Equatorial and tropical weathering of recent basalts from Cameroon : allophanes, halloysite, metahalloysite, kaolinite, gibbsite.

by

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ABSTRACT

The evolution of allophanes in young soils in Cameroon, developed on basalts under different tropical conditions were studied.

- Under a mean annual rainfall of 10 m. , without a dry season, allophanes change into gibbsite and well-crystallized kaolinite;
- Under a mean annual rainfall of 3 to 6 m. , with a dry season, allophanes give rise to halloysite and metahalloysite;
- Under a mean annual rainfall of 1,5 m., with a long dry season, the allophane stage is very restricted and metahalloysite appears rapidly.

In the two climatic zones with heavy rainfall the upper horizons of the soils with allophane contain many diatoms ; the silica of wich plays a role in the neoformation of clay minerals.

The distribution of rainfall controls the rate of desaturation of soils and the seasonal concentration of solutions, which are the two principal factors governing neoformation.

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The federal Republic of Cameroon contains many areas covered with volcanic and pyroclastic rocks, scoria, tuffs and ash of basaltic composition. The genesis of soils and the weathering of these rocks were studied in three different climatic zones (fig.1).

Zone I - Equatorial climate, always humid, on the western flank of Mont Cameroun.

Zone II - Equatorial climate, more moderate, with a dry season, on the southeastern and eastern part of Mont Cameroun.

Zone III - Tropical climate with a well-marked dry season on the Central Adamaoua Plateau of Cameroun.

Nomenclature : - The term allophane here designates amorphous silica-alumina products with a SiO_2/Al_2O_3 molecular ratio between 0.9 and 1.9. The term halloysite designates the hydrated halloysite or hydrohalloysite of 10 Å spacing. The term metahalloysite designates the dehydrated halloysite of 7.4 Å spacing (Caillère and Hénin, 1963 ; Brindley *et al.*, 1966).

I. Zone I. - Andosols developed from recent basaltic rocks on the western part of Mont Cameroun.

The climate is equatorial with a mean annual precipitation of about 10 meters (400'') and without a dry season. Mean annual temperature is 29°C. Drainage is good.

Six soil profiles were studied varying in thickness from 30 to 140 cm. They are "weakly developed soils formed on volcanic deposits" (oxy-hydrandepts), rich in organic matter, with A(B)C profile. The sum of exchangeable bases, measured on the clay fraction, varies between 3 and 10 meq/100g at the bottom and between 1 and 4 meq/100g at the top. Base exchange capacity is between 20 and 32 meq/100g. Base saturation (ratio of the sum of exchangeable bases to base exchange capacity) is low : 5 %. The pH varies from bottom to top between 6.4 and 5.

The clay fraction (less than 2μ) is characterized by a SiO_2/Al_2O_3 molecular ratio between 1 — 1.3. Thermal analysis and X-ray diffraction reveal predominant allophane with a small admixture of gibbsite and a well crystallized kaolinite. The composition of the amorphous fraction, analysed by the method of Segalen (1968) is the following : SiO_2, 23 % ; Al_2O_3, 32 % ; iron hydroxides, 27 % ; H_2O, 18 %. The specific surface varies between 120 — 400 m^2/g.

All these soils contain numerous diatoms in their upper part. The fragments of their tests frequently constitute more than 10 % of the < 2μ fraction, and this occurs down to 50 cm in depth (pl.I).

Electron micrographs show fuzzy flakes wich can be considered to be allophanes (Pl. II), as shown or described by many authors: Birrel and Fieldes (1952); Aomine and Yoshinaga (1955); Sudo and Takahashi (1956); Fieldes *et al.* (1955, 1966); Yoshinaga and Aomine (1962 a); Alonso *et al.* (1963); Chukrov *et al.* (1963, 1964); Giuseppetti *et al.* (1963); Robertson (1963); Kirkman, Mitchell and Mackenzie (1966); Colmet-Daage *et al.* (1967); Sieffermann, Yehl and Millot (1968). But one must note in addition the presence of well crystallized kaolinite (Pl. II, fig. 8 and Pl. III, fig. 9) and gibbsite. Neither tubular or globular-shaped halloysite, nor fibrous allophane were observed.

