THIRD INTERNATIONAL WORKING-MEETING ON SOIL MICROMORPHOLOGY
WROCŁAW, 1969

ZESZYTY PROBLEMOWE POSTĘPÓW NAUK RCLNICZYCH 1972 z. 123

The clay illuviation

(A micromorphological study) *

N. FEDOROFF

Laboratory of Geology and Pedology, E.N.S.A., 78-Grignon, France

Micromorphology is the most suitable technique to study clay migrations in soils. All types of clay accumulations are in the range of the magnifications of the optical microscope. The clays migrate in a colloidal solution. They deposit on peds and in macro and mesovoids as rather thick (not less than ten microns) and large entities; they do not enter microvoids.

The development of a modal "lessivé" soil can be divided into three successive phases: clays coagulation, primary illuviation and secondary illuviation. Another type of clay accumulation appears in very developped "lessivés" soils; we called it "flaky" illuviation (in opposition to the previous types the argillans of which have a waxy aspect). Migrations of coarse mineral matter also take place (silt, loam and even fine sand); they can be associated or not with the clay migrations.

I. CLAYS COAGULATION

As soon as dispersion of clays becomes possible, local clays rearrangement appears. The clays coagulate on skeleton grains as a thin film (free grain argillans) with strong continuous orientation and in the plasma between skeleton grains as little, birefringent domains.

In loesses, the leaching of carbonates leaves a microporous fabric and liberates fine clays: very favorable conditions for local rearrangements for these clays. According to R. Brewer's terminology this fabric is described as a skelinsepic.

In coarse calcareous sands (for instance faluns of the Loire valley), free grain argillans appear just over the zone of leaching and little vesicle argillans with strong continuous orientation develop in the packing voids (Fig. 1). We think that most of the domains of the insepic fabric of the loesses have the same origin as these vesicle argillans.

* This paper is written according to R. Brewer's terminology.

