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Morphology, genesis and classification of surface crusts in loamy and sandy soils

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ABSTRACT

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In an attempt to organize the knowledge of soil crusting processes and to group soil crusts on the basis of common morphological features and physical properties, we synthesized and reinterpreted information from previous publications. As a result, we propose a classification system for surface crusts formed by rainfall in loamy and sandy soils. Although this system does not aim to be comprehensive, it was designed from the study of a great number of crust samples collected in the temperate and tropical zones, thus corresponding to a wide range of environmental and land use conditions. Three main classes of crusts: structural, erosion and depositional, were distinguished, each with subclasses. Where possible, correspondence has been made with former systems.This system helps predict infiltrability in accounting not only for total porosity of surface crusts but also for pore shape and continuity. Since crust classes are genetically related, this classification system also supplies some insight into predicting soil degradation and selecting the most suitable control techniques.

INTRODUCTION

Soil surface sealing sharply reduces infiltration rate, decreases water storage in the soil and triggers runoff, and hence soil erosion (McIntyre, 1958a, b; Boiffin and Monnier, 1986; Casenave and Valentin, 1992; and many others). Moreover, surface crusts may prevent seedling emergence and hamper stand establishment. Preventing such problems requires an understanding of how soil surface degradation develops according to soil and environmental conditions. In this respect, reliable features must be found which are diagnostic of the various crusting processes. This implies the use of a classification system. Two main types of soil crust, namely structural and depositional crusts, are generally distinguished according to their mechanisms of formation (Chen et al., 1980). Structural crusts are due to water drop impact, whereas deposi-

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tional crusts are formed by translocation of fine particles and their deposition at a certain distance from their original location. Arshad and Mermut (1988) suggested using "disruptional" rather than "structural" since this type of crust is formed by structural disruption, and "sedimentational" rather than "depositional" because this term has been used as a possible synonym to "washed in zone" (McIntyre, 1958a, b; Levy et al., 1986). Furthermore, these authors named "lamellar" crust the type which they considered comparable to "skin seal" (McIntyre, 1958b). In addition to structural and depositional crusts, Valentin (1991) identified in northern Niger two types of pavement crusts: (1) "filtration pavement", also designated as "three-layered" crust (Casenave and Valentin, 1992) formed by vertical particle sieving, where finer materials overlie coarser particles, and (2) "erosion pavement" which consists of an exposed plasmic layer after the removal of sandy layers of the erosion pavement by wind or runoff. More detailed classification systems were based upon the micromorphological characterization of the different types of layers that make up soil crusts. Distinguishing such typical layers enabled identification of crust development stages (Boiffin and Bresson, 1987; Valentin and Ruiz Figueroa, 1987; Bresson and Boiffin, 1990). However, most studies were based on a limited number of soil crust samples which generally belonged to a single textural class.

The objective of this paper is to outline a classification system of soil crusts based on micromorphology and genesis. This study involves interpretation and synthesis of results from previous publications. It stems from the comparison of soil crust samples from a wide range of loamy and sandy soils from temperate and tropical areas. We focused on morphological types and associated crusting patterns, i.e. the space- and time-dependent sequence for each crust type. All of the considered previous studies were based on field samples, because soil crusting processes greatly depend on specific conditions which are not easily reproduced in the laboratory. Among these conditions are: (i) soil surface moisture and suction gradient in the upper few centimeters, (ii) initial structural state and surface microrelief, and (iii) free water flow and particle movement over several meters. The system includes the identification of several features which are related to mechanisms involved in crust formation as affected by environmental conditions.

MATERIALS AND METHODS

The crust samples, reported on in previous publications, have been collected in the temperate, arid and humid tropical zones (Table 1). The temperate soils studied were cultivated, loamy Alfisols of the Paris basin, which showed variations in organic matter, pH and exchangeable sodium (Boiffin and Bresson, 1987; Bresson and Cadot, 1992). Some of them belong to long-term experimental plots with various fertilizer and amendment treatments

TABLE 1

Range of some chemical properties of the samples

Climatic zone	Organic matter (%)	pH	ESP[1]	Dominant clay[2]
Temperate	0.4–1.7	3.7–8.2	0–12.5[3]	I,V
Arid	0.1–2.0	5.0–7.7	0–0.2	K,S
Humid Tropics	1.1–6.3	4.9–7.3	0–0.1	K

[1]ESP: exchangeable sodium percentage.
[2]I: illite, K: kaolinite, S: smectites, V: vermiculites.
[3]Including a plot fertilized with $NaNO_3$ (Bresson and Boiffin, 1990).

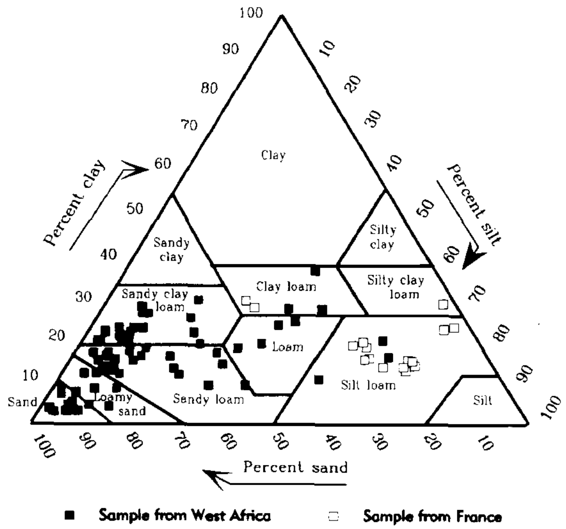

Fig. 1. Texture of the studied samples.

