULTS

Field Observations on Geomorphology

The La Mancha region is uniquely situated in a section of the coastal plain within a volcanic massif. In this region the following landscapes are observed (Fig. 2):

– Andesite Hills. These are usually 300 to 500 m high with steep slopes partly covered by pyroclastic deposits (ash and lava flows) dated from Middle to Late Miocene (14 to 7 million years ; CANTAGREL and ROBIN, 1979).

– Beach Ridges. These are often parallel, running from north to south and separated by long shallow depressions. They resulted from sea-level variations during and just after the last transgression event (3 500 B.C. ; MICHEL, 1977). These ridges delineate former coastal lines.

– Parabolic Dunes. Built during the small regression period subsequent to the 3 500 B.C. transgression, these dunes show north-to-south alignment with alternate blowout hollows. They support a scattered arboreal vegetation.

– Transverse Dunes. These are recent sand deposits running from north to south. They overlap parabolic dunes and beach ridges. No arboreal vegetation is observed.

– Beach and Foredunes. These are actual smooth sand deposits along the shoreline.

– Prelittoral Depression. This corresponds to a flat swampy zone located between the shore and the volcanic hills. It is protected from marine influences by the beach ridges.

– Alluvial Plain. This slightly inclined surface is composed of alluvial sediments.

Along the coastal plain of Veracruz ancient sand accumulations (beach ridges, parabolic dunes) are generally extensive and well preserved in smooth ondulating grasslands and rough dune fields. But the La Mancha area differs from this general aspect in three points: (i) survival of a prelittoral swampy depression; (ii) disappearance of recent transverse dunes and reduced extension of the beach ridges; (iii) irregular shape of the shoreline

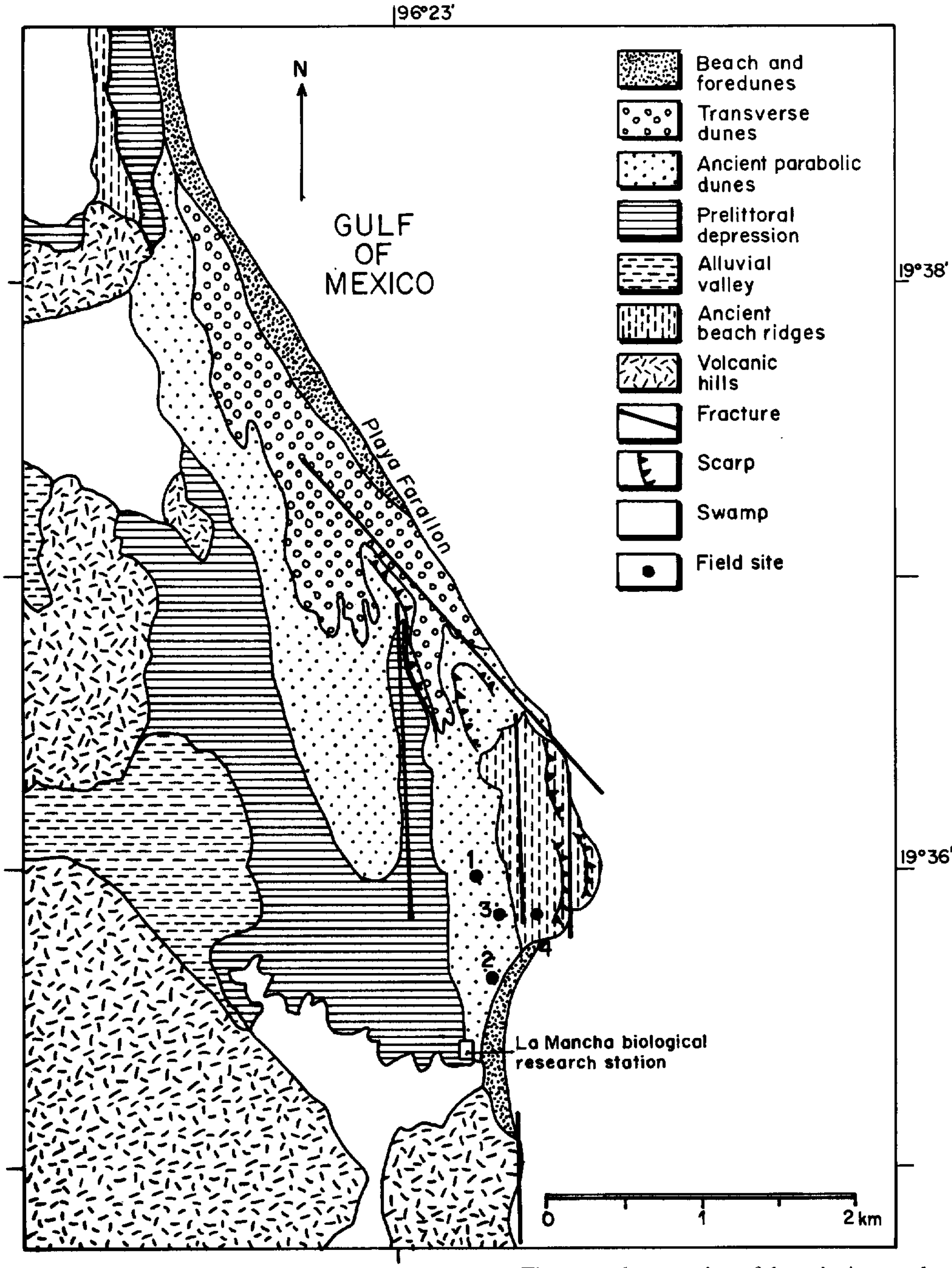

FIG. 2. – Morpho-structural map of the La Mancha area, Veracruz. The normal succession of deposits is completely modified. The ancient beach ridges are found close to the shore and recent transverse dunes nearly disappear.
Carte morpho-structurale de la région de La Mancha, Veracruz. L'ordre normal de succession des dépôts côtiers est complètement modifié. Les anciens cordons littoraux se trouvent près du rivage et les dunes récentes transversales sont absentes.

and receding beach surface (Fig. 2). Here, the normal succession of deposits is completely modified and old beach ridges are encountered close to the shore.

Field Observations on Soil

Seven "horizons" or soil layers are observed in the zone. Although the seven horizons look different, they originate from the same coastal material consisting of continental deposits mixed with marine biological fragments.