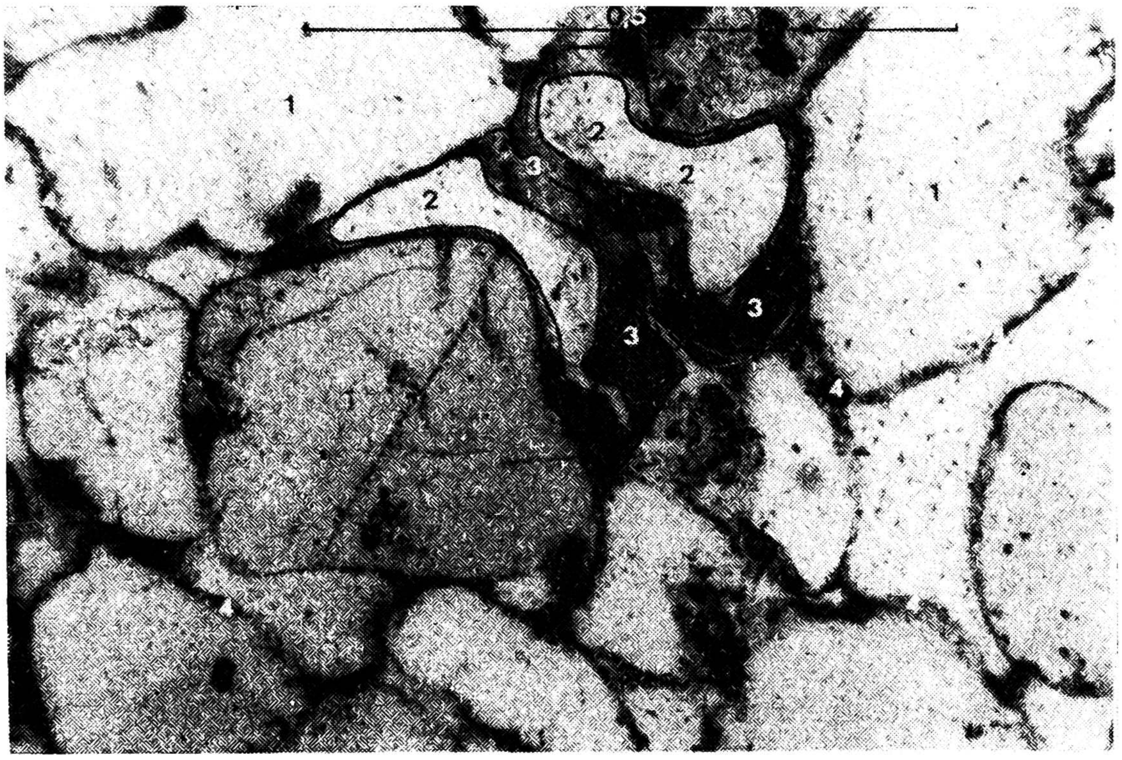

Fig. 1. B_3t of a "lessivé" soil developed on faluns of the Loire valley (natural light). The quartz are coated with thin, reddish yellow argillans. Little argillans develop in the packing voids. *1* — quartz, *2* — vesicule, *3* — vesicule argillan, *4* — free grain argillan.

In most non-calcareous clayey sands, the grains are coated with clay with strong continuous orientation all through the thickness of the sediment. Some of these coatings may have been formed in-situ, but most of them are inherited.

It is obvious that the free grain argillans are closely tighted to the surface of the grain. In the process of clay illuviation, they appear first and they disappear the last when a soil is destroyed.

Fig. 2. B_3tg of a "lessivé" soil developed on clayey continental sediments of the Chateauroux forest (crossed nicols). The fragments of clayey sediment are coated with thick, yellowish white argillans with strong continuous birefringence. *1* — quartz, *2* — void, *3* — free grain argillan.

In clayey material, in the zone of fragmentation, one can see free grain argillans on the fragments (Fig. 2). The latter behave as quartzic grains.

Most of the cambic horizons (brown and red) have oriented clays on skeleton grains and birefringent domains between these grains; their number is variable.

Free grain argillans are also typical for the deepest part of "lessivés" soils (for instance the B_3 of the "lessivé" on faluns of the Loire valley, Fig. 1 or the B_3 of the "lessivé" on continental clays of the Chateauroux forest, Fig. 2).

II. PRIMARY ILLUVIATION

During this phase, the aggregation is strong; the B has a very fine (primary peds have volume not exceeding some cubic millimeters), stable, blocky structure. In consequence, the drainage is good and the dissociation of clay and iron complex do not occur; the dispersion of this complex is low.

This phase of illuviation is characterized by thin ferri-argillans; they can be yellow, yellowish red and red. Clays deposit on peds and in macro and mesovoids. Clays accumulation during this phase can be important in volume. The primary peds being very little, so the net of argillans can be dense when the soil is enough developped. During this phase, the illuviation is still rather diffuse. The ferri-argillans are integrated to the s-matrix. This integration is slow when only biologic pedoturbation takes place. It can be fast, even immediate when the B possesses an internal dynamism (mechanical pedoturbation).

In the loesses of western Europe, argillans appear first in the little voids, mostly vesicles; then, they develop on peds. These argillans are yellow, thin, homogeneous, with strong continuous orientation. In "sol brun lessivé", we find the first argillans in the base of the A_1, the maximum being in the upper part of the Bt. In thin sections, surfaces without argillans do not exceed some square millimeters. Biologic pedoturbation integrates slowly argillans to the s-matrix (Fig. 3).

In coarse siliceous sands, the process is continuous from the coagulation to primary illuviation. The vesicle argillans become more and more numerous. In the same time, the pedoturbation presses these argillans, obturating the vesicles. All free space is slowly filled with illuviated clay; the Bt acquires a porphyroskelic fabric. In a well developped Bt, we see some ferri-argillans, but most of them have been completely integrated to the plasma, plasmic fabric of which is mosepic, being locally omnisepic.

