PROCEEDINGS
OF THE
24th ANNUAL MEETING

August 15 to 20, 1988

Ocho Rios, Jamaica

Editor:
Walter I. Knausenberger
University of the Virgin Islands

Published by:
Caribbean Food Crops Society

PHYSICO-CHEMICAL AND PHYSICAL PROPERTIES OF HALLOYSITE RICH SOILS IN GUADELOUPE

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ABSTRACT

In Guadeloupe, under moderate humid climatic conditions (1800 - 3000mm.), hydrolysis of young andesitic parent rock lead to the pedogenesis of 1:1 lattice clay (halloysite) rich soils (Rusty brown soils). But in the old, highly weathered north-eastern part of the island, covered by ferrallitic soils, halloysite equally appears to be the major mineral soil constituent. For the latter soils, in addition to the dominant 1:1 lattice clay, the presence of accessory 2:1 clay minerals has been noted. In these highly impoverished soils, the presence of such 2:1 minerals causes an important variability of physico-chemical properties, in particular the cation exchange properties and the occurence of exchangeable aluminium. Soil water properties of halloysite rich soils show remarkable differences with regard to water retention, total porosity and shrinkage. In addition to their mineralogical nature, the morphology and size of the halloysite particles, as well as their spatial arrangement seem to play a leading part with regard to the soil's physical behaviour.

Keywords: Halloysite; Clay soils; Physico-chemical soil behaviour; Physical soil behaviour.

INTRODUCTION

In Guadeloupe, the often complete hydrolysis of andesitic parent rock lead to the neogenesis of secondary minerals. According to local pedo-climatic conditions, these minerals show a dominant allophanic, smectitic or halloysitic character. In the southern part of the isle of Basse Terre, Andosols are developed on young pyroclastic material, under high annual precipitations (4,000 - 10,000mm.). Smectite rich Vertisols developed on andesitic parent rock occupy a very small area near sealevel, on the leeward side of Basse Terre (<1,500mm. ann. rainfall). In the intermediate zone, the presence of halloysite rich "rusty" brown soils (Cambisols) was described by COLMET DAAGE (1969). These soils, developed on recent aerial pyroclastic deposits, with annual precipitation rates of 1,700 - 3,000mm. contain high amounts of 1:1 lattice halloysite clay, some unweathered rock fragments being still present in the soil profile.

Recently, the geologically older northern and north-eastern part of Basse Terre, covered by highly weathered ferrallitic soils (Oxisols) was shown to contain equally a dominant halloysitic mineralogical composition (upto 90%, GRANDJEAN, 1983; van OORT, 1988). Because of the mineralogical homogeneousness (nature, size and morphology) and the sometimes very high amounts of halloysite particles in the latter two soil types, a detailed study of specific clay properties was carried out in order to comprehend and predict macroscopical soil behaviour.

* Physico-chemical behaviour: Physico-chemical constraints for agriculture are particularly important for the highly leached and acidified ferrallitic soils. Contrarily to the soil map legend dressed by COLMET DAAGE (1967), mentionning a rather homogeneous ferrallitic soil cover, these soils show an important variability of physico-chemical parameters, i.e. adsorbing complex properties, exchangeable aluminium rates. The presence of 1:1 lattice clay only is unsatisfactory to explain this variability, thus supposing the existence of other high charged 2:1 lattice mineral constituants. This hypothesis has been confirmed recently (van OORT, 1988). The origin and weathering stage of these 2:1 minerals considerably varies, depending on environmental factors (local pedogenetic conditions, volcanic deposits).

* Physical behaviour: Fundamental knowledge about the physical behaviour of such heavy clay soils is of prime importance with respect to soil water behaviour, modifications of soil structure, soil tillage etc. Besides, the specific physical properties of the halloysite particles, i.e. an irreversible loss of interlayered water upon drying, contitutes an additional interest for a detailed study of the physical properties of halloysite rich soil materials.