The identification of each soil horizon can be based on the following field criteria :

1. Recent sand: an inconsistent calcareous sand (effervesces in all parts with cold diluted HCl) partially removed by wind effects, with very small calcareous biological fragments and black volcanic minerals;

2. Weathered sand: a light-grey calcareous sand with secondary calcite crystals in the biological fragments;

3. Hydromorphic sand: a dark-grey waterlogged calcareous sand including carbonate nodules with aspect of cemented sand found in contact with the groundwater level;

4. Brown surface horizon: a humiferous dark brown material with sandy-loam texture, non calcareous (the fine earth fraction does not effervesces with diluted HCl) except in some places where tiny carbonate dots are discernible;

5. Red-brown horizon: a compact reddish-brown non calcareous material with sandy-clay texture and massive structure (the fine earth fraction does not effervesces except in contact with some very fine cabonate nodules);

6. Yellow sandy horizon: a yellow non calcareous loose sand with some fine carbonate nodules;

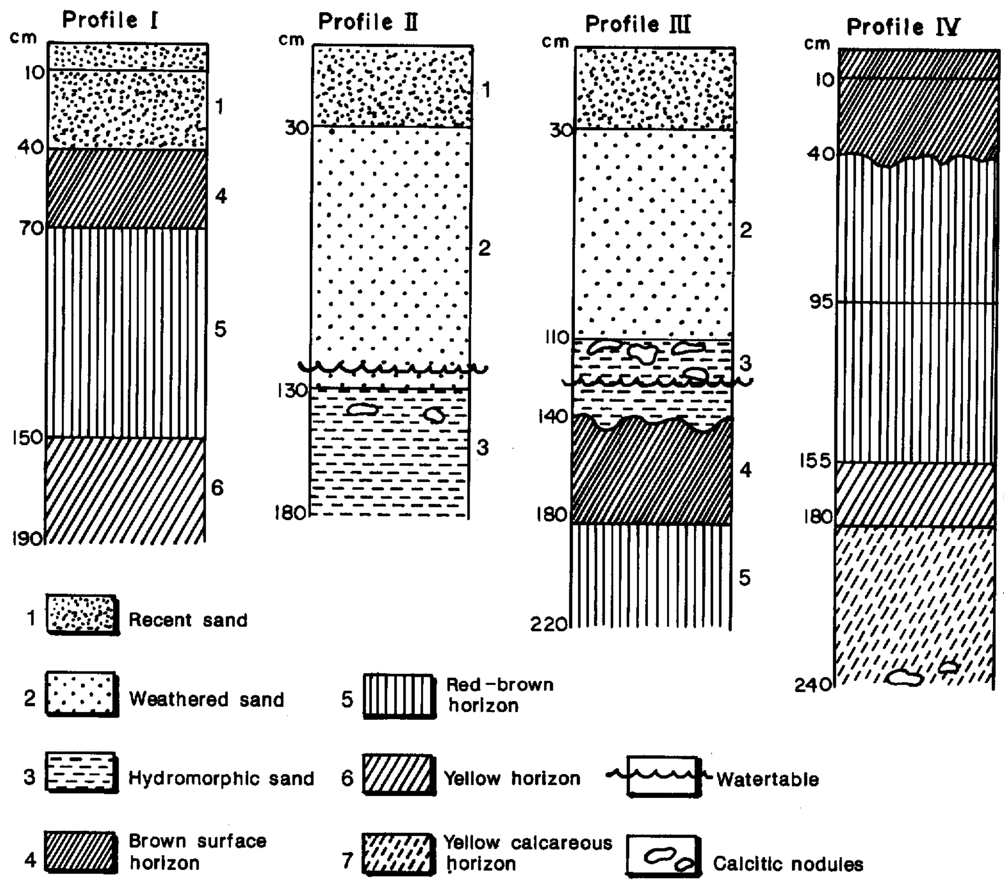

FIG. 3. – Soil profiles of the La Mancha area. Both profiles II and IV show a single soil in the dune, but the former develops in conditions of hydromorphism and the latter develops under forest in good drainage conditions. In contrast, both profiles I and III display a superimposition of two soils, a recent upon an old soil. But the former profile evolves in good drainage conditions and the latter withstands conditions of hydromorphism.

Les profils de sol de La Mancha. Les profils II et IV représentent chacun un sol de dune mais le premier se développe dans des conditions d'hydromorphie et le second se développe sous forêt en conditions de bon drainage. À l'inverse les profils I et III montrent des sols superposés, un sol récent sur un sol ancien. Le premier se développe en conditions de bon drainage et le second est soumis à des conditions d'hydromorphie.

7. Yellow calcareous horizon: a yellow calcareous loose sand with grey dots and numerous big carbonate nodules.

Various dune materials were deposited, probably during or just after the occurence of major climatic and environmental changes in the zone. Soil profiles have registered these successive changes and they display a superimposition of soils, each one with its own rate of weathering. Recent soils overlap old soils. Three horizons are mainly representative of the different periods of evolution. The red-brown horizon is part of a tropical soil and probably an old material in which weathering is very advanced. The weathered sand is a material from subactual stabilized dune. Recent sand is a material actually removed by wind action. The profile of the four soil types observed in the zone can be schematized by superimposing the different horizons (Fig. 3). Soil I displays the horizons 1, 4, 5, 6, from the top to the bottom. It is a red-brown soil covered by a thin layer of recent dune sand. Soil II displays the horizon succession 1, 2, 3. It is a dune material already weathered in which a permanent subsuperficial groundwater is present. Soil III displays the horizons 1, 2, 3, 4, 5. This profile shows a red-brown tropical soil buried under a thick layer of weathered sand and waterlogged in a shallow watertable. Soil IV shows the superimposition of horizons 4, 5, 6, 7. Here the red-brown tropical soil normally develops within the sand dune without any effect of a shallow watertable. The groundwater is only found in the deep (3-4 m) strata of the soil.

Field Observations on Vegetation

In the four different sites selected for the study, we observed that the various plant communities constitute different associations between two major opposite groups: the medium subperennial tropical forest and the bush with coriaceous-leave shrubs. The following describes these plant communities.

The vegetation surrounding the profile I is located in an interdunal valley with a very smooth shape of ancient parabolic dunes. It corresponds to an open low deciduous tropical forest with dense understorey layer of *Bidens pilosa, Iresine celossia*. Trees are no higher than 6 m and average trunk perimeter is no larger than 72 cm. All these species are found in a wide variety of environments and are widely distributed (table II). *Dyphysa robinoides* is originally a tree of the perennial to subdeciduous tropical forests. But it has now found dunes as a good environment to establish itself. Some of these species, which are common to a secondary vegetation, show disturbances and most of them are adapted to edaphic conditions temporarily subdued by a severe water deficit.

Site II, surrounding profile II, corresponds to a flooded depression among dunes with recent sand.

TABLE I.