II. Zone II. - Andosols developed from recent basaltic rocks on the eastern and southeastern part of Mont Cameroun.

The climate here is equatorial with a mean annual precipitation between 2.5 and 6 meters (90 - 250"). A moderate dry season occurs three months of the year. The mean annual temperature is between 27 - 29 °C. Drainage is good.

Eleven profiles, ranging from "weakly developed soils formed on volcanic deposits" to "eutropic brown soils of tropical lands" were studied. They are generally A(B)C profiles ranging from 20 to 100 cm. in thickness. The sum of exchangeable bases, measured on the clay fraction, is between 2 - 20 meq./100g. at the bottom and between 8 - 30 meq./100 g. at the top. Base exchange capacity ranges from 20 - 60 meq./100 g. at the bottom to 40 - 75 meq./100 g. at the top. Base saturation varies between 4 - 20 % at the bottom, and 20 - 50 % at the top. The pH varies between 6 at the bottom and 5 at the top.

The < 2μ fraction is characterized by a SiO_2/Al_2O_3 molecular ratio between 0.9 — 2 at the bottom and between 1.6 — 2 at the top. The amorphous fraction analysed by the method of Segalen shows, as previously, a SiO_2/Al_2O_3 molecular ratio close to 1, but with a smaller percentage of iron hydroxides than in zone I. The specific surface varies from 80 - 400 m^2/g. Thermal analysis and X-ray diffraction reveal a mixture of allophane, halloysite (10 Å), metahalloysite (7.4 Å) and disordered kaolinite with traces of gibbsite at the bottom.

Electron micrographs show allophanes in the form of either amorphous fuzzy flakes or exceedingly fine, fibrous and thread-like particles (pl.III, fig.10) (Yoshinaga and Aomine (1962 b) ; Aomine and Wada (1962) ; Aomine and Miyauchi (1965) ; Miyauchi and Aomine (1966) ; Jaritz (1967) ; Wada (1967) ; Yoshinaga *et al.* (1968)) ; tubular or globular - shaped halloysite (Pl. III fig 11 and 12) (Kinoshita and Muchi (1954) ; Sudo and Takahashi (1956) ; Kurabayashi and Tsuchiya (1960) ; Sieffermann and Millot (1968)) ; and the outlines of hexagonal flakes.

At the bottom of the profiles allophane is the dominant phase, whereas at the top halloysite and metahalloysite predominate, which indicates a replacement of allophane by halloysite.

III. Zone III. - Soils developed from recent basaltic rocks on the Central Adamaoua Plateau of Cameroon.

The climate is the tropical mountain climate of Adamaoua. Mean annual precipitation is between 1.5 and 1.6 meters, with a well-marked dry season lasting five months. Mean annual temperature is 23°C and drainage is good. These soils range from "weakly developed soils, formed on volcanic deposition", to "humic, weakly-desaturated ferrallitic soils."

Six soil profiles were studied ranging in thickness from 40 cm. – 2 m.. The sum of exchangeable bases varies from 9 - 15 meq./100g. at the bottom, and from 15 – 24 meq/100g at the top. Base exchange capacity is between 15 — 30 meq/100g at the bottom and between 30 — 50 meq/100g at the top. Base saturation is between 50 — 80 %, and the pH varies from bottom to top between 7.3 — 6.

The clay fraction is characterized by an SiO_2/Al_2O_3 molecular ratio of 2 - 3 for the youngest soils, reaching 2 for the most advanced ones, and shows only a small amount of allophane. The specific surface of the clay fraction varies from 74 – 150 m^2 /g.

Thermal analysis and X-ray diffraction show that the mixture contains little or no allophane and that it is composed of halloysite (abundant at the bottom) and of metahalloysite (abundant at the top) (Sieffermann and Millot , 1968).

Electron micrographs show amorphous masses corresponding to iron oxides, tubular forms of halloysite or metahalloysite and abundant globular-shaped halloysite. These globules either have a distinct helical or concentric structure and are ovoid or polyhedral in form. In many cases the winding consists of rectilinear fragments with curved ends. These elements sometimes seem to separate from the globules, whose crystalline nature can be discerned by electron microdiffraction. If disaggregated by ultrasonic energy, they yield the X-ray diffraction peaks of halloysite.