In this paper, we first discuss the mineralogical composition of several characteristic halloysite rich soil samples. For the ferrallitic soils, we try to relate the presence and nature of accessory 2:1 minerals and the soil's physico-chemical properties. Finally, we point out the typical physical behaviour of halloysite soils, in particular their microscopical properties, studied in the laboratory. We confront these results with macroscopical field observations and measurements.

Mineralogical Composition

Soils and Methods

a) Soil material. At INRA's experimental domain, DUCLOS, 4 soils from a chronosequence including respectively a ferrallitic soil s.s. developed on late volcanic ash deposits, overlying a pyroclastic fan (unit 1), two soils formed on weathered fluvial terrace deposits (units 2 and 3) and a young alluvial brown soil (unit 4) were sampled in the B horizons (40 - 60cm). Because of the complexity of this vulcano/fluvio-sedimentary environment, some characteristic and well defined ferrallitic soil materials, representative for late volcanic ash deposits (SARCELLE 50 - 80cm) and for old, highly weathered massive andesitic boulders (ROUTA) were also studied. CHANGY, a halloysitic rusty brown soil was sampled in the B horizon (70 - 100cm). This sample may be considered as a reference with regard to the mineralogical behaviour of the halloysitic clay fraction (COLMET DAAGE, 1967). Some physico-chemical data of these samples are presented in Table I.

b) Methods. A detailed analysis of the mineralogical composition of the clay fractions of halloysite rich soils appears to be quite difficult to realize for several reasons:

1) Dispersion of the strongly micro-aggregated bulksamples into separated clay particles interferes with the action of organic matter complexed trivalent iron and aluminium cations.

2) Contrarily to halloysite dehydration behaviour cited in literature (BRINDLEY and BROWN, 1980), separated soil-halloysite may show a very rapid hall. 10Å --> hall. 7Å evolution. (cf. Fig 1).

3) In order to identify the presence of accessory 2:1 lattice clay minerals (undetectable by thermal analyses), complementary sample treatments using specific reagents (destruction of organic matter with hydrogen peroxide, iron extraction with oxalic acid/ammonium oxalate, aluminium extraction with sodium citate, cf. ROBERT and TESSIER, 1974) is needed. This kind of sample treatment may cause important modifications of halloysite X-ray diagrams.

Hence, a special clay sample preparation way has been employed here. Clay dispersion was obtained by repeated washing of undried, stirred bulksamples with destilled water. For the identification of the 1:1 lattice clay, X-ray analyses were carried out on undried, oriented clay samples submitted to various relative humidities. Formamide intercalation, described by CHURCHMAN et al., (1984) was used in order to confirm the halloysitic character of these minerals. A second part of the separated clay is chemically treated, and than Mg and K saturated. Subsequent swelling with Ethylene Glycol and heating then allow identification of the nature of 2:1 clay minerals.

Interpretation of X-ray diagrams

a) influence of sample drying (fig. 1). Starting with a wet oriented clay sample, the drying time before X-ray analysis shows a twofold effect: first, as the orientation of the clay particles increases, the definition of the diffraction patterns also increases. Then, progressively, the intensity of the 10Å (d001) and 4.46Å (d02,11) relexions of full hydrated halloysite decreases and, simultaneously the 7.2Å (d001) and 3.56Å (d002) reflexions of metahalloysite increases. Thus, after two hours drying, a X-ray diffraction diagram, almost identical to a kaolinite diagram has been obtained.

b) influence of a varying relative humidity (fig 2). Significant differences regarding the hydration conditions of the 1:1 lattice clay minerals are observed. In the Duclos unit 1 sample, only halloysite 7Å is present: no swelling to 10Å is caused by formamide intercalation. For Duclos units 3 and 4, for Sarcelle and Routa, hall. 10Å is present at 100% r.h., but from 98% r.h. the hall. 10Å --> 7Å evolution is observed. Here, formamide intercalation causes an important swelling to 10Å. In the case of Changy, full hydrated halloysite is present upto 60% r.h.: a total dehydration is observed at about 30% r.h., analogue to data presented by HUGHES, (1966). Transmission Electron Microscope observations on SPURR impregnated, undried samples (TESSIER, 1987) revealed in all cases the specific tubular and/or spherical halloysite morphology.