Physical and chemical data on different soil horizons from coastal sand dunes of La Mancha per 100g dry soil less than 2.0 mm fraction (me = me/100g). The excess of exchangeable Mg in profile II and exchangeable Ca in all the profiles is due to the carbonates

Résultats d'analyses physiques et chimiques de différents horizons des sols de dune de La Mancha exprimés pour 100g sol sec inf. à 2.0 mm (me = me/100g). L'excès de Mg échangeable dans le profil II et de Ca échangeable dans tous les profils est dû à la présence de carbonates

profile N°	Clay	Silt g	Sand	pH	CEC me	$CaCO_3$ g	Na	K	Ca	Mg
							exchangeable me			
	recent sand									
III	6.8	2.0	92.7	7.9	3.0	17.1	0.13	0.06	47.7	1.3
	weathered sand									
III	7.3	1.75	91.0	8.4	5.0	21.1	0.11	0.06	43.7	2.1
	hydromorphic sand									
II	5.7	11.4	81.7	8.8	2.4	19.5	0.11	0.05	24.0	2.8
	red-brown horizon									
III	21.6	7.1	70.6	8.0	19.6	5.7	0.13	0.27	23.9	4.5
IV	16.4	4.7	78.2	8.2	19.4	11.1	0.19	017	42.0	4.2
	brown surface horizon									
IV	28.8	14.5	73.7	7.4	20.4	7.2	0.22	0.57	55.3	5.9
	yellow horizon									
IV	6.3	4.4	77.5	8.3	9.22	10.1	0.11	0.14	35.8	2.3

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TABLE II.
Plant communities in the various field sites
Associations végétales des différents sites

Site	Tree Species	Community	Origin
IV	*Brosinum alicastrum* *Ficus* spp *Cedrela odorata* *Coccoloba barbadensis* *Ginoria nudiflora* *Elaeodendron laneanum* *Astronium graveollens*	non-disturbed subperennial trop. forest	primary
	Enterolobium cyclocarpum *Bursera simaruba* *Tabebuia rosea*	deciduous trop. forest	secondary
	Randia laetevirens	bush	ubiquitous
III	*Enterolobium cyclocarpum* *Guazuma ulmiflora* *Bursera simaruba*	deciduous trop. forest	secondary
I	*Dyphysa robinoides* *Tecoma stans*	deciduous trop. forest	pioneer
	Opuntia stricta *Lantana camara*	bush	widely ubiquitous
II	*Dyphysa robinoides* *Enterolobium cyclocarpum*	deciduous trop. forest	pioneer
	Randia laetevirens	bush	widely ubiquitous

The vegetation is a low deciduous secondary tropical forest (table II) which reaches 13 m high. The closed shrub canopy is a rather dense thorny undergrowth composed of *Randia laetevirens*, perennial with coriaceous leaves. A water saturated sandy soil with high pH (table I) is found in this place.

The vegetation from site III corresponding to profile III is a rather small patch of arboreal cover, located in a valley among parabolic dunes. The soil receives constantly recent sand from the adjacent dunes. An annual herbaceous stratum almost monospecific of *Pseudoconyza viscosa* spreads beneath an open shrub stratum and a closed arboreal stratum that reaches 15 m. It is the patch with the largest number of arboreal species. Most of these elements belong to secondary communities from the low deciduous tropical forest (table II). In this zone, the watertable ranges between depth 0 and 130 cm, and the pH in the upper part of the soil is 8.

The vegetation of site IV, where profile IV is located, corresponds to a remnant of a medium subperennial tropical forest covering about 25 hectares. The upper arboreal stratum can be as high as 20 m with a large quantity of lianes, without a well defined understorey layer. The species commonly found are separated in two groups (table II). The first species are specific and some of them retricted to the non-disturbed upper and medium tropical forest (*Brosimum alicastrum*). The second species present a wider distribution and belong to the secondary deciduous tropical forest, including hydromorphic areas (*Randia laetevirens*).

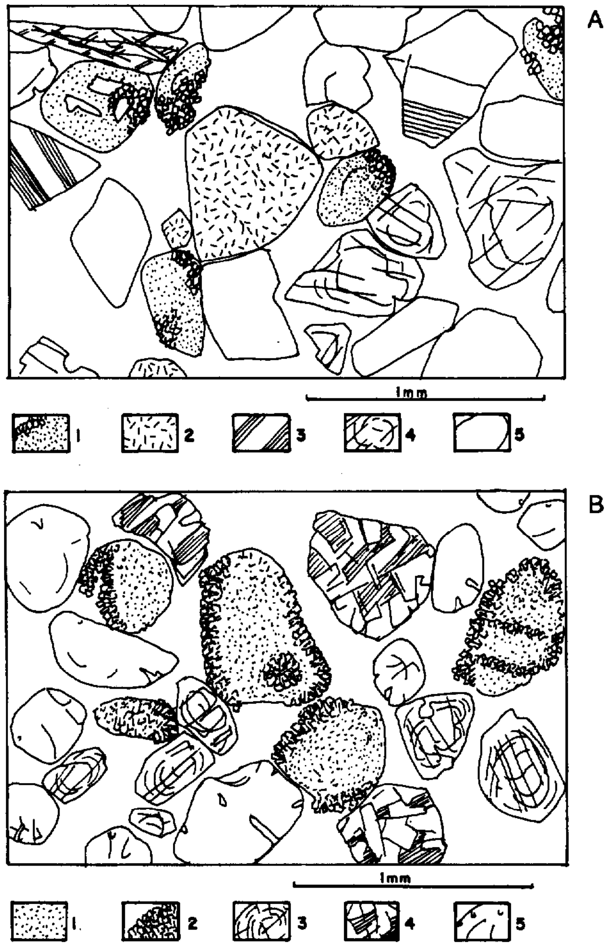
Mineralogical Aspects of the Sand Dune Soil

Observed through an optical microscope, features of soil structure and the nature of the minerals can bring some explanations concerning the origin of the parent sandy material and the weathering processes acting in the dunes.

The recent loose sand removed by wind action is composed of 0.2 to 0.3 mm size grains. Numerous rounded shell fragments and exoskeleton of marine arthropods (aragonite-type carbonates) mixed with volcanic minerals, such as pyroxenes (augite), andesite and basalt microliths, fragments of weathered volcanic rocks, feldspars (sanidine, plagioclases) are found (Fig. 4 A). Quartz represents no more than 15 % of the grains. The composition of this sand suggests the presence of coastal deposits, probably beach ridges.

The weathered sand dune is rather similar as recent sand, except for the development of calcite crystals (rhombohedric secondary carbonate) growing superficially and inside the marine calcareous fragments (Fig. 4 B). Pyroxenes are also severely fractured and partially weathered into clay and iron oxides. Quartz fissures and cavities attest to the silica dissolution. This alteration occurred probably in the past during conditions quite different from actual. XRD analysis of samples from profile III confirm the presence of very small quantities of smectite (montmorillonite) and chlorite. These two clay minerals develop in a cation-rich environment and point to an incipient weathering process.