In most clayey soils having the macro and analytical characters of a weakly "lessivé" soil typical argillans do not exist, but their plasma has a well developped mavosepic (plus inskelsepic) fabric (Fig. 4). We call the Bt of these soils *dynamic* [4]. The birefringent domains of this ma-

Fig. 3. B_2t of a "brun lessivé" soil developped on late würm loess in the Park of Grignon, west of Paris. Most of argillans are still in the voids but some are integrated to the s-matrix, *1* — void, *2* — s-matrix typic of loessic material, *3* — argillan.

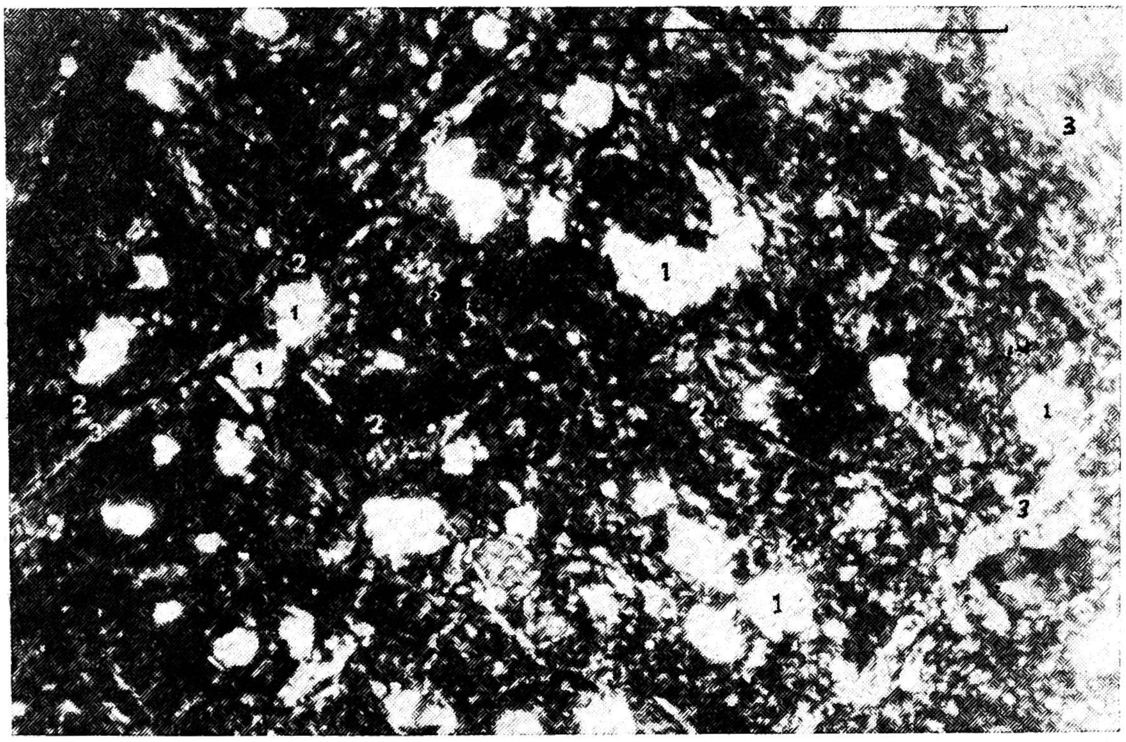

Fig. 4. B_2t of a red "lessivé" soil, south of Ciudad Real, central Spain (crossed nicols). Homogeneous, red s-matrix with a mavo-inskelsepic plasmic fabric. *1* — quartz, *2* — void, *3* — domain of the ma-vosepic plasmic fabric.