c) X-ray diagrams of 2:1 lattice clay (Fig. 3). The presence of 2:1 lattice clay is observed in Duclos and Sarcell samples, contrarily to Routa and Changy. Considering the geographical location of the first two sites, the occurence of these minerals is likely to be related to late volcanic ash deposits, covering the older, highly weathered pyroclastic parent rock (van OORT and CABIDOCHE, 1986). Their swelling with Ethylene Glycol, subsequent to selective iron- and aluminium extraction and peak collaps after heating to 250°C, often are incomplete, indicating an aluminium intergrade character.

Physico-chemical Soil Properties.

Generally 1:1 lattice clay rich soils show rather low fertility potentials, because of the low CEC values of the clay fraction. However, physico-chemical data from the Duclos sequence samples reveal several concomitant features (Table I): with an increasing ferrallitic alteration, the clay percentage also increases whilst CEC remarkably decreases. The highest exchangeable aluminium rates are observed for Duclos units 2 and 3, but Kamprath's ratio, R_K (R_K=Al/Al+S; S=sum of exchangeable bases), for a given pH_{KCl} (pH 4) progressively decreases from unit 1 to unit 4.

As a matter of fact, these Duclos samples contain accessory 2:1 phyllosilicates (cf. Fig. 3). Under ferrallitic pedogenetic conditions these minerals are geochemically unstable and consequently, their hydrolyses causes modifications of specific surface properties: in an early stage (Duclos, unit 4) a true smectitic character is noted. Progressively, octahedral aluminium is released occupying in a first time the cation exchange capacity sites (units 3 and 2) and finally the interlayer positions (unit 1). During this intergrade formation the soil's CEC decreases, and the proportion of exchangeable aluminium increases. Sarcelle samples, also containing 2:1 minerals equally show high R_K values at pH_{KCl} 4, whereas in the case of Routa with exclusively halloysitic clay, R_K is rather low. For Changy, less than 0.1

meq. exch. aluminium has been detected.

For the ferrallitic soil cover we are actually establishing physico-chemical relationships such as $R_K = f(pH_{KCl})$ and $CEC_{min} = f(\%$ clay, % Org. matter) on geomorphologically well defined soil units in order to provide soil fertility advise (liming).

Physical Soil Properties

Data concerning the water content, porosity and bulkvolume of samples are expressed here in terms of water ratio (e_w), air ratio (e_A) and void ratio (e), that is in cm^3/cm^3 of solid material.

a) Void - water retention curves of halloysite rich soils. Although containing all very high amounts of halloysitic particles, the void - water retention curves of the studied samples may show important differences.

* Sarcelle (Fig. 4^a) shows high water and void ratios at low suctions. Between pF 4 (10 bars) and pF 4.8 (70 bars) both parameters dramatically decrease with $\Delta e > \Delta e_w$! Similar physical behaviour was observed on allophanic soil samples (van OORT et al., 1988). The water content at pF 1 after rewetting from pF 6 ($e_{wpF6\to1}$) shows a 40% decrease, identical to the loss of total pore volume, thus indicating the irreversible character of the internal reorganization of the solid phase and the pore geometry

* Routa's physical behaviour (Fig. 4^b) is characteristic of rigid poreous media: no changes in the void ratio with an increasing soil suction; major water loss occurs between pF 3 and pF 4 (1 - 10 bars). An identical water content at pF 1, before and after drying to pF 6 is noted.

* Changy (Fig. 5^a) shows an intermediate behaviour: at low suctions (0.01 - 10 bars) a rigid soil organization and very low water release are observed. At higher suctions (> 10 bars) an important water release is noted and the void ratio shows a 40% decrease.