In the dune sand with permanent hydromorphism, quartz grains are strongly alterated with deep dissolution cracks and cavities. A dense secondary crystalline calcite cement grows between the sand grains, along with a reduction of the clay coatings (Fig. 4 C). Mineralogical composition of the clay fraction from profile 2 shows smectite and chlorite clays in small quantities, as well as microcrystalline quartz and calcite (table III). Chlorite is detected in XR diagramms



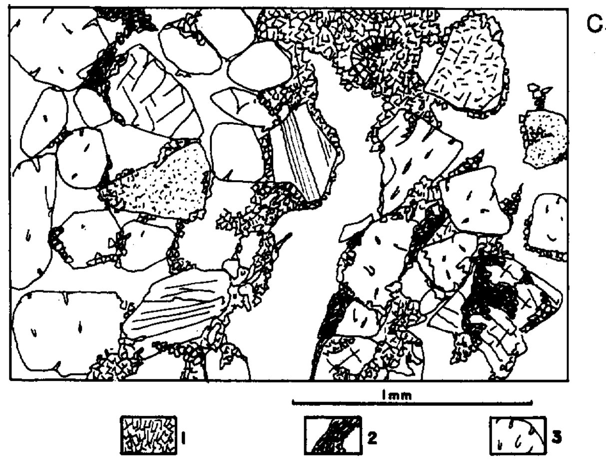


FIG. 4. – Observation of sand dune soil horizons with incipient weathering under optical microscope. A. Recent sand: 1 = Calcite crystals with calcareous biological fragments. 2 = microlithic andesite crystals. 3 = Feldspars. 4 = Augite. 5 = Quartz. B. Aspect of the weathered sand: 1 = Calcareous marine fragments. 2 = Secondary calcite crystals. 3 = Alterated pyroxenes. 4 = Alterated feldspars. 5 = Fissured quartz. C. Aspect of the hydromorphic sand: 1 = Crystalline calcitic cement. 2 = Gray clay coatings with organic matter. 3 = Quartz with dissolution alveoles.
Observation des sols sableux de dune en microscopie optique. A. Sable récent : 1 = cristaux de calcite sur des fragments biologiques calcaires. 2 = grains microlithiques d'andésite. 3 = Feldspaths. 4 = Augite. 5 = Quartz. B. Aspect du sable altéré : 1 = Fragments calcaires marins. 2 = Cristaux secondaires de calcite. 3 = Pyroxènes altérés. 4 = Feldspaths altérés. 5 = Quartz fissurés. C. Aspect du sable hydromorphe : 1 = Ciment cristallin calcitique. 2 = Revêtements argileux gris liés à de la matière organique. 3 = Quartz avec des alvéoles de dissolution.

of sample MAA23 from profile 2 (Fig. 5) with the 14-Å spacing not changed on moderate heating to about 400°C, and a weak peak at 14-Å spacing conserved after treatment with glycol (GRIM, 1968 ; ROBERT et TESSIER, 1974). In sample MAA23 corresponding to the hydromorphic sandy horizon, the subdivision of the 060 ray in two separate peaks at 1.50-Å and 1.53-Å (Fig. 6) suggests the presence of two mixed clay minerals. The first is a dioctahedral smectite, montmorillonite or beidellite as both minerals yield a 060 spacing at about 1.50-Å (WILSON, 1987) and the second is presumably chlorite, as this specie has been detected with heating treatment and its 060 spacing is 1.53 to 1.56-Å (ROBERT et TESSIER, 1974).

Mineralogical Aspects of the Red-Brown Dune Soil

Structure and composition of the soil under forest in site IV are clearly different from the dune soil without permanent arboreal cover.

In the litter is observed a very reduced quantity of plant residues, mostly small branches without leaves. During the observation period, in April 1991, the organic decomposition was very advanced. Within an annual cycle marked by the biological activity mostly of land crabs (DELFOSSE, 1990) and ants, which mainly consume fresh organic residues, the end of the dry season corresponds to the complete incorporation of plant residues to the soil.

The dark brown color and the sandy-loam texture of the upper humic horizon under forest is mainly due to a reddish-brown organic plasma with dark granulations, in clusters of small particles juxtaposed to the minerals (Fig. 7 A). Particles are very fine fragments (0.025 mm) where plant tissues are discernible. They result from a fine crushing of plant residues probably due to arthropods, without undergoing any transformation into more dense and dark organic forms related to microbiological activity. Results of