vosepic fabric must be considered as fragments of ferri-argillans which have been crushed and incorporated to the plasma by internal pressures. In some soils, in the lower part of the B_2t, it is possible to see the transition from a mavosepic fabric to a net of ferriargillans typical for primary illuviation (Fig. 5). We find the mavosepic fabric in clayey patches, s-matrix of which has the characters of a well developped B_2t (their fabric is porphyroskelic) and the net of ferri-argillans in patches with a lower clay percentage, s-matrix of which has the characters of a C (their fabric is intertextic). In the first type of patches, internal pressures squeeze the illuviated clays soon after they have been deposited and so this mavosepic fabric appears. In the second type of patches, the intertextic fabric makes the transmission of pressures impossible and so the ferri-argillans keep their original aspect. In soils having a B_2t overlying a B_3K_3, the plasmic fabric of the B_2t is mavosepic without any ferri-argillans, but the planes of the B_3K_3 are filled with typical ferri-argillans. In the B_2t, the internal pressures squeeze all the illuviated clay as soon as it is deposited, while in the B_3K_3 the rigid form given by calcium carbonate preserves the illuviated clay from deformation.

In the regions having every year periods of severe drought (for instance the mediterranean basin), the s-matrix contracts on itself during these periods. Voids open, they are large between the prisms and narrow between primary peds. After a heavy rain, waters loaded with loam and clays rapidly enter the Bt by the prisms, but soon the infiltration is con-