Obviously, in addition to the mineralogical nature of the halloysitic particles, their spatial arrangement as well as their size and morphology also play an important part with respect to the physical soil behaviour.

b) Physical properties and soil structure (Fig. 5). The Changy soil profile, under banana plantation, is submitted every four or five years to important soil tillage (plowing, subsoiling, drilling), often carried out under unfavorable conditions (water excess, abundant banana tree debris). Consequently, in the profile several horizons can be observed with distinct soil structures (Fig. 6). We determined the void - water retention curves for each horizon (Fig. 5).

In comparison to above discussed B horizon curves (Fig. 5^a), the compacted A_{p2} horizon (Fig. 5^b) shows decreased total void and water ratios at all suctions. Besides, no additional air entrance is noted between pF 1 and pF 5! In both cases, $e_{wpF5\rightarrow1}$ is slightly lower than the initial water content at pF 1. In the A_{P1} horizon (Fig. 5^{c}), the void ratio shows a twofold increase. The water loss, observed between pF 1 and pF 2 (0.01 - 0.1 bars) corresponds to a rapid draining of gravitational water, without contributing to plant nutrition. In this horizon, the water and void ratio determined on the individual soil aggregats are even lower than those measured on undisturbed soil clod from the A_{P2} horizon (Table II). In all cases the usefull available water (UAW = $e_{w(pF\ 3)} - e_{w(pF\ 4.2)}$) is low for such clayey soils!

In addition to water retention capacity and soil porosity, these modifications of soil structure also may affect the critical water content range for soil compaction, and the water infiltration rate (measured in the field by the Müntz-Laine method, fig. 6). Irrigation water rapidly runs trough the surface horizons, maintaining high moisture contents in the subjacent B horizon. However, the important structural discontinuity between the B and A horizons drastically impedes capilary rise. One way to improve irrigation efficiency may be the obtaining of a more gradual change of the soil structure (i.e. the pore system) between the B and A horizon. Therefore, IRFA recommands a rotation cycle where soil tillage is carried out at the end of one year fallow land. This practice has been tested succesfully in Ivory Coast.

CONCLUSIONS

In Guadeloupe, halloysite is the major mineral soil constituent of young "rusty" brown soils and of old ferrallitic soils. Because of the high amounts of clay particles, the soil's physico-chemical and physical behaviour seems closely related to the specific properties of the halloysite minerals. Consequently, one may expect rather homogeneous constraints for agriculture. However, minor mineralogical differences cause important variability of soil behaviour.

For ferrallitic soils, the presence of accessory 2:1 phyllosilicates gives rise to a remarkable variability of the adsorption complexe properties (CEC, exch. aluminium). The distribution of these minerals depends on recent landscape development factors. A fundamental comprehension of their origin, their spatial distribution as well as their mineralogical nature and evolution is necessary in order to provide fertility advise (liming, fertilizers, organic matter).

Physical properties highly depend on the geological origin of the parent material. The results of void - water retention curves obtained on undisturbed halloysite rich samples show physical behaviours characteristic both of a highly deformable (allophane like) and, on the contrary of a very rigid (chalk like) poreous media. The part played by the arrangement, size and, eventually, the morphology of the halloysitic particles in the physical behaviour remains to be specified.

The irreversible hall. 10Å --> hall. 7Å transformation effect on the void - water retention curves has not been observed.

The soil fabric, and therefore the physical properties of these halloysite rich soils are easely and deeply modified by intensive drying, compaction, tillage etc. Hence, a detailed study of the micro-organization and the pore geometry of these soils are essential if we want to improve their water management.

Fig. 1. Influence of drying on the X-ray diagrams of a halloysite rich clay sample (Co filter, 2.2θ, 10^3c/s, 40kV, 30mA). S: Smectite; H: hydrated Halloysite; MH: dehydrated (meta)Halloysite; G: Gibbsite; C: Cristoballite; Q: Quarts.