(Bresson and Boiffin, 1990). The arid soils studied were Aridisols, Entisols and Alfisols of western Africa which are located on extensively grazed pasture lands or cropped lands with a rather low organic matter content (Valentin, 1985, 1986; Casenave and Valentin, 1989; Valentin, 1991). Soils from the wet tropics were cultivated and fallowed Alfisols and Oxisols with fairly high organic matter content (Valentin and Ruiz-Figueroa, 1987; Valentin and Janeau, 1989). These samples represent a wide range of texture (Fig. 1), organic matter content and clay mineralogy (Table 1). Soils hereafter referred to as "loamy" include loam, clay loam, silty clay loam and silt loam; "sandy" soils include sand, loamy sand, sandy loam and sandy clay loam. In the selected previous studies, a total of 434 crust samples (Table 2) were air-dried and impregnated with polyester resin. Thin sections were prepared and examined with an optical microscope. In addition, the thin sections from sandy

TABLE 2

Major characteristics of study sites

Location	Mean annual rainfall (mm)	Number of soils	Number of crust samples	Country
Silt loam				
Tin Adjar	220	2	6	Mali
Palaiseau	580	1	5	France
Versailles	605	5	25	France
Montluel	910	1	11	France
Coutances	990	2	3	France
N'Dorolla	1020	1	16	Burkina Faso
Papara	1420	2	2	Ivory Coast
Silty clay loam				
Boigneville	610	2	2	France
Clay loam				
Agadez	150	2	82	Niger
Kountkouzout	380	5	5	Niger
Rambouillet	640	2	30	France
Loam				
Kobo	1200	3	10	Ivory Coast
Sandy clay loam				
Bidi	620	12	18	Burkina Faso
Koghnere	690	1	6	Burkina Faso
Sandy loam				
Revane	450	11	12	Senegal
Kazanga	910	1	2	Burkina Faso
Maroua	810	5	5	Cameroon
Booro-Borotou	1360	21	84	Ivory Coast
Marabadiassa	1400	2	77	Ivory Coast
Loamy sand				
Banigourou	800	2	2	Niger
Sand				
Tatki	360	9	9	Senegal
Tessekre	350	12	12	Senegal
Oursi	460	1	4	Burkina Faso
Adiopodoumé	1950	1	6	Ivory Coast

soils were observed using SEM (Backscattered Electron Scanning Image, BESI mode) in order to describe more easily the changes in microstructure which, in such apedal samples, mainly occurred at the textural organization level (coarse/fine related distribution pattern). Emphasis has been placed on arrangement, microstructure, degree of particle sorting and porosity.

RESULTS AND DISCUSSION

Soil crust types

Samples have been classified into three main groups: structural, erosion and depositional crusts.

Structural crusts

Structural crusts are characterized by in situ rearrangement of particles without a distinct evidence of lateral movement. Four main types of structural crusts can be distinguished morphologically and named after their dominant forming process.

Slaking crusts consist of a thin layer, typically apedal, but rather porous with a weak void interconnection (Photo 1). Generally, no clear textural disjunction, i.e. separation between coarse particles (skeleton) and fine particles (plasma), can be observed, even in sodic soils. In loamy cultivated soils, such structural crusts mainly result from aggregate breakdown probably induced by entrapped air compression (Boiffin, 1986; Norton, 1987; Le Bissonnais, 1990) or microcracking from shrink–swell phenomena (Valentin, 1981; Le Bissonnais, 1990). Such disaggregation processes predominate when the soil is dry before rainfall. A peculiar form of slaking crust is the *swelling crust* which is is characterized by the banded distribution of bare skeleton grains within the superficial parts of clods while the centres remain unchanged. Such crusts are observed in tilled arid loamy soils with dominant smectite clay. Due to wetting, clay lattices expand, turn into slush and fill the interstices between clods (Valentin, 1991). This very rapid process can trigger runoff within a few minutes of rainfall, even under previously dry soil moisture conditions (Casenave and Valentin, 1992). The swelling process then combines with the rapid slaking of aggregates into smaller parts due to the explosion of entrapped air. As recently demonstrated by Grant and Dexter (1990), the tensile strength is markedly reduced when the two processes occur simultaneously.

Infilling crusts display bare silt grains which clog the interaggregate interstices and form net-like infillings (Photo 2). These bare silt grains are deposited a few millimetres deeper into the interaggregate packing voids, which induces a decrease in infiltration rate and an increase in cohesion. Experimental evidence (Bresson and Cadot, 1992) showed that such crusts mainly result from the slow erosion of the top of the surface aggregates and the subsequent illuviation of the separated silts. Gradual wearing of surface aggregates can occur only if the soil and climatic conditions are not favourable to

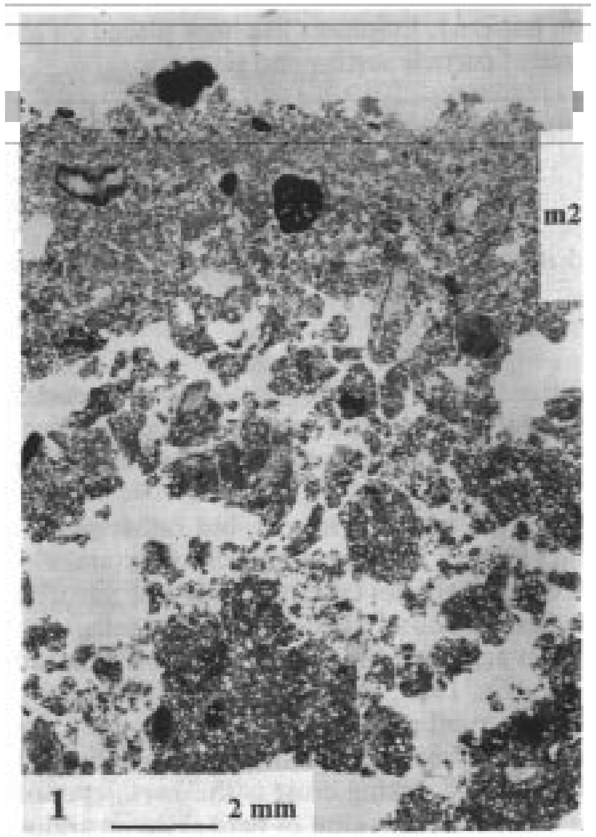

Photo 1. Slaking structural crust on a loamy soil (vertical thin section, plain light): thin, apedal layer (*m2*), without any clear textural disjunction.