In some profiles the only mineral occurring at the bottom is halloysite, while in all the profiles metahalloysite predominates at the top. This indicates a replacement of halloysite by metahalloysite. In soils from older Quaternary results are similar, but gibbsite is even more highly developed at the top of these profiles.

IV. Interpretations.

1) Allophanes. - It is difficult to purify allophanes. In particular the presence of diatoms, constituting up to 20% of the clay fraction (Pl.I, fig. 1, 2, 3 and 4) makes the interpretation of the SiO_2/Al_2O_3 molecular ratio (0.9 - 1.5) difficult. Moreover the silica of the diatoms in contact with allophane having a high alumina content, may be incorporated into newly formed clay mineral. (Pl. I, fig. 3 and 4).

Under an equatorial climate the genesis of allophane, by weathering of basaltic material, is very important. We think that humidity and contineous leaching favor the preservation of allophane.

2) Kaolinite and gibbsite in andosols. - In Zone I, wich is equatorial and permanently humid, allophanes are always present in the form of amorphous fuzzy flakes, never as imogolites (Pl.II). Halloysite or metahalloysite in the form of tubes or globules never occur. But the clay fraction of these andosols may contain up to 10 % of very beautiful plates of well-crystallized kaolinite (Pl.III, fig.9) and up to 20 % of gibbsite, especially at the bottom of the profiles.

Locally desaturation permits the direct regular crystallization of kaolinite, particularly due to the silica of diatoms.

More important is the direct genesis of gibbsite immediately upon the first stages of weathering. This occurs in a desaturated, always humid environment without any dry season and without transition through halloysite.

3) Halloysite and metahalloysite. - Halloysite can form in two habits ;

- in the form of tubes only : in profiles, the exclusive occurrence of tubes often coincides with the presence of amorphous products rich in thread-like fine fibrous particles (Pl.III, fig. 10 and 11).

- with globular shape, the form and crystalline nature of which is defined. They occur in soils in wich allophanes predominate as amorphous flakes (Pl.III, fig. 12). Subsequently these globules give rise to tubes (Pl. III, fig 12).

The genesis of halloysite takes place only in Zone II and III, where an annual dry season occurs. In Zone III, where the dry season is very intense, allophanes are characterized by a high SiO_2/Al_2O_3 molecular ratio (2 to 3) and the neoformation of halloysite is sufficiently rapid to keep the allophane content down to a few percent.

At the top of the profiles of Zone II, and particularly of Zone III, metahalloysite replaces halloysite and in older soils metahalloysite becomes predominant. In very ancient soils gibbsite occurs at the top of profiles, by degradation of metahalloysite (Sieffermann, Besnus and Millot, 1968).

4) Evolution according to climates and time. - Two weathering sequences can be discerned :

a) Parent rock → allophane + kaolinite sensu stricto + gibbsite (ZoneI)

b) Parent rock → allophane → halloysite → metahalloysite → gibbsite (Zones II and III)

The first sequence is typical of an equatorial environment which is always humid. Well-crystallized kaolinite and gibbsite form early in andosols, from basaltic materials.

The second sequence and the gibbsite formation under different conditions were reported partly or entirely by several authors : (Sudo (1953) ; Fieldes *et al.* (1955, 1966) ; Sudo and Takahashi (1956) ; Jackson (1959) ; Aomine and Wada (1962) ; Gastuche, Fripiat and De Kimpe (1962) ; Keller (1963) ; Wada (1967) ; Pedro and Lubin (1968) ; Sieffermann and Millot (1968) ; Trichet and Svoronos (1968)). Here it is described, beginning with basalts in intertropical regions :

in soil profiles (vertical variation) ;

in the transition from a humid equatorial climate to intermittent tropical climate ;

in the course of time.

5) Geochemical evolution of silicates.

In intertropical regions basaltic material of fine grain size is rapidly hydrolyzed, giving rise to allophanes.

Gibbsite and well-crystallized kaolinite may occur in the initial stages of weathering in permanantly humid regions, which lack annual dry seasons.

In the less leached zones, which have a dry season, halloysite occurs. The seasonal concentration of solutions makes crystallization easier, but the weaker desaturation gives rise to disordered and hydrated crystalline lattices.

In the upper horizons, which are preferentially exposed to dehydration metahalloysite replaces halloysite.

In the course of time, a second generation gibbsite can occur, but this requires both desaturation and removal of silica by seasonal dessication.