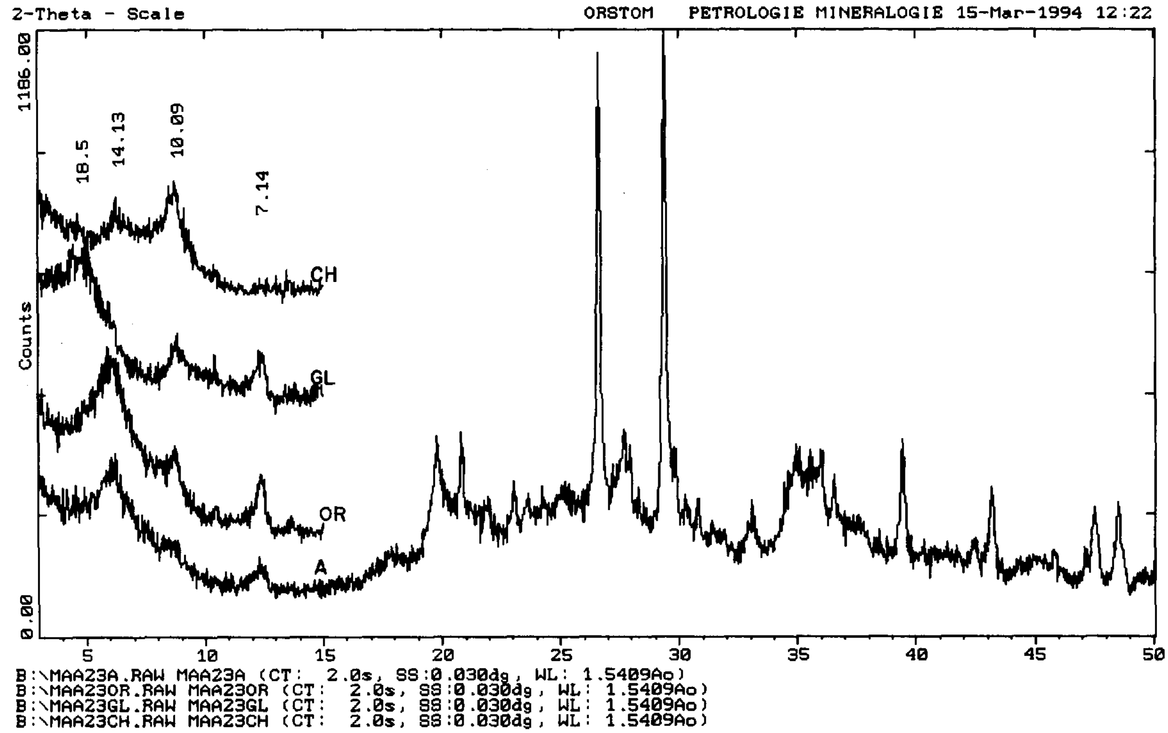


FIG. 5. – XR diagramm of profile II clay samples. OR = Oriented clay. A = Clay powder. GL = Gycol treatment. CH = Heating at 400 °C.
Diagramme de diffraction-X d'un échantillon d'argile du profil II. OR = argile orientée. A = poudre. GL = Traitement Glycol. CH = Chauffage à 400 °C.

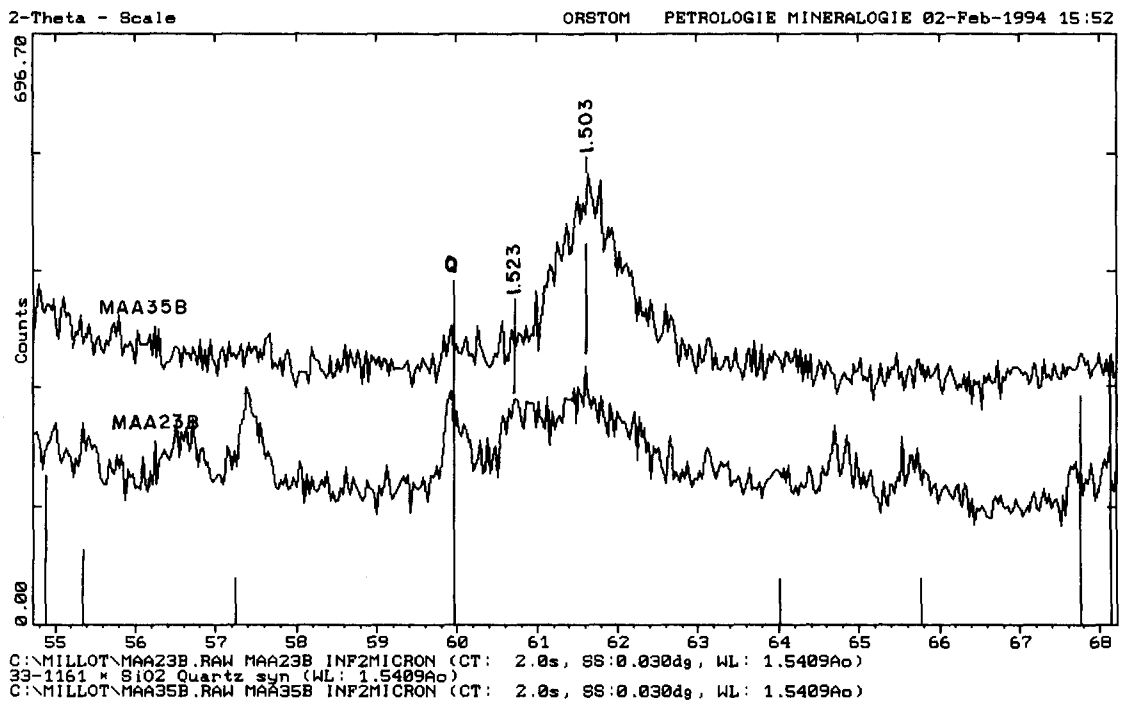


FIG. 6. – XR diagramm of 060 diffraction ray of a sample of hydromorphic sand dune MAA23B and a red-brown horizon sample MAA35B. 060 diffraction ray is subdivided into two rays in sample MAA23B.
Diagramme de diffraction-X de la raie 060 d'un échantillon de sable dunaire hydromorphe MAA23B et d'un échantillon d'horizon brun-rouge MAA35B. La raie 060 se dédouble en deux raies dans l'échantillon MAA23B.

XRD analysis show the presence of smectite similar to montmorillonite type with low crystalinity and in small quantity, suggesting only a slight secondary clay formation in this horizon. Primary minerals, referred to the littoral sand, are halloysite (clay of volcanic materials), quartz, feldspars, cristobalite (volcanic glass) and some marine calcareous fragments.

In the red-brown horizon an intense alteration of the sand grains is observed: cavities and vacuoles in quartz grains, total dissolution of calcareous marine fragments which, in some cases, can turn into fine calcitic nodules (Fig. 7 C). Volcanic rock fragments become smaller and clayey. A brown homogeneous reddish clay plasma covers the sand grains (Fig. 7 B). Clay plasma orientation, evidenced under polarized light, follows the grain surface, that means an *in situ* arrangement in relation with the primary sand grains. XR diagrams of samples from profiles III and I (Fig. 8), with sharp and high peaks of various order, show that clay is a well-crystallized smectite. The spacing and intensity of the 060 ray can provide information on the cations Fe or Mg substituting Al in octahedral position. In the samples MAA14 and MAA35 from red-brown horizons, the 1.503-Å spacing indicates a moderate substitution where only two-thirds of the possible positions are filled (GRIM., 1968). This smectite is dioctahedral and probably a beidellite as compared with reference minerals (Fig. 9). The smectite is mixed with small quantities of illite (table III). The resulting clay exhibits high cation exchange capacity: 90 cmol(+) per kg clay are reported for sample MAA35. The reddish colour is probably due to a notable content of iron but only traces of hematite are detected in XR diagramms (table III). As observed in profiles I and IV, the red-brown horizon is generally found in soils with good drainage conditions. Clay formation in the dune soil is a result of a weathering process. Old soils reach generally higher rate of weathering and present higher clay content than recent soils, due to the