a more rapid process such as slaking. This form of drop erosion can take place when the soil is wet and rainfall intensity low (Le Bissonnais, 1988; Bresson and Cadot, 1992).

Coalescing crusts are generally thick and the void convexity increases toward the surface. Photo 3 shows a diffuse boundary with the underlying undisturbed layer, which led us to describe a transitional layer where most macropores are typical packing voids with a polyconcave shape. They result mainly from gradual compaction due to aggregate coalescence by deformation under plastic conditions; such a crusting process is observed in wet soils under rainfall with rather high kinetic energy (Bresson and Boiffin, 1990). Earthworm casts in wet savannah may produce coalescing crusts when they are freshly formed and subjected to a heavy shower.

Sieving crusts are made up of a layer of loose skeleton grains overlaying a plasmic layer (Photo 4). They develop in sandy soils under tropical climatic conditions. In its most advanced form, the structural sieving crust exhibits

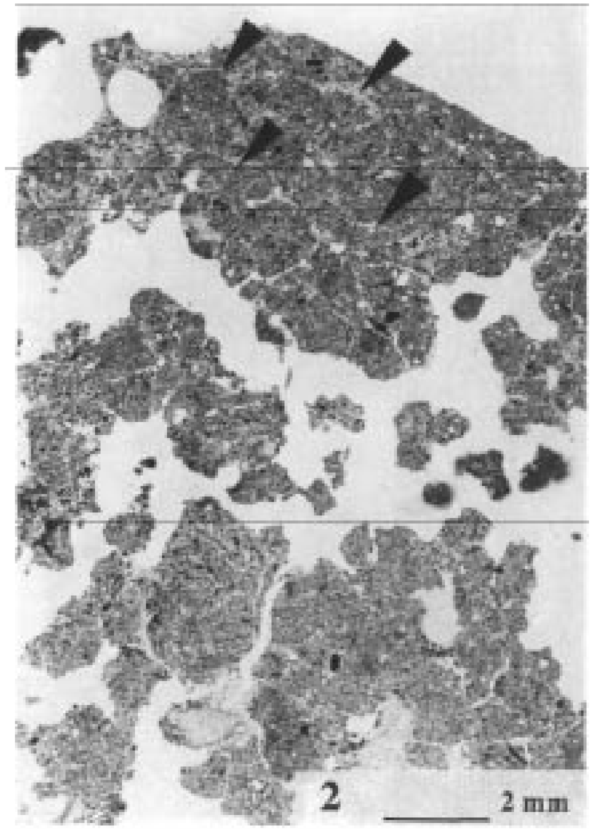

Photo 2. Infilling structural crust on a loamy soil (vertical thin section, plain light): bare silts clogging interaggregates voids (arrows) and forming net like infillings.

three well-sorted layers (Photo 5): the uppermost layer is composed of loose, coarse grains, the middle one consists of fine, densely packed grains with vesicular voids and the lower layer (plasmic layer) shows a high content of fine particles with considerably reduced porosity (Valentin, 1991). A close time-dependent sequence of sampling shows that structural crusts develop primarily as a result of waterdrop impact which form micro-craters, the walls of which present a clear, vertical sorting of particles. This suggests that textural differentiation within structural crusts mainly results from mechanical sieving so that the finer the particles, the deeper they are deposited (Valentin, 1986). Moreover, the downward translocation of clay through the coarse-grained top layer can be enhanced by the percolating water. Fine particles then accumulate and form the plasmic layer. The depth of accumulation is probably related to the depth of reduced porosity due to compaction by raindrop impact (Valentin, 1991). Collinet (1988) suggested that deeper illuviation might be

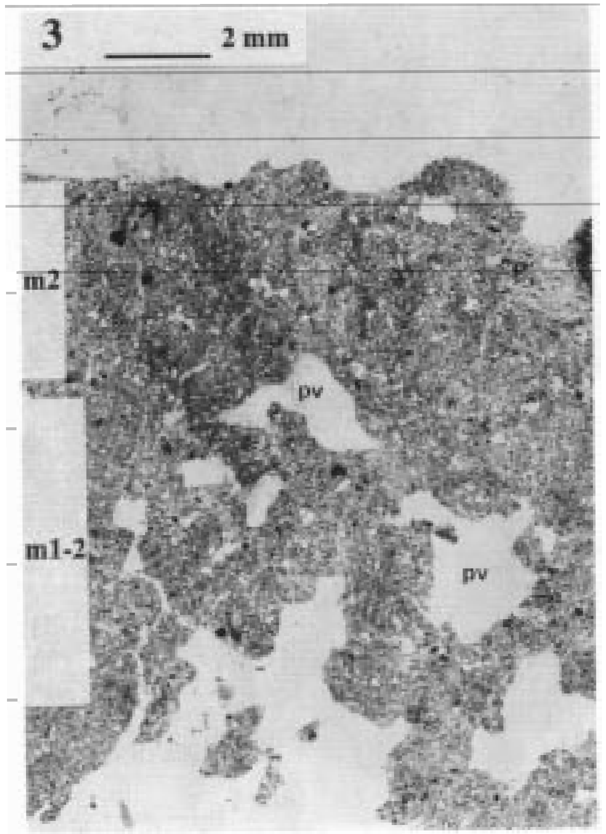

Photo 3. Coalescing structural crust on a loamy soil (vertical thin section, plain light): apedal layer with isolated pores (*m2*), overlying a compacted layer (*m1-2*) with convexo-concave packing voids (*pv*).