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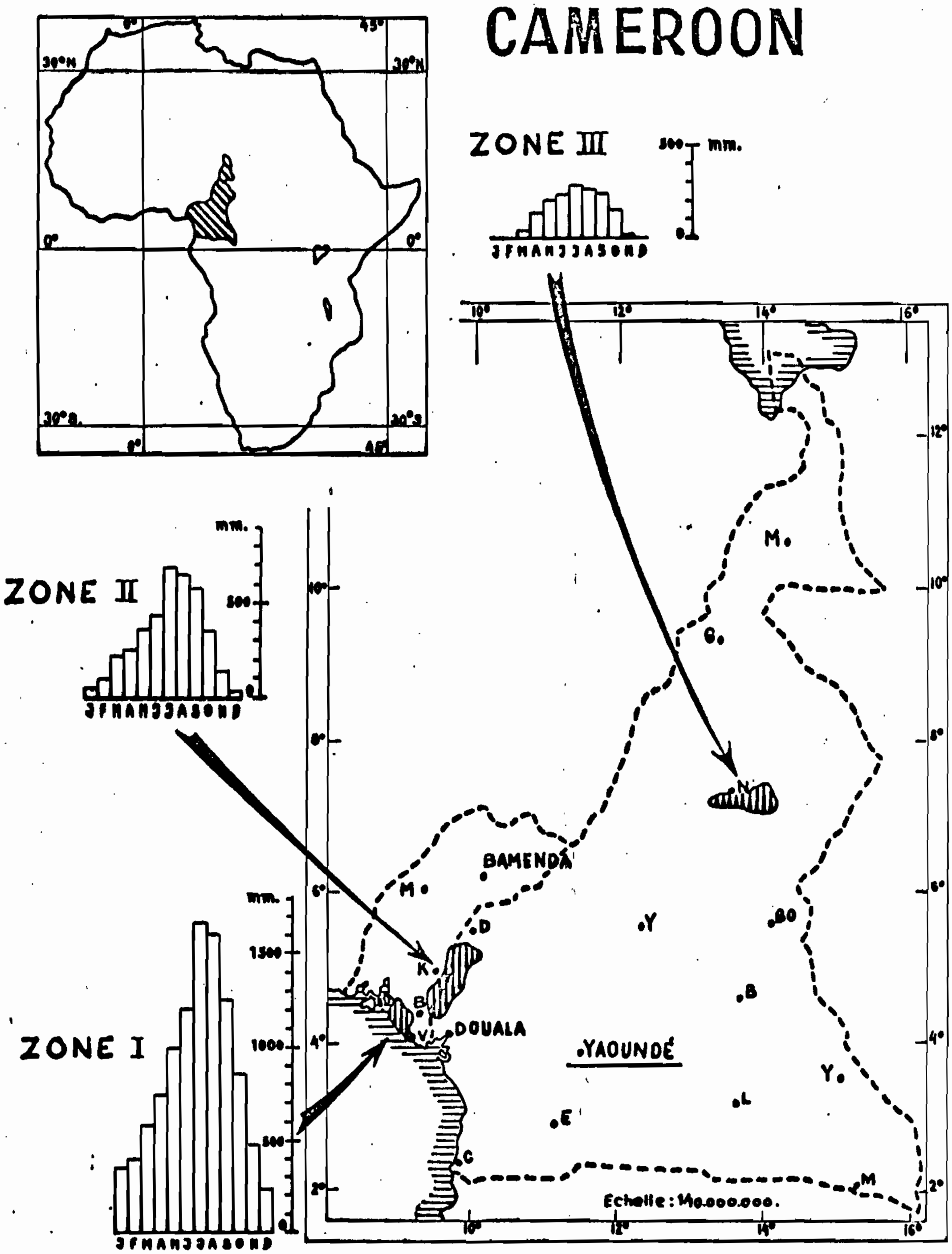

Figure 1 :

Localization of the three climatic zones and annual rainfall distribution.

Plate I : Samples from Zone I.