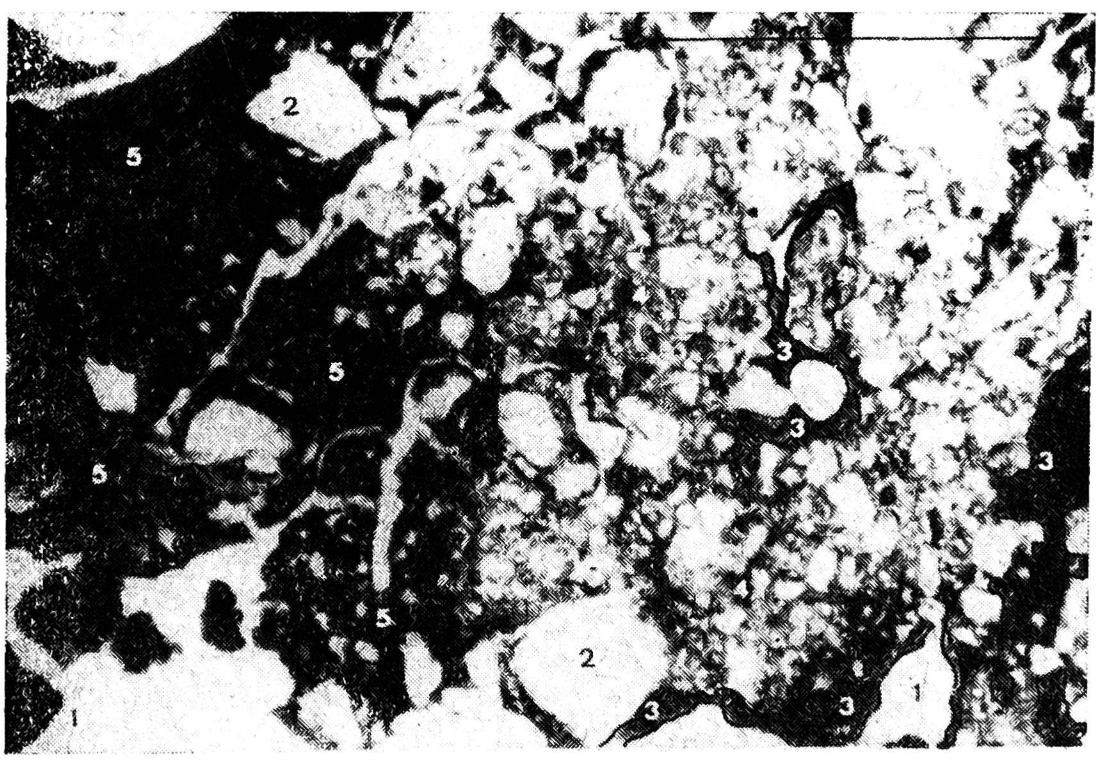

Fig. 5. Lower part of a B_2t of a red "lessivé" soil, Plateau de Valensole, south east France (natural light). Two different types of elementary fabric: right, fabric of the C (siliceous residium after calcium carbonate leaching) with typical ferriargillans and left, fabric of the B_2t (clayey, ferrugineous s-matrix) with a ma-vosepic plasmic fabric (not seen on the photograph). *1* — quartz, *2* — void, *3* — ferriargillan, *4* — s-matrix of the C, *5* — s-matrix of the B_2t.

siderably slowed down in the B_3. So the coarser material deposits in larger voids and waters with only colloidal clays enter narrow voids. Before water penetrates into primary peds, these clays deposit on them. The penetration of water in the primary peds induces their swelling. So the voids close, the newly deposited argillans are crushed and integrated to the s-matrix; they will be described as vosepic fabric. During the next period of drought, new primary peds appear; their limits are not necessary the same as during the previous period. So the vosepic fabric integrates little by little to the inner part of the ped and becomes masepic.

In these regions, such dynamic Bt can develop in non-swelling or few swelling clays. Under more humid climates, without season of droughtness (for instance north-western Europe), dynamic Bt exist only in soils having a high percentage of swelling clays. We find such Bt on marly parental materials.

III. SECONDARY ILLUVIATION

During this phase, the aggregation of the Bt degrades: the blocky primary peds loose their stability; in the same time a large secondary structure, in general prismatic appear. The drainage becomes low and the clay and iron complex dissociates. In these conditions, the dispersion of clays is high.

This phase of illuviation is characterized by white or grayish white argillans (more seldom they can be yellow). Thin sections show that the greater part of the grayish patches seen in the field are not secondary illuviation clays. In the upper part of the B, there are tongues and spots of degradation (A_2 fabric) and in the lower part of the soil, spots of deferrification. In general, the secondary illuviation clays are in the middle of the spot of deferrification.

The typical argillans of secondary illuviation are found on the surfaces of peds of the new generation and in the macrovoids of the lowest part of B_2, of B_3 and even of C. These argillans are thick, they can have a thickness up to one centimeter. In the B_2, they often contain silt and even loam. The coarse material can be mixed with clay; or they may consist of irregular beds, some clayey and other coarse (skeletans). These argillans have not a continuous orientation; in general their plasmic fabric is omnisepic, but it can be mosepic. Deeper in the soil, the coarse material disappears and they can have a continuous orientation; often they are better coloured than in the upper part of the soil. In some soils, we find white, rather thin argillans without coarse material in the mesovoids of the B_2.

In this phase, the net of argillans is wide; the clay accumulation is more important than in the previous ones, but it is diluted in a greater thickness (base of B_2, B_3 and even C).

Fig. 6. A secondary argillan in the lower part of a B_2tg of an hydromorphic intergrade between a glossisol and a planosol. In loess of the middle terrace of the Garonne, near Agen (natural light). *1* — void, *2* — loessic elementary fabric with imbedded argillans, *3* — secondary argillan mixed with silty material, *4* — ferrugineous impregnation.

As in the previous phase, we must divide the B in static and dynamic ones. The glossisols developped on loesses of north-western Europe show typical secondary illuviation. In the nodules found in the base of the A_2 and in the A and B, we see the fabric of a "brun lessivé" preserved by iron oxides. The tongues are filled with silty material having a silasepic plasmic fabric. In the lowest part of the tongues, we see white, rather thick, mixed with silt, argillans. In the little voids of the B_2, there are white, rather thick, pure argillans (Fig. 6). The plasma of the B_2 shows a weak masepic fabric (plus inskelsepic).