hampered also by compressed air below the surface. This type of sieving crust was also called filtration pavement (Valentin, 1991) or layered structural crust (Casenave and Valentin, 1992).

A particular form of this type of crust was identified and named *coarse pavement crust* (Photo 6). In this case, coarse fragments are embedded in a crust, the microstructure of which is very similar to the sieving crust described above with a pronounced vesicular structure, especially below the pebbles. Such soil crusts commonly occur in arid and semi-arid areas (Springer, 1958; Evenari et al., 1974; Figueira and Stoops, 1983). Most studies focused on the origin of the vesicular structure but so far little information exists on the processes involved in the formation of these coarse pavement crusts. Differences in texture between topsoil and subsoil suggest that surface materials are wind-deposited particles which have subsequently been subjected to processes similar to those described for the formation of sieving crusts.

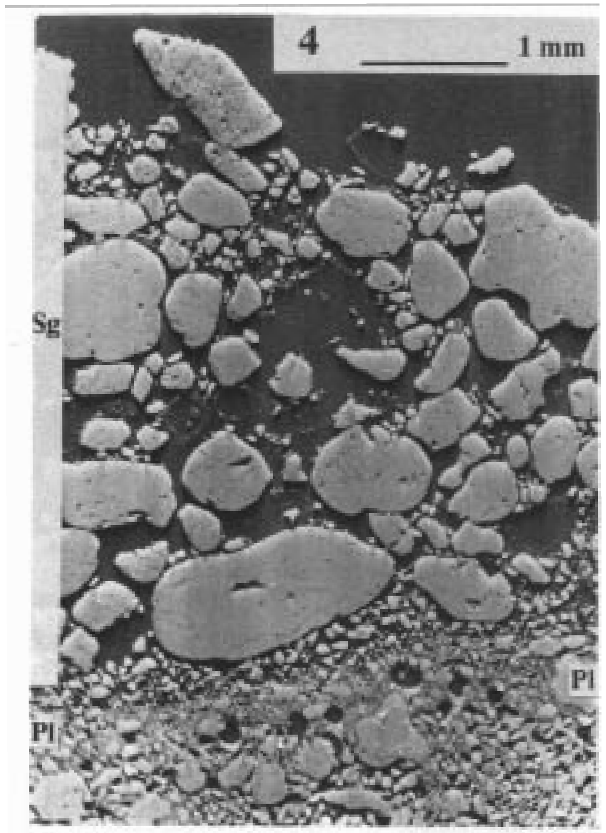

Photo 4. Sieving structural crust on a sandy soil (vertical polished section, BESI mode): two-layered crust, made up of a layer of loose skeleton grains (*Sg*) ovelying a plasmic layer (*Pl*).

Depositional crusts

Runoff depositional crusts are typically apedal and very compact, and characterized by a microbedded layer (Boiffin and Bresson, 1987) (Photos 7 and 8). Runoff and disjunction between fine particles (plasma) and coarse particles (skeleton) induce alternate submillimetric microbeds which are more or less contrasted in texture and uncomformable with the underlying layer. Such microbedded layers most often overlay a structural crust. In the lower part of the crust, the bedding is generally less distinct and particle sorting is poorer in that some microaggregates are often mixed with poorly sorted basic particles.

Still depositional crusts consist of densely packed and well-sorted particles, the size of which gradually increases with depth (Photo 9). The vertical particle size distribution with coarser particles at the bottom and finer particles at the top is the reverse of that observed in the sieving crusts described above. When dry, these crusts often break up into curled-up plates. Still depositional

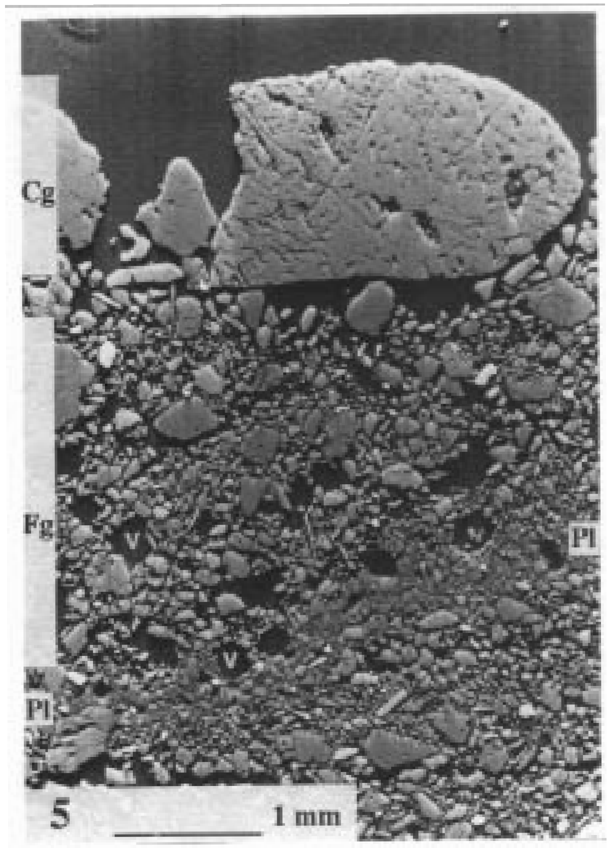

Photo 5. Sieving structural crust on a sandy soil (vertical polished section, BESI mode): three-layered crust with loose coarse grains at the top (*Cg*), fine, densely packed grains and vesicular voids (*v*) in the middle (*Fg*), and a plasmic layer (*Pl*) at the bottom.