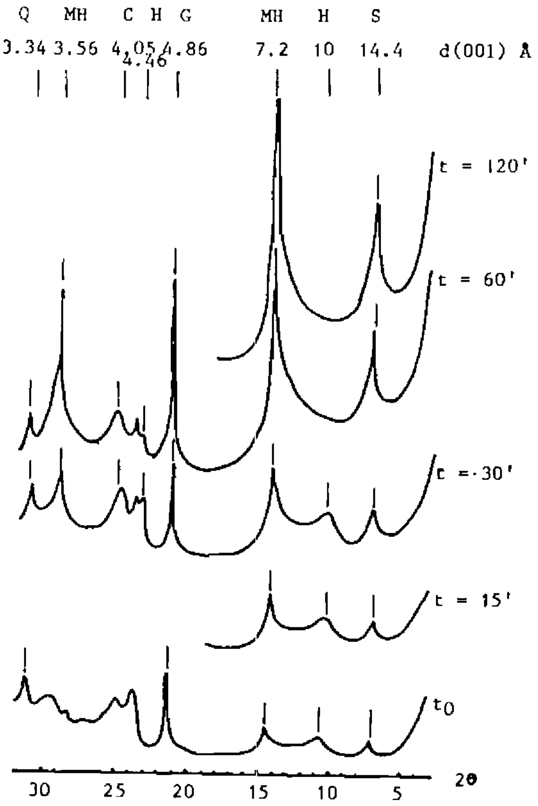
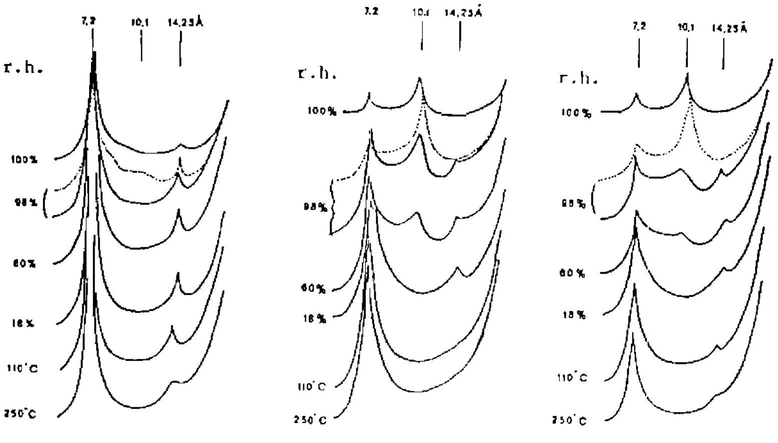
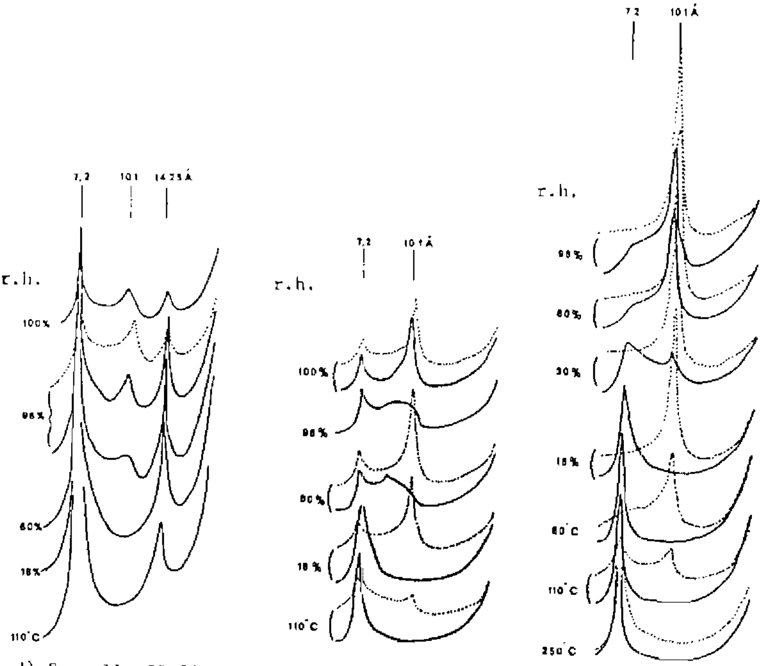