In the B of typic planosols, there are no argillans, but the plasma is highly birefringent; its fabric is complex, rather difficult to classify. The mavosepic fabric well expressed exists in the dynamic soils of the previous phase, but the striated elongated zones (ma- and vosepic) are rather scarce; their domains are larger with a prolate form and irregular limits. Dispersed in the plasma, there are numerous domains, most with a continuous orientation, but some only with an omnisepic fabric; in general they are large, prolate, with irregular limits and without (or little) skeleton. Between these highly birefringent domains, there are patches of s-matrix rich in skeleton with an insepic plasmic fabric (Fig. 7).

We find planosols in France only in regions where there are abundant swelling clays (inherited); there are abundant in subtropical and tropical countries. Between two rains, the s-matrix of the B contracts on itself.

Fig. 7. A planosolic B_{23}tg developped in a loessic material, Saint-Arnould forest, south of Rambouillet (crossed nicols). On the left, a thick, white, deformed argillan. *1* — secondary argillan with an omnisepic plasmic fabric; elsewhere, a well developed vo-masepic plasmic fabric, *2* — domain of the vo-masepic plasmic fabric.

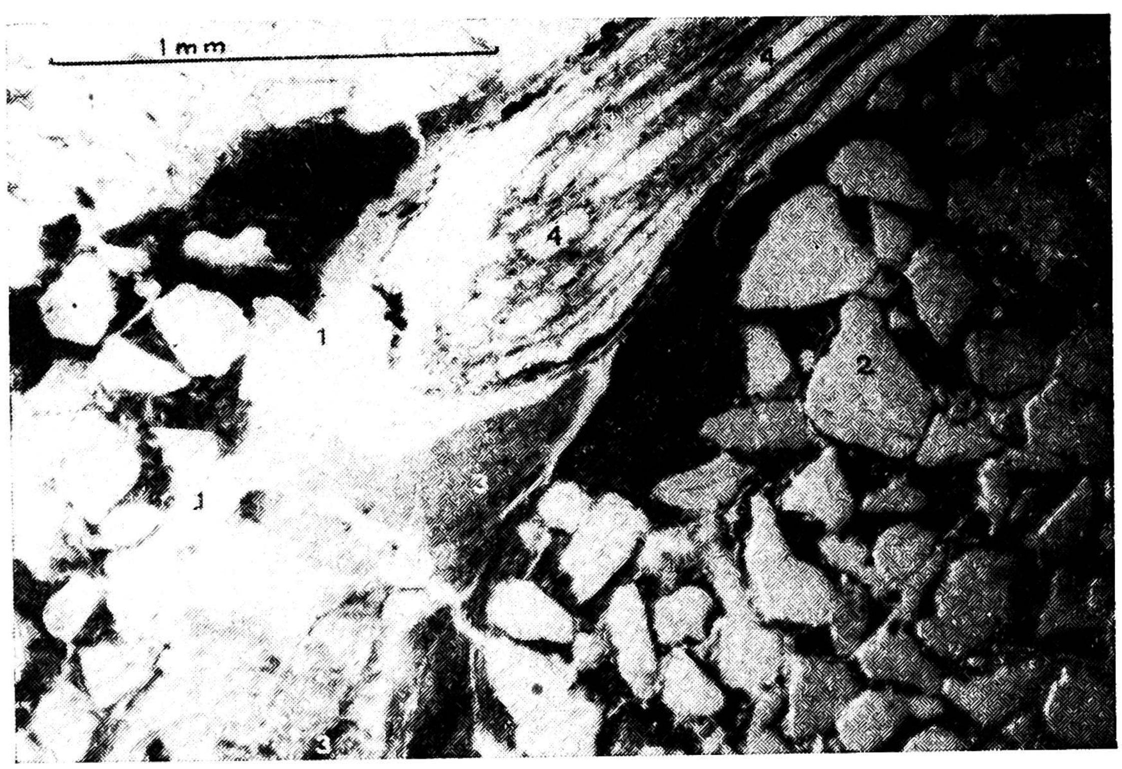

Fig. 8. Secondary illuviation in a coarse siliceous sand. Inherited B_2tg, Broué, near Nogent-le-Roi, west of Paris (natural light). The dark plasma is primary illuviation, ferruginous clay. *1* — void, *2* — quartz, *3* — secondary illuviation argillan, *4* — root.