crusts form in standing water and develop where surface flow is hindered. In puddles, the larger grains sink rapidly and form the bottom layer, whereas the finer grains deposit more slowly and form the top layer. The clayey microbeds are usually thicker, better sorted and more birefringent when they are located in the middle of the microdepression where the still depositional crust has formed.

Depositional crusts are most often made up of a combination of runoff and still depositional crusts. Their main micromorphological features such as microbedding, sorting, packing and orientation of coarse and fine particles are related to the hydrodynamic conditions of particle sedimentation (Mücher and De Ploey, 1977; Valentin, 1981; Bresson and Boiffin, 1990). Well-sorted microbeds deposit in laminar flow, poorly-sorted dense microbeds in turbulent flow. The flow type depends on runoff conditions (velocity, solid charge,

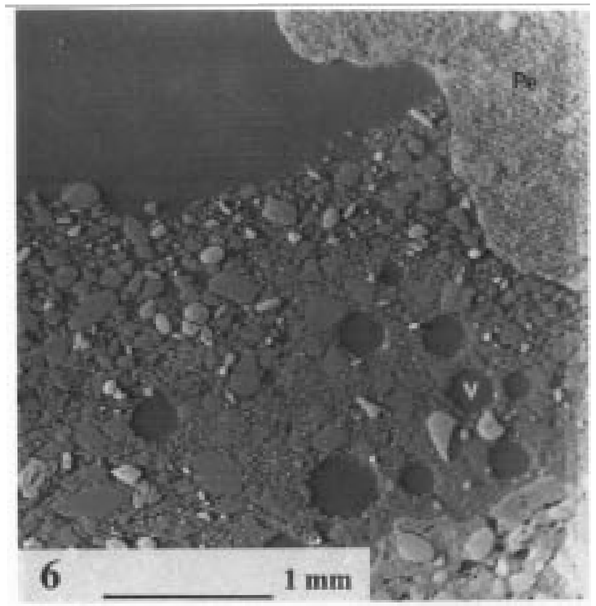

Photo 6. Sieving structural crust on a sandy soil (vertical polished section, BESI mode): pavement crust, consisting of coarse fragments (*Pe*) embedded in a sieving crust with a pronounced vesicular porosity, especially under the pebbles (*v*).

surface roughness) as well as on splash which is a major source of turbulence. In this respect, abundance, size and duration of puddles play an important part in the characteristics of sedimentary layers which therefore appear to be partly controlled by the properties of the underlying structural crusts (Bresson and Boiffin, 1990). The beginning of runoff is characterized by a muddy flow which clearly constitutes a crusting stage in temperate areas (Bresson and Boiffin, 1990). This process would explain the frequent occurrence of microaggregates in the lower sedimentary microbeds.

Erosion crusts

Erosion crusts consist of only one rigid, thin and smooth surface layer enriched in fine particles (Photo 10). Voids are generally restricted to some cracks and vesicles. Such plasmic layers, or seal skins (Chen et al., 1980), result from the erosion of slaking or sieving crusts. In the latter, the plasmic layer becomes exposed where the coarse particles of the top layer(s) are removed by wind or overland flow (Valentin, 1985). In the case of erosion crusts evolved from slaking or coalescing crusts, a dense plasmic layer must first be formed since there is no previous vertical textural differentiation. Several authors (Chen et al., 1980; Valentin, 1991) have shown that raindrops with high kinetic energy can disjoint coarser particles from the finer particles.

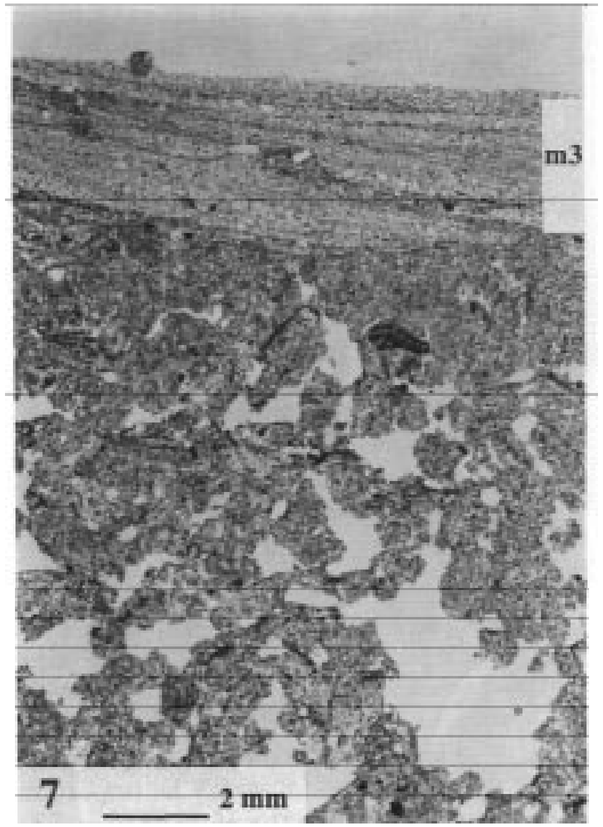

Photo 7. Runoff depositional crust on a loamy cultivated soil (vertical thin section, plain light): microbedded layer with submillimetric moderately sorted microbeds (*m3*), overlying a previously-formed structural crust.