Fig. 2. X-ray diffraction diagrams of initially undried, oriented clay samples at various relative humidities.
——— : Mg-clay Normal: ·····: Mg-clay + Formamide



a) Duclos, unit 1 b) Duclos, unit 3 c) Duclos, unit 4



d) Sarcelle 50-80cm e) Routa f) Changy

Fig. 3. X-ray diffraction diagrams of chemically treated, innitially undried, oriented clay samples (Hydrogen peroxide, Oxalic acid/ Ammonium oxalate, Sodium citrate, cf. Robert and Tessier, 1974) of Duclos soil units 1, 2, 3 and 4.

——— : Mg-clay Normal; ·····: Mg-clay + Ethylene Glycol; - - - : Mg-clay, heated to 250°C (on untreated sample).

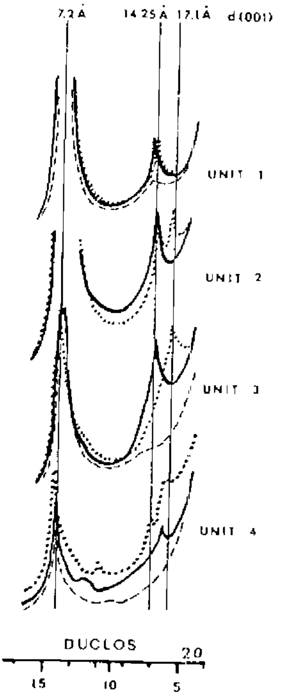


Fig. 4. Void - water retention curves of undisturbed soil clods from Routa (4^a) and Sarcelle (4^b). e: void ratio (◇), e_w: water ratio (◆), e_a: air ratio (▽), ★: e_w after rewetting from pF 1; pF: $^{10}\log$(suction); suction in cm water.

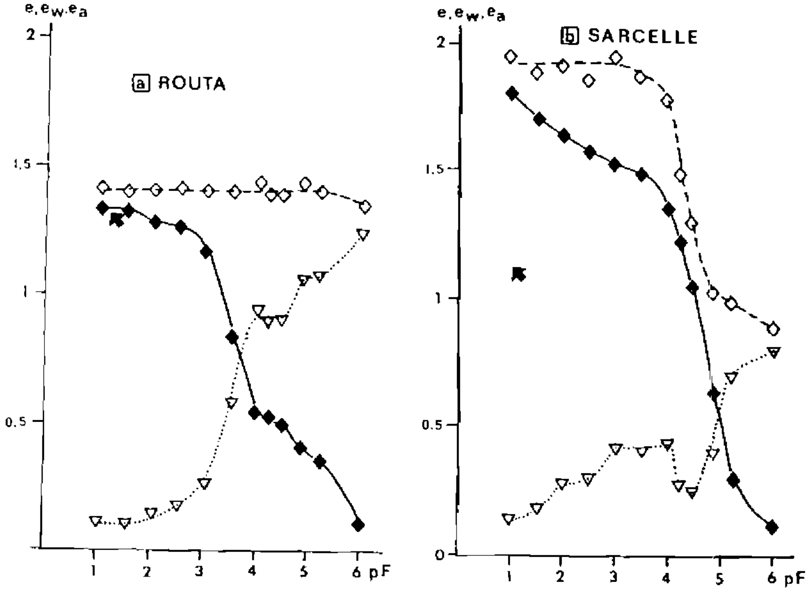


Fig. 5. Void - water retention curves of undisturbed soil samples from three soil horizons with characteristic soil structures of Changy. e: void ratio (▽), e_w: water ratio (◇), e_a: air ratio (◆), ■: e_w after re-wetting from pF 1; pF: ^{10}log(suction); suction in cm water.