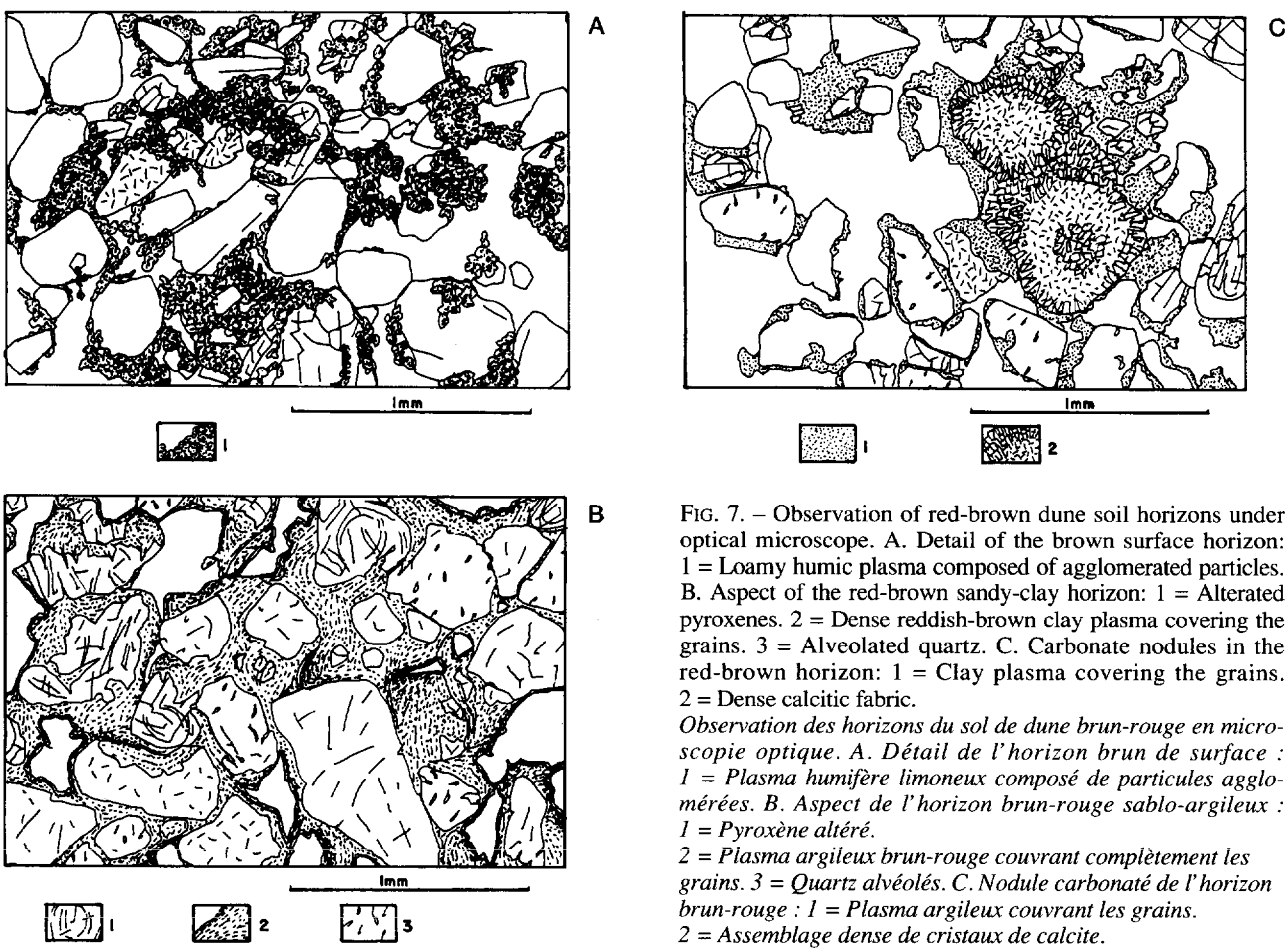


FIG. 7. – Observation of red-brown dune soil horizons under optical microscope. A. Detail of the brown surface horizon: 1 = Loamy humic plasma composed of agglomerated particles. B. Aspect of the red-brown sandy-clay horizon: 1 = Alterated pyroxenes. 2 = Dense reddish-brown clay plasma covering the grains. 3 = Alveolated quartz. C. Carbonate nodules in the red-brown horizon: 1 = Clay plasma covering the grains. 2 = Dense calcitic fabric.

Observation des horizons du sol de dune brun-rouge en microscopie optique. A. Détail de l'horizon brun de surface : 1 = Plasma humifère limoneux composé de particules agglomérées. B. Aspect de l'horizon brun-rouge sablo-argileux : 1 = Pyroxène altéré.
2 = Plasma argileux brun-rouge couvrant complètement les grains. 3 = Quartz alvéolés. C. Nodule carbonaté de l'horizon brun-rouge : 1 = Plasma argileux couvrant les grains.
2 = Assemblage dense de cristaux de calcite.