The finer particles are partly removed and partly compacted at the surface where they form a plasmic layer. Such a layer, which initially formed on the higher points, expands over the surface as the microtopography associated with crumbs diminishes.

Whatever type of crust they derive from, erosion and depositional crusts may be strengthened by certain algae or fungi (Fletcher and Martin, 1948; Barbey and Couté, 1976; Valentin, 1981). These crusts commonly form pedestal features when the surrounding uncolonized crust has in turn been eroded (Casenave and Valentin, 1989). Such soil crusts consist of mineral layers with minor amounts of associated algae. They differ therefore from the cryptogamic crusts described in Australia (Mücher et al., 1988) which are made up of continuous cryptogam mats.

Photo 8. Runoff depositional crust on a sandy soil (vertical polished section, BESI mode): submillimetric microbeds exhibiting various mean particle sizes and sorting.

Crusting patterns

Time- and space-dependent variations

In loamy soils, crusting always follows the same pattern: (i) sealing of the surface by a structural crust, and (ii) development of a depositional crust (Fig. 2). The change from the first to the second stage mainly depends on a decrease in the rate of infiltration due to the structural crust properties, which induces microrunoff (Valentin, 1981; Boiffin, 1986). In micro-depressions, this time-sequence is reflected in microstratigraphy: initial structure at the bottom, structural crust in the middle, and runoff depositional crust at the top, possibly capped with a still depositional crust. Spatial variability is often associated to soil roughness: structural crusts occur on the top of the remaining clods, with rather large and continuous pores whereas depositional crusts

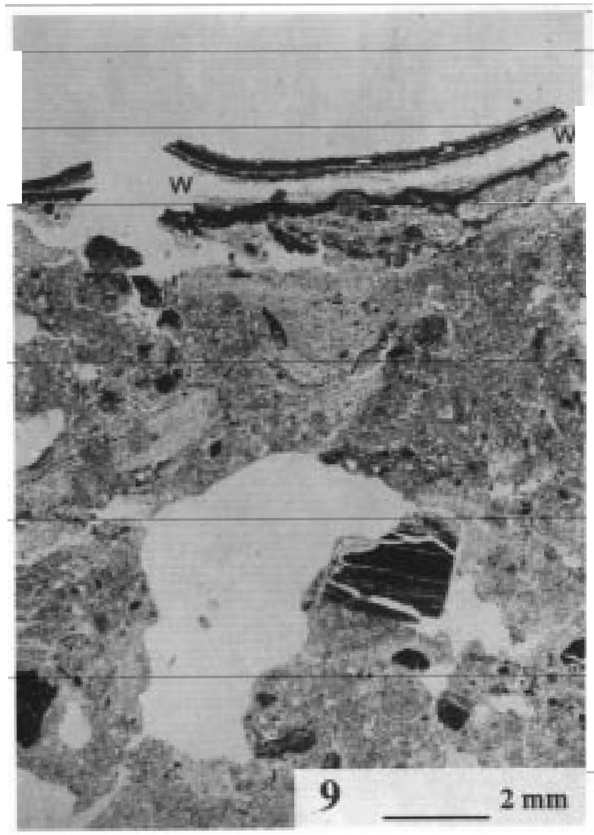

Photo 9. Still depositional crust on a loamy soil (vertical thin section, plain light): well-sorted layer (*W*), broken up into curled-up plates due to drying, and overlying a structural crust.

form in micro-depressions with only few, small, vesicular pores and cracks (Valentin, 1991).

In sandy soils, the specific time-sequence includes sieving crust, depositional crust and erosion crust, and possibly coarse pavement crust. Since tillage-induced surface roughness is more transitory than in loamy soils, macro-variability of soil crusts generally occurs over larger distances. They form a typical space-sequence along the slope: structural crusts upslope, erosion crusts, and possibly coarse pavement crusts midslope, and depositional crusts downslope.

Comparison between temperate and tropical soil crusts

Crusts from temperate and tropical soils were found to differ in some details. Under the temperate conditions studied, soil surface degradation was generally restricted to structural and depositional crusts; no further stage was

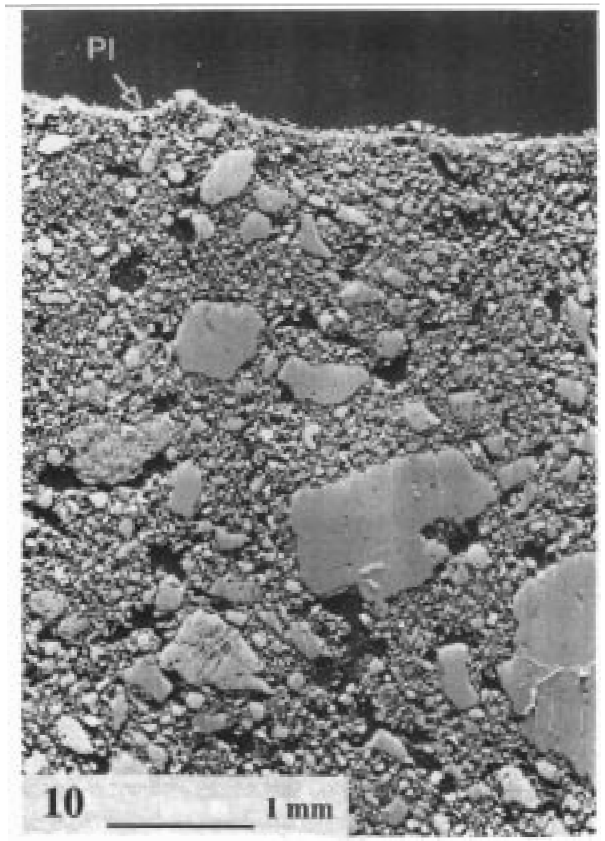

Photo 10. Erosion crust on a sandy soil (vertical polished section, BESI mode): thin and smooth plasmic layer (*Pl*).