Wide cracks and a net of secondary voids open. After a rain, waters loaded with loam and clay enter the B by the cracks, but soon the infiltration is stopped. In the cracks, loam and clay deposit, only clay in the thinner voids. Water slowly penetrates in the s-matrix which swells, closing the voids and crushing the newly deposited argillans. The process is the same as in a dynamic weakly "lessivé" soil, but under hydromorphic conditions.

In south-west France, the "boulbènes" (intergrade to planosols) have a s-matrix intermediate between that of glossisols and planosols. In the B of these soils, it is possible to see plane argillans becoming a vosepic fabric and deformed argillans, integrated to the s-matrix, but keeping some cutanic characters.

In coarse siliceous sands, when the B has been completely filled with illuviated clay of 1:1 type and had acquired a porphyroskelic fabric, hydromorphic conditions appear and a net of secondary planes develops. The upper part of the B is destroyed and its clays having lost their iron migrate through these planes and deposit on them as thick white or yellowish white argillans with strong continuous orientation (Fig. 8). In France, this type of soil is always inherited.

IV. "FLAKY" ILLUVIATION

This type of illuviation appears in the horizon of degradation of a "lessivé" soil having in its A_2 a spodic horizon or a wet podzol.

In the most developped planosols of Orléans forest [4], this type of illuviation exists in a thin, yellowish brown, enriched in organic matter, with a fluffy structure horizon of degradation overlying the B_2tg. The elementary fabric of this horizon is agglomeroplasmic, with porphyroskelic patches. The plasma is brownish gray, flaky; with a high concentration of light, its fabric is lattiskelsepic (the latter is better developped in porphyroskelic patches). In the voids, we see numerous, thin, grayish brown, weakly birefringent argillans. Their flakiness is not so strong as in the plasma (Fig. 9). With a high magnification, they appear as being composed of a weakly birefringent plasma, but with a continuous orientation, they are regulary strewn with numerous, grayish black, opaque in crossed nicols silty particles.

In Brenne (central France), the plasma of degradation horizon of very low drainage planosols (intergrading to glossisols) is dark gray, very flaky, agglomerating in heaps, grayish black in natural light and pearly white in reflected light [4]. Some of these heaps must be considered as having an illuviated origin. We find them in voids but they never form a regular film. With a high magnification, they appear as being composed of opaque in crossed nicols silty particles.

Such flaky heaps have been seen by G. Bocquier on the top of the column of solodized solonetz of Tchad (Central Africa).

We think that there is a continuity between the typic argillan with strong continuous orientation and these flaky heaps. In France, we find mostly intermediate types, like the one of the Orléans forest. Undoubtly this continuity follows the development of the degradation. The flaky argillans appear in already degraded soils; the A_2 must be grayish white. At this moment, we have no analysis of these flaky argillans and heaps. In the comparative study of lessivage and chemical podzolisation, it will be of great interest to know the degree of weathering of clays in them.

Fig. 9. "Flaky" illuviation in a Bth of a planosol in Orléans forest (natural light). *1* — void, *2* — quartz, *3* — "flaky" cutan, *4* — "flaky heap".

V. COARSE ILLUVIATION

We have already noticed that migration of coarse material can happen during primary as well as during secondary illuviation.

In dynamic soils, wide cracks open during periods of drought. After a heavy rain, these cracks are filled with unclassified material.