Fig 1 : Test of diatom (d) coated with allophane (a) - x 14 000

Fig 2 : Fragment of diatom less than $0{,}2\mu$ (d) in an allophanic mass (a) - x 100 000

Fig 3 : Unperforated fragment of diatom (d) coated with allophane (a) - x 70 000

Fig 4 : Fragment of diatom in process of dissolution (d) coated with allophane (a) - x 45 000

Plate II : Facies of allophanes of Zone I

Fig 5 : Felt-like facies of allophane (a) - x 100 000

Fig 6 : Fuzzy flakes of allophane (a) - x 100 000

Fig 7 : Allophane (a) and unidentified mass in process of organization - x 100 000

Fig 8 : Allophane (a) and kaolinite (k) - x 100 000

Plate III

Fig 9 : Allophanic mass (a) and kaolinite (k) - x 60 000 - Zone I.

Fig 10 : Imogolite (Im) - x 80 000 - Zone II.

Fig 11 : Metahalloysite (MH) and thread-like fine fibrous particles (a) which may be imogolite - x 80 000 - Zone II.

Fig 12 : Globular and tubular shaped halloysite (Hall) and amorphous mass (a) - x 210 000 - Zone III

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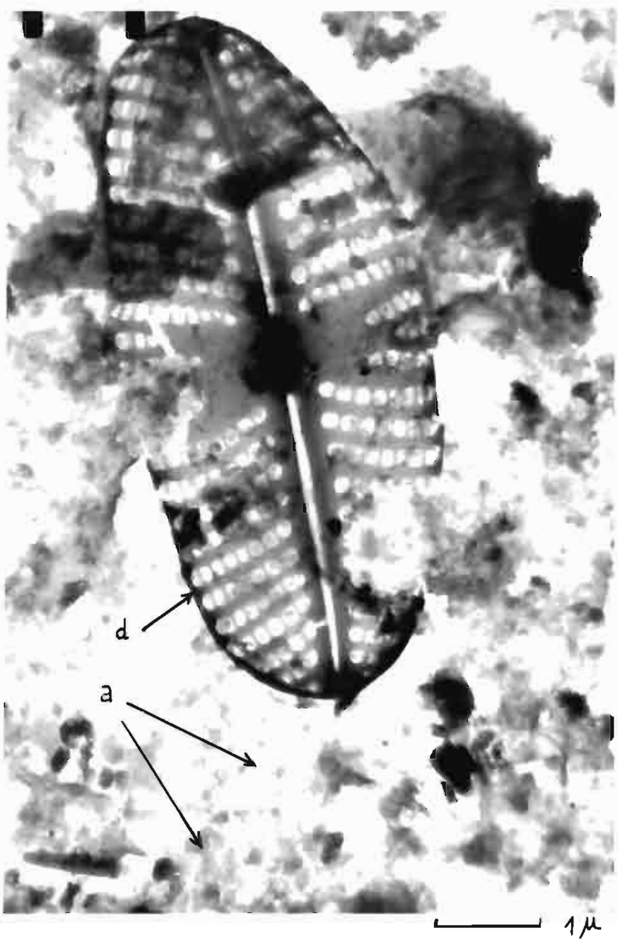

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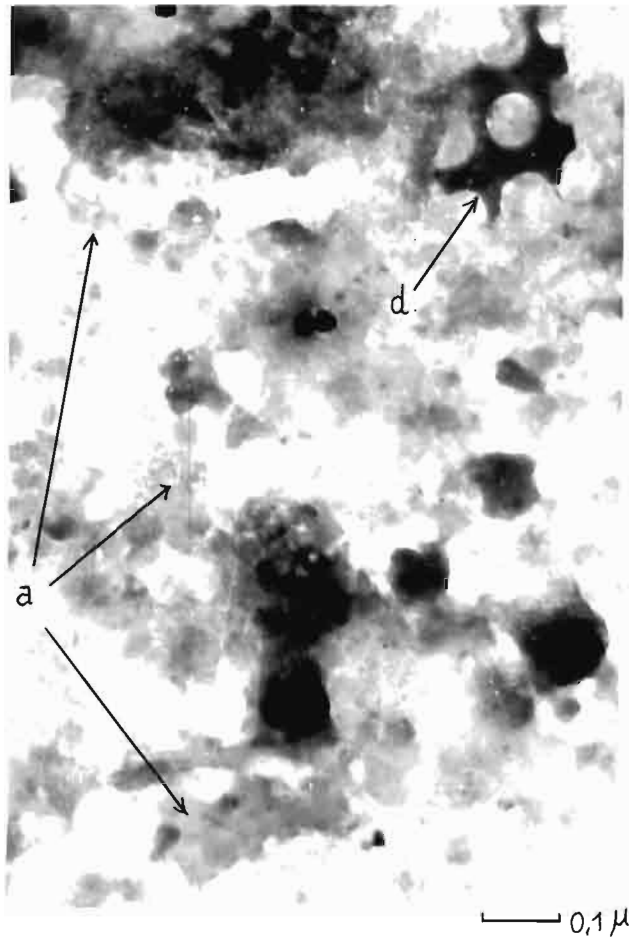