observed. In particular, erosion crusts did not develop presumably because (1) the kinetic energy of rainfall was too low to separate coarse and fine particles and to compact accumulated fine particles at the surface; (2) crusting mainly occurs on rough seedbeds which hinder runoff along the slope, and limit the velocity of overland flow, and (3) temperate crusts cannot develop in cultivated soils over a long period due to their rapid destruction by faunal activity, cracking and tillage. By contrast, whole space- and time-dependent sequences (structural, erosion and depositional crusts) commonly occur under tropical conditions. Furthermore, lateral differentiation is enhanced by wind, under arid conditions, which promotes the formation of erosion crusts surrounded by sandy micromounds.

The comparison of surface crusts from various environments improves our understanding of surface crusting processes. Only a few of the temperate-zone soils have crusts. They occurred mainly on cultivated, loamy soils under a

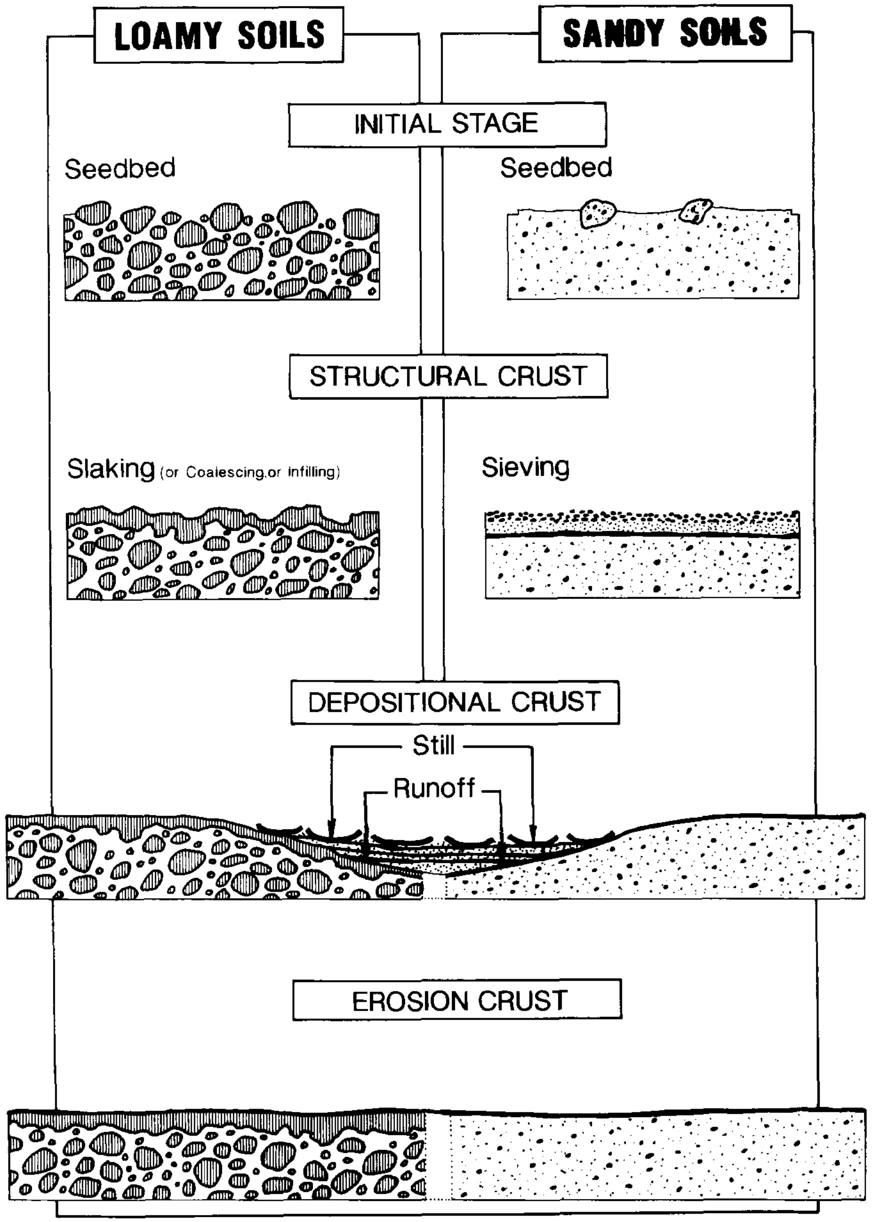

Fig. 2. Diagrammatic representation of the time-sequence soil crusts in loamy and sandy soils.

wide range of soil moisture conditions and rainfall intensities. A predominant crusting process can be identified for each of the four main pedo-climatic conditons, including the combinations of soil moisture prior to rain (dry or

wet) and rainfall intensity (low or high). Conversely, the number of such combinations is more restricted in tropical zones where high intensity storms generally beat dry soil surface, but a larger range of soils are affected by surface sealing. Under such conditions, soil crusts generally develop within the first minutes of rainfall rending arduous any detailed analysis of the simultaneous and intermingled processes involved. In this respect, knowledge of the more gradual and distinct processes involved in the structural stage in temperate regions helps to scrutinize the temporal micro-variability during crust formation under tropical conditions. Likewise, the macro-variability of surface crusts described in relation to topography in tropical areas assists in investigating the spatial micro-variability of surface crusts in temperate cultivated soils.