In glossisols, the upper part of the tongues contains only loam and silt; progressively as the tongues get narrower, their material becomes finer. In some thin sections, we see illuviated clays mixed with silt, in others we find alternate irregular beds of clay and silt.

In primary podzolic soils, coarse illuviation can develop; it is inde-

Fig. 10. A complex cutan in the B_2t of a red "lessivé" soil developed on siliceous limestone, Plateau de Vaucluse, south-east France (crossed nicols). *1* — void, *2* — s-matrix, *3* — primary argillan (reddish yellow), *4* — coarse cutan constituted of silty particules (papules and siliceous elements).

pendent of any clay illuviation. The material migrates through a net of packing voids and deposits on the surface of the grains; we have never seen accumulation between them.

On the plateau of Millevaches (Central Plateau of France), we have found coarse illuviation in crypto-podzolic soils developped on weathered granites. In the field, the coatings can be differenciated from clay skins only by an accurate examination. They are thick (some millimeters), dark pinkish, little micas shining on their surface; they coat all sandy and stony elements of the granite. In thin sections, they appear to be constituted of particules no bigger than 10 microns. We see muscovites parallel to the surface of coated grains; their plasmic fabric is silasepic (Fig. 11).

The precise conditions in which this type of coarse illuviation occurs, are not yet known.

CONCLUSION

In cambic horizons (brown and red), the clays coagulate on skeleton grains and may rearrange between them. In primary argillic horizons (brown and red), the clay and iron complex migrates on short distances; the illuviation is diffuse, but it can be dense.

When the aggregation of the argillic horizon degrades and this horizon becomes hydromorphic, the clays having lost their adsorbed iron, disperse easily and migrate in longer distances. They deposit as thick argillans in the basal part of the B_2, in the B_3 and even in the C. This is the secondary illuviation.

In the static argillic horizons, the argillans keep their form a long time; they are slowly integrated to the s-matrix by biologic pedoturbation. In the dynamic argillic horizons, the argillans are crushed and rapidly integrated to the s-matrix by internal pressures.

Fig. 11. Coarse free grain cutan in a cryptopodzolic soil, Plateau de Millevaches (Central Plateau of France). *1* — void, *2* — quartz, *3* — coarse free grain cutan.

In the horizon of degradation of very well developped "lessivés" soils, we see flaky argillans and flaky argillic heaps.

The clay illuviation has been mostly studied in soils developped on loesses [1, 6]. But recent micromorphological studies of mediteranean and african soils show that the basic processes in clay illuviation are the same everywhere. But the intensity of the clay illuviation and the degree of development of the lessivage are under the influence of climate.

SUMMARY

The development of a modal "lessivé" soil can be divided into three successive phases: clay coagulation, primary illuviation and secondary illuviation. Another type of clay accumulation appears in the horizon of degradation of very developped "lessivés" soils; we called it "flaky" accumulation in opposition to the previous types the argillans of which have a waxy aspect. Migrations of coarse mineral matter also take place, associated or not with the clay migrations.

In the static argillic horizons, the argillans keep their form a long time; they are slowly integrated to the s-matrix by biologic pedoturbation. In the dynamic ones, the argillans are crushed and rapidly integrated to the s-matrix by internal pressures.

REFERENCES

1. Altemüller H. J., 1957. Thesis. Institut für Bodenkunde, Bonn, 250 p.
2. Brewer R., 1964. John Wiley, 470 p.
3. Buol S. W., Hole F. D., 1961. Soil Sci. Soc. Am. Proc. 25, 377-379.
4. de Coninck F., Laruelle J., 1964. Proc. Intern. Meeting on Soil Micromorphology Arnhem. Elsevier, 169-188.
5. Fedoroff N., 1968. Science du Sol 1, 29-65.
6. Fedoroff N., Jamagne M., 1967. Bull. Information Géologues Bassin, Paris 13, 191-192.
7. Fedoroff N., Rossignol J. P., 1969. Bull. Ass. Fran. Etude du Sol, in press.