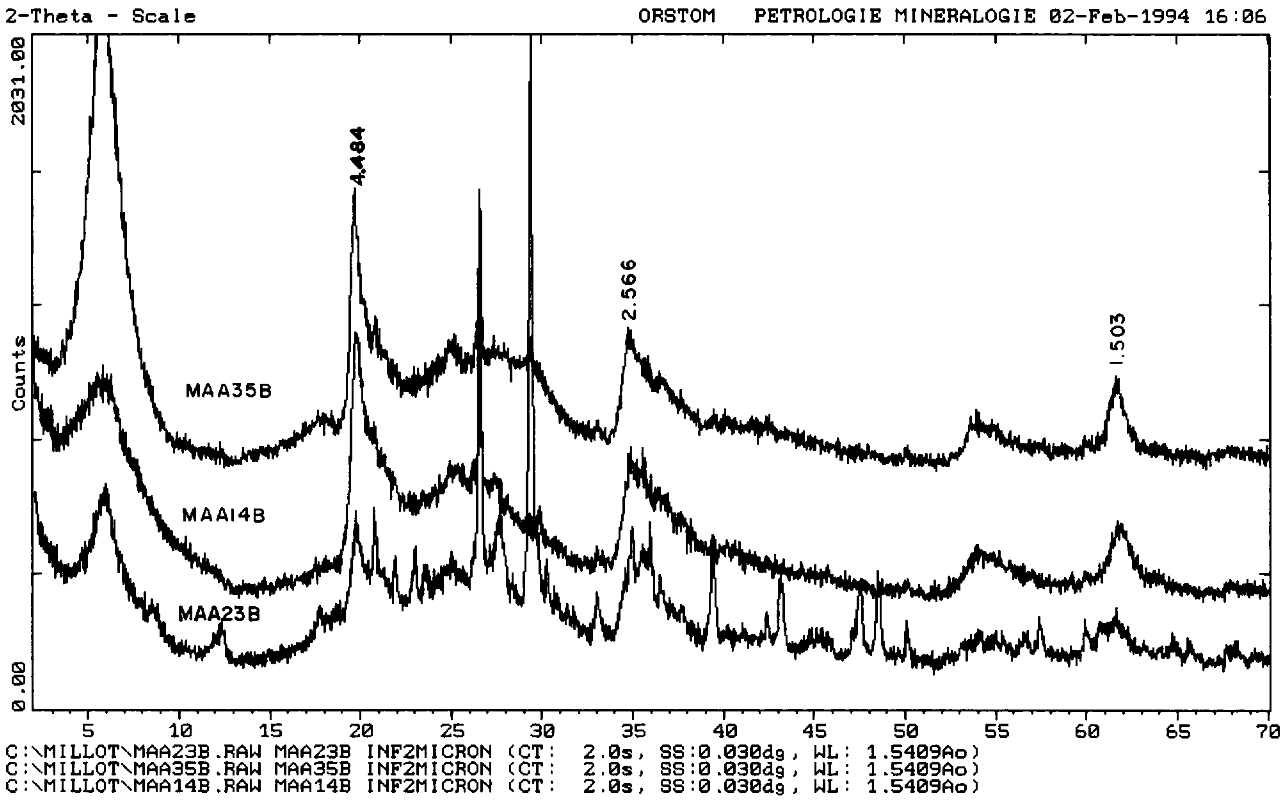


FIG. 8. – Comparison of XR diagramms of red-brown horizon samples (MAA35B and MAA14B) with hydromorphic sand dune sample (MAA23B). Diffraction peaks of clay minerals are more intense and higher in samples 35B and 14B in comparison with sample 23B.
Comparaison des diagrammes de diffraction-X d'échantillons d'horizon brun-rouge (MAA35B et MAA14B) avec un échantillon de sable hydromorphe (MAA23B). Les pics de diffraction des argiles sont plus intenses et plus fins pour les échantillons 35B et 14B que pour l'échantillon 23B.

duration of the evolution. This fact suggests that the buried red-brown soil in profile III has been subject to a long period of weathering and is older than soil IV, because clay content is higher (table I).

The yellow sandy horizon underlies the red-brown horizon. An important decrease in clay content is the prominent characteristic. Under microscope thin yellow clay coatings and alveolated quartz grains are observed.

At depth, in the yellow calcareous horizon, the clay content decreases even more and thin clay coatings only subsist. Calcite crystals are abundant either in voids, where they constitute nodules, or in contact with the coarse grains where they build a calcitic cement in replacement of the clay coatings. Weathering features are still evident such as alveolated quartz grains and intensely fragmented pyroxenes. Basically this horizon displays the same composition as the coastal sand.

TABLE III

Mineralogical composition of the clay fraction in two soil horizons resulting from two contrasted evolutions of the sand dune material: a red-brown horizon and a hydromorphic sandy horizon

Composition minéralogique de la fraction argileuse de deux horizons résultant de deux évolutions opposées du sable dunaire : un horizon brun-rouge et un horizon de sable hydromorphe

Red-brown horizon soil IV	Hydromorphic sand soil II
well-crystallized smectite illite quartz some calcite traces of 7Å clay traces of feldspars traces of hematite	smectite chlorite quartz calcite a little illite a little kaolinite

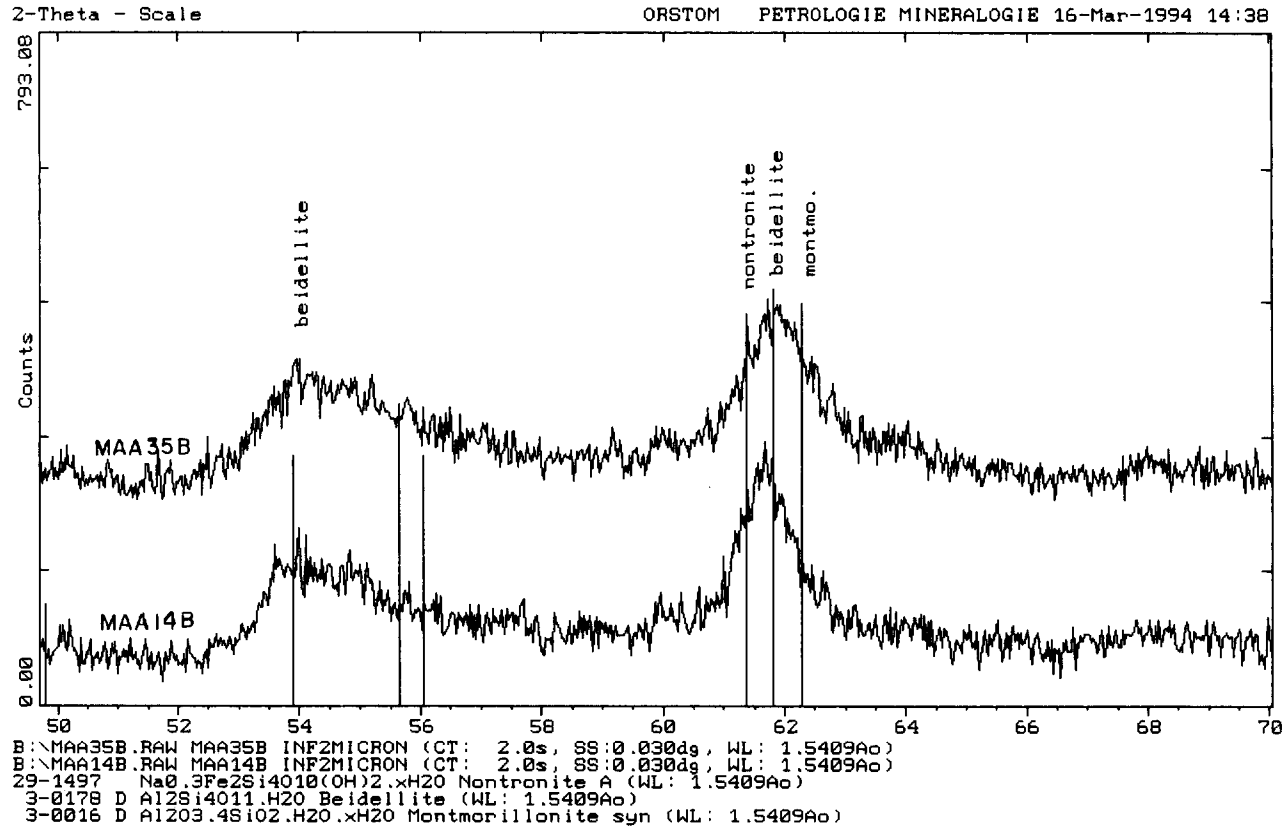


FIG. 9. – Comparison of 060 peak of two red-brown horizon clay samples with various reference clay samples. The XR diagramms are similar to that of beidellite in the region of 060 ray.
Comparaison de la raie 060 de deux échantillons d'argile de l'horizon brun-rouge avec des argiles de référence. Les diagrammes RX sont semblables à ceux de la beidellite dans la région de la raie 060 du spectre.