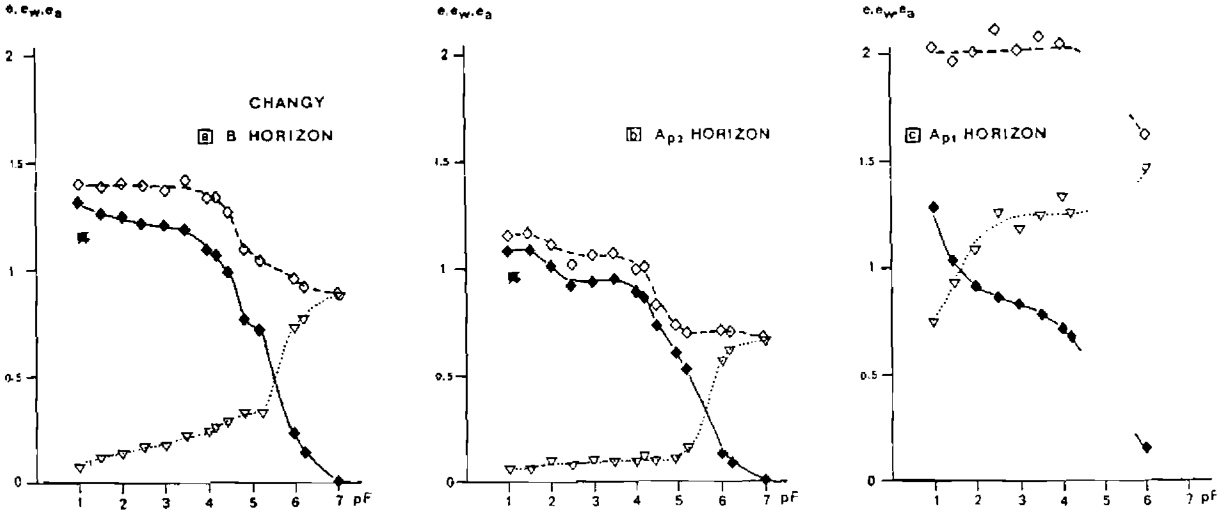
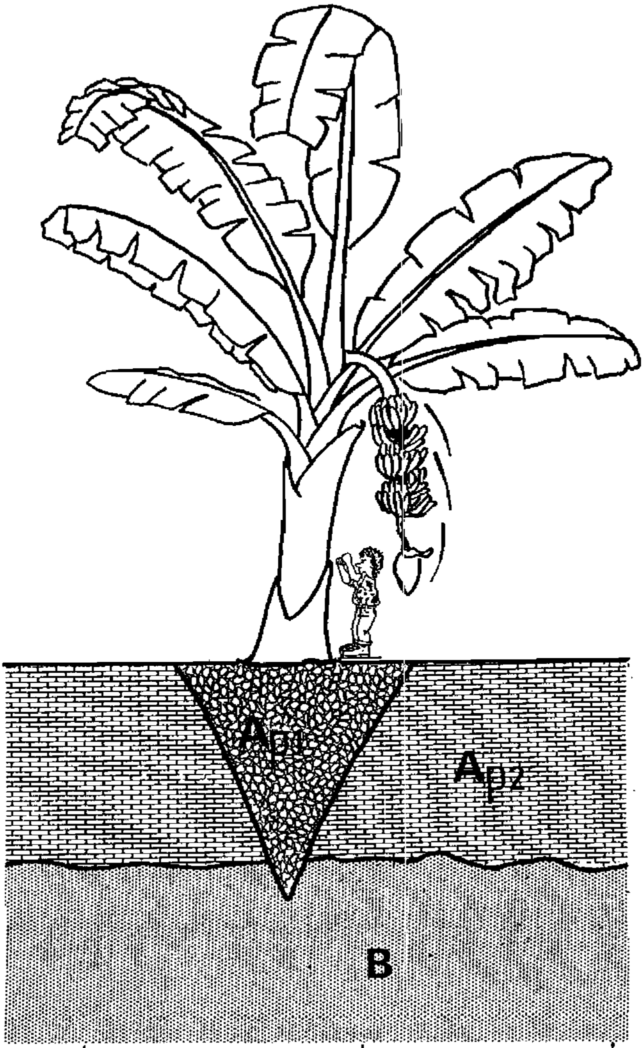