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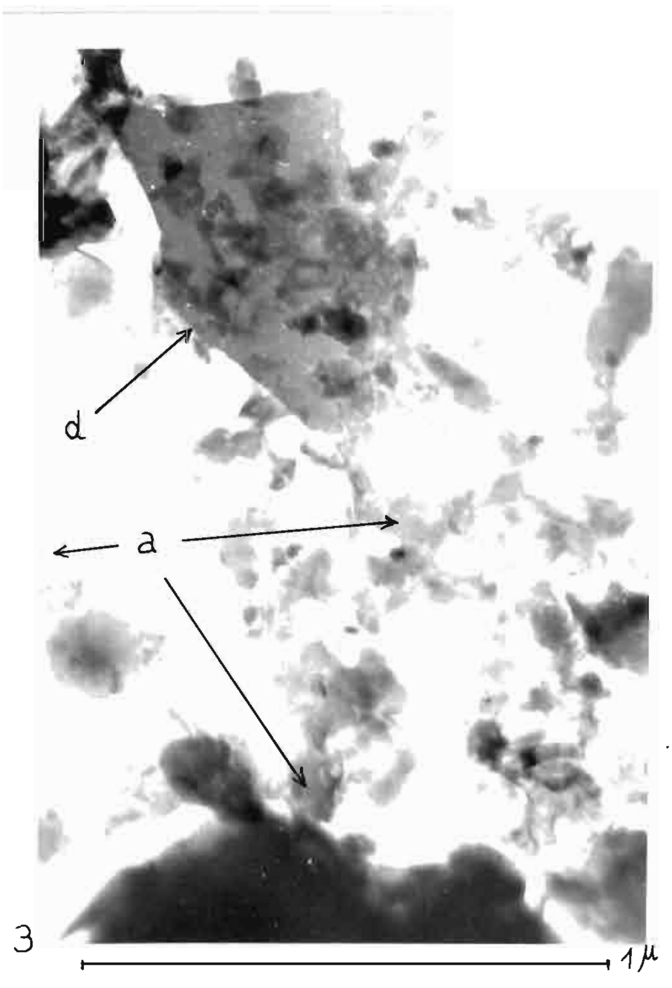

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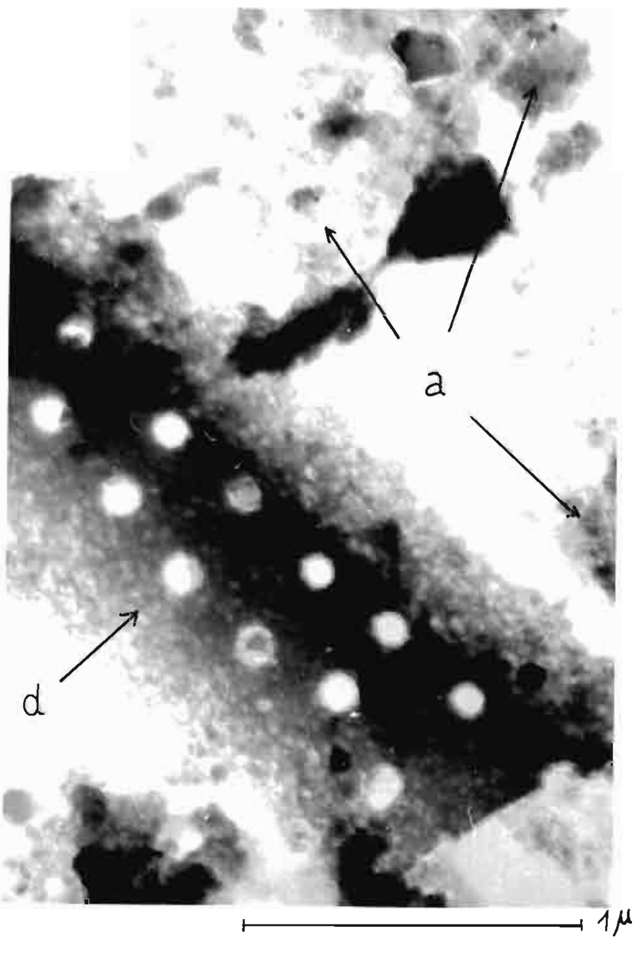