INTERPRETATION

The Two Main Soil Evolutions

The mineral evolution in the red-brown dune soil under forest (soil IV) and in the dune soil with hydromorphism (soil II) are quite different and even opposite. The first evolution is controlled by clay neoformation, mostly Fe-smectite (beidellite) with some quantity of illite and iron oxides. Calcareous fragments are dissolved and carbonates are eliminated from the soil, without any other crystal growth. The second evolution is mainly controlled by the presence of a shallow groundwater level. A limited formation of smectite (montmorillonite or beidellite) mixed with chlorite is observed as well as a congruent calcium carbonate dissolution that produces a secondary calcitic cement.

In the second evolution, calcite crystal growth prevails upon other secondary mineral formation such as clays and oxides.

On the contrary, the first evolution hinders calcite crystallisation and facilitates the clay neoformation between the coarse grains. The result is a soil structure with microporosity that allows water storage and an increased exchange capacity. Exchange properties enable both nutrient retention on clay minerals and progressive release of nutrients to locations where they may be taken up by roots. These processes that occur in the red-brown horizon of the tropical dune soil under forest are instrumental in sustaining a high plant biomass.

The Vegetation Evolution

A system of coastal dunes usually involves, at the same time, a complete sequence of stabilization stages reflected in different degrees of vegetation cover. In the zone of La Mancha, a patchwork of grasslands with shrubs and/or arboreal islets predominates, resulting from a nucleal-growing process. These islets are surrounded by closed herbaceous communities due to the completely different environmental conditions coexisting from place to place on the dunes.

But two vegetation poles in two completely different edaphic situations are separated: (i) a medium subperennial tropical forest on a well drained substratum within 3 m deep, where smectite and illite clays are found; (ii) a deciduous arboreal strata and perennial shrub undergrowth with coriaceous leaves on a sandy substratum with a shallow groundwater level, where carbonates and soluble elements and high pH prevail.

Vegetation of sites IV and II are closely related with these two major vegetation groups. On the other hand, sites I and III are not related with these groups and are not integrated among them either.

In site I where a red-brown soil with a thin layer of recent sand is observed, no specific species of the low subperennial tropical forest are encountered but only secondary species of the low deciduous tropical forest. This fact suggests that the tropical forest originally developed in the red-brown soil but then disappeared probably under anthropic action. Actually a secondary low deciduous tropical forest covers the area again, following the normal dune stabilization process. Later and without other disturbance, the tropical forest will develop again probably.

In site III a red-brown tropical soil buried under a thick layer of weathered sand is found waterlogged in a subsuperficial groundwater. Here, conditions prevailing to the formation of the red-brown soil are not actually valid. This is the reason why some late secondary species are still present but are not able to develop in present conditions of hydromorphism. Tectonic movements caused a recent sinking of this site and changed the water-table level, producing new edaphic conditions more similar to a substratum saturated with water than those of the former tropical forest soil.

The Landscape Evolution

The morphological changes observed in the area are due to volcanic action and the occurrence of recent tectonic movements. The most important is an uprise of the NE coastal margin along a NW-SE fracture, followed by an oscillation and sinking to the SW. The resulting fault scarp, with a slope of 60% and an elevation of 100 m, stops the way to the transverse dunes proceeding from the "Playa Farallon" and preserves the beach ridges. The other changes are breakings, spread over three parallel fractures running from north to south. They separate an eastern block of beach ridges uprisen at more than 80 m high, a central block of parabolic dune at 40 m, and a western block with another parabolic dune and the prelittoral depression that progressively descends to 20 m high (Fig. 2). These successive faulting and tilting produced an elevation of the northern side of the blocks and a sinking of the southern part of the blocks. The result is now that old red-brown soils are beneath the groundwater level in some places, and considerably above in others (Fig. 10).

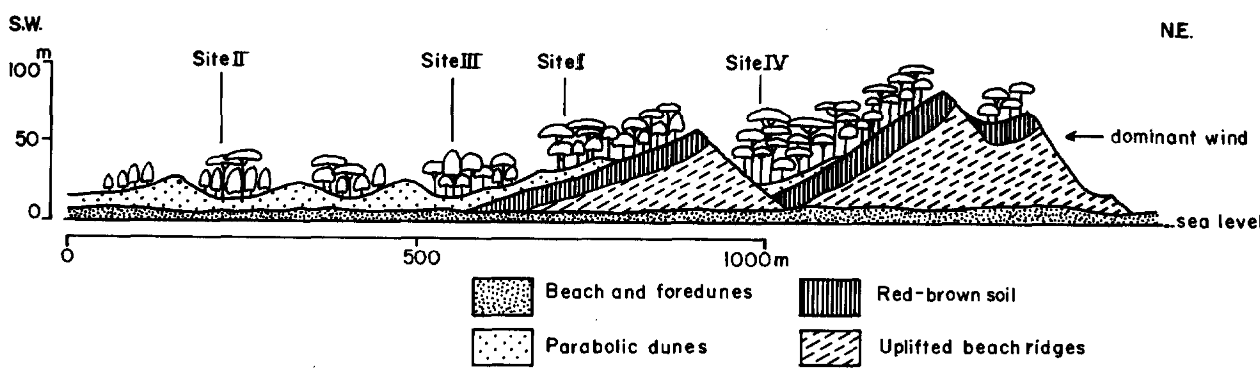


FIG. 10. – Sketch of the shoreline along the area, view from the sea. Blocks of beach ridges are uplifted and tilted forming a barrier against the strong winds from the north.
Schéma de la côte vue depuis la mer. Des blocs de plateforme comportant des cordons littoraux sont soulevés et basculés. Ces reliefs protègent des vents violents provenant du nord.

CONCLUSION

There is a normal sequence of landforms and soils from the shore to the alluvial plain inland. It is composed of active dunes near the beach, colonized parabolic dunes, beach ridges and prelittoral depression. This sequence of parent materials is related to a sequence of plant communities among which the medium subperennial tropical forest is located on the beach ridges in weathered sand and good drainage conditions.

In La Mancha region, the normal sequence of material and vegetation has been deeply modified, on one hand as a result of anthropic action and on the other hand as a result of tectonic movements. A large range of soil evolution and plant colonization are coexisting. Nevertheless, semi-deciduous forest does not grow on hydromorphic sand. Only under appropriate conditions with a groundwater level within 3 or 4 meters deep and beneath a medium subperennial tropical forest the red-brown soil can actually develop as observed in site IV. Both nucleal-growing semi-deciduous forests and good drainage conditions are necessary to create the forest ecosystem on dunes. By means of the permanent arboreal cover and the fauna and microfauna activity the forest ecosystem interacts with soil evolution and contributes to the formation of the red-brown dune soil.

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