Practical implications

The proposed classification system conveys information which may be used in several fields.

Predicting infiltrability

Parallel studies indicated that the classification system may be applied to prediction of infiltrability (Boiffin and Monnier, 1986; Bresson and Boiffin, 1990; Casenave and Valentin, 1992). Each crust type refers not only to total porosity of crust, but also to pore shape and pore continuity, two characters considered as essential to infiltration. In France, infiltrability was assessed as the observed rainfall intensity above which ponding occurs under saturated conditions, either under natural rainfall, or using the dropper method. In tropical areas, infiltrability was determined as the steady minimum infiltration rate recorded on very wet soils under simulated rainfall (Valentin, 1991, Casenave and Valentin, 1992). Results showed that whatever the soil and climatic conditions, infiltrability remains rather high for the incipient crusting stages and very low for the most advanced stages (Table 3). The identification of surface crust types provides a very efficient tool for predicting runoff occurrence (Casenave and Valentin, 1992). The classification system of surface crusts combined to other major factors such as surface roughness, soil cover, faunal activity, were used to develop original soil conditions mapping in arid and semi-arid areas in an attempt to improve watershed hydrological modeling (Casenave and Valentin, 1992). Such a surveying method, based on standardized criteria, can be greatly assisted through remote sensing analysis (Courault et al., 1991).

Diagnosing land degradation

Papy and Boiffin (1989) proposed a procedure for ranking rill erosion hazards in loamy soils in the temperate zone based on the stage of soil crust de-

TABLE 3

Main features and range of infiltrability (after Boiffin and Monnier, 1986; Bresson and Boiffin, 1990; Casenave and Valentin, 1992) of the main types of soil crusts

Crust types	Thickness (mm)	Total porosity	Other features (pore shape, pore continuity, size, ...)	Infiltrability ($mm \cdot h^{-1}$)
Structural crusts				
Slaking	1–3	moderate	weak textural differentiation, weak void interconnection	5–20
Infilling	2–5	low	porosity partly filled with bare silts	5–8
Coalescing	3–>15	moderate	increase of pores convexity from the bottom of the top	3–9
Sieving				
-two-layered	1–3	moderate	sandy layer at the top over a thin seal of finer particles	5–15
-three-layered	1–3	low	coarse sandy layer at the top, vesicular fine sandy layer, seal of fine particles at the bottom	0–5
-coarse pavement	2–30	very low	similar to the three-layered sieving crust including coarse fragments and much pronounced vesicular porosity	0–2
Depositional crusts				
Runoff	2–>50	low	interbedding of sandy layers and seals of finer particles, possible vesicles	1–5
Still water	2–>50	very low	larger particles at the top, finer particles at the bottom, possible vesicles	0–2
Erosion crusts	<1	very low	exposed seal made of fine particles, possible vesicles	0–2

velopment (cloddy initial state, structural crusts and depositional crusts), the percentage of wheel tracks, and surface roughness. This approach, based on the temporal and spatial variabilities of surface condition due to crop management, improves modeling of rill erosion.

In arid areas, surface crusting processes self-accelerate when the soil surface is no longer in equilibrium with the vegetation and the soil fauna (Casenave and Valentin, 1989). The successional stages of the various surface crusts help identify the degree of soil degradation. The first stages involve structural, depositional and erosion crusts. The restoration of the surface soil structure remains reversible due to the capacity of arid vegetation and soil fauna to recolonize crusted areas when conditions are improved (higher rainfall and lower human or cattle pressure). The final stage occurs when the erosion crust and the top layers have been scoured by water erosion so that the gravelly B layers become exposed. The extension of coarse pavement crusts makes the recovery processes unlikely in the short and medium runs (Valentin, 1985).

Adapting techniques of soil crusting control

The choice of a technique for preventing or controlling crusting requires some knowledge of the factors and processes involved. In this respect, the proposed classification system provides some guidelines. For instance, a hydrophobic mineral conditioner, such as that studied by Le Souder et al. (1990), which slows down water entrance into clod pores and thus limits shattering hazards, mainly operates in the soil and environmental conditions which are the most favourable to the occurrence of structural slaking crusts, namely dry loamy soils subjected to intense rainfall. Similarly, mulching is most effective in limiting the development of structural sieving crusts and subsequent erosion in sandy soils (Collinet and Valentin, 1985). Beneficial effect of covering soil surface is more questionable for tropical loamy soils. Slaking of dry aggregates due to rapid wetting can occur independently of raindrop impact (Fapohunda, 1986; Valentin and Ruiz-Figueroa, 1987).

Additional experiments are still needed to select the most appropriate techniques for controlling the various types of soil crusting processes.

CONCLUSIONS

Simple morphological criteria were used to characterize a large set of soil surface crusts formed on loamy and sandy soils in both temperate and tropical areas. Such criteria include porosity (abundance and type), and arrangement of coarse and fine particles (related distribution pattern, orientation and distribution). Several types of crusts were then distinguished which could be related to our present knowledge of crusting processes which are determined by both soil and environmental conditions (slaking, coalescing, infilling and sieving structural crusts, runoff and still depositional crusts, and erosion crusts). Such a system appeared to be relevant to the prediction of infiltrability but further work is required to test its applicability to the prediction of gaseous transfer through crusts, and mechanical impedance. Soil crusting consistently follows typical time- and space- sequences. Identifying soil crusts and the associated degradation stage therefore provides valuable information for predicting soil evolution.

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