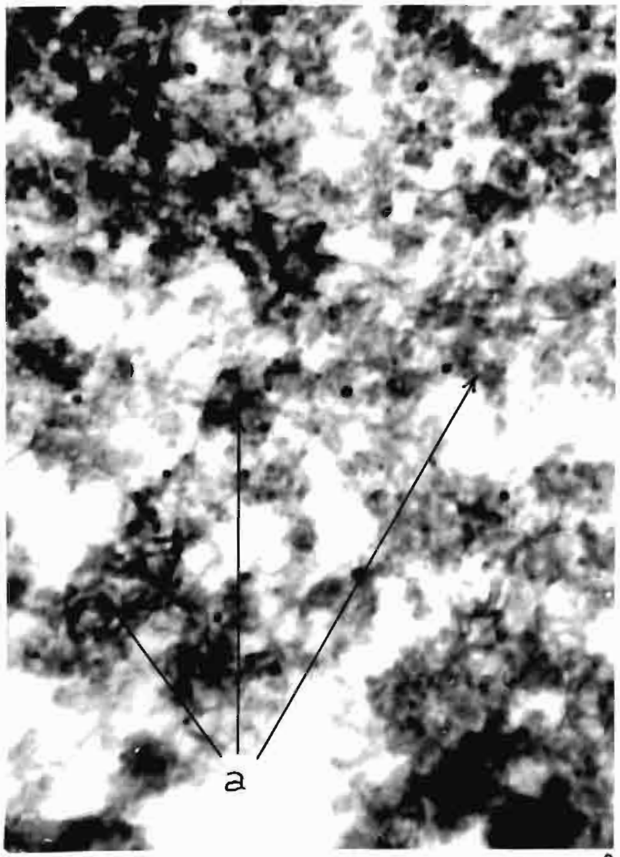

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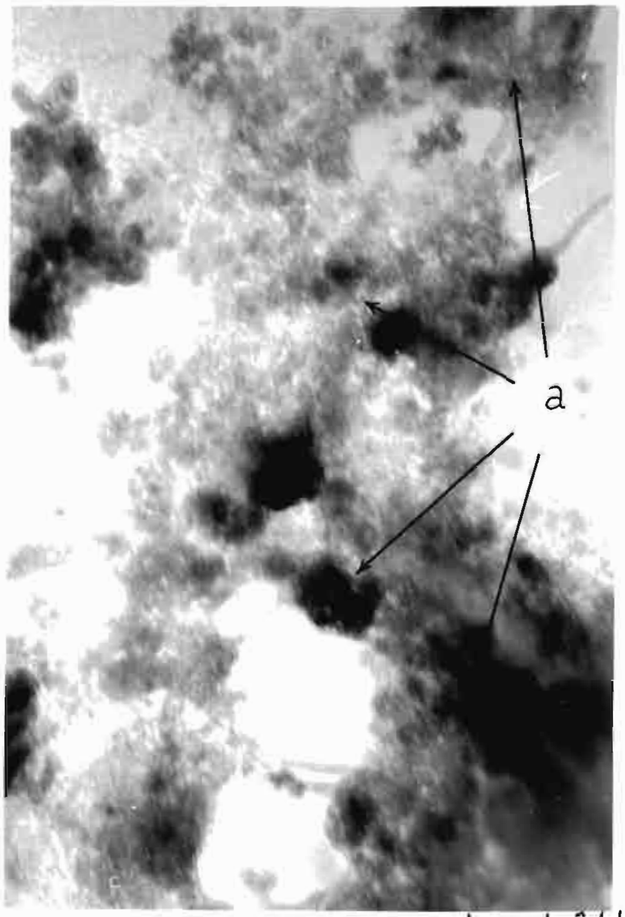

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