Fig. 6. Schematic soil structure differentiation of the Changy profile, resulting from intensive soil tillage practices. I.R.: Water infiltration rates, measured by the Müntz-Laine method



HORIZON	STRUCTURE	TILLAGE PRACTICES	I.R.
A_{P1}	small aggregates some cracked clods	crumbling (rome plough); drilling	60cm/h
A_{P2}	joined angular clods few fine material	compaction; rome plough, drilling	25cm/h
B	massive		10cm/h

TABLE I: Physico-chemical data of the studied samples. C.E.C.: Ammonium acetate method, buffered at pH 7; R_K: KAMPRATH's ratio Al/(Al + S), determined at pH_{KCl} = 4. S = Sum of exchangeable bases

SAMPLE		GRAIN SIZE DISTRIBUTION(%)					Org.C	pH		ADSORPTION COMPLEX (meq/100g)						R_K
		A	Lf	Lg	Sf	Sg	(%)	water	KCl	Ca	Mg	K	Na	Al	C.E.C.	(pH 4)
DUCLOS (40 - 60cm.)	1	80.3	11.1	2.3	2.4	3.9	1.16	5.4	3.97	0.49	0.25	0.02	0.12	1.72	8.3	0.67
	2	53.1	24.4	6.9	6.2	9.6	0.95	4.8	3.69	1.71	0.31	0.03	0.15	4.51	16.0	0.25
	3	43.0	24.4	7.5	13.2	11.9	0.57	5.1	3.73	2.74	1.42	0.20	0.22	4.79	19.7	0.16
	4	20.4	19.3	5.3	10.9	44.1	0.60	5.6	4.04	6.14	3.26	0.06	0.63	0.78	21.4	0.09
SARCELLE	50-80cm.	36.6	10.8	1.6	5.9	45.3	0.99	5.2	4.2	0.20	0.56	0.09	0.48	1.40	11.3	0.68
	150-170cm.	45.4	9.0	2.4	11.1	32.1	0.32	5.0	4.2	0.00	0.26	0.05	0.39	1.71	8.1	0.82
ROUTA		13.3	32.1	13.1	11.6	29.9	0.06	4.3	3.6	0.21	0.71	0.03	0.40	5.12	9.3	0.34
CHANGY (70-100cm.)		49.7	28.8	12.8	4.6	4.1	0.39	5.9	5.0	6.89	1.51	0.10	1.76	-	14.2	-

Table II. Void and water ratio data and available water contents determined on centimeter and milimeter sized samples from three soil horizons of the Changy profile. All data expressed in cm^3 of voids or water/cm^3 of solid material.

		CENTIMETER SAMPLES			MILIMETER SAMPLES
		Clods		Cylinders	Aggregates
		B	A_{P2}	A_{P1}	A_{P1} 0.8-2.0mm.
e_w	pF 3.0	1.20	0.96	0.83	0.74
	pF 4.2	1.07	0.88	0.68	0.66
	pF 6.0	0.23	0.14	0.15	0.15
UAW		0.13	0.09	0.14	0.08
e	pF 3.0	1.37	1.07	2.02	0.92
	pF 4.2	1.33	1.01	1.93	0.83
	pF 6.0	0.96	0.72	1.62	0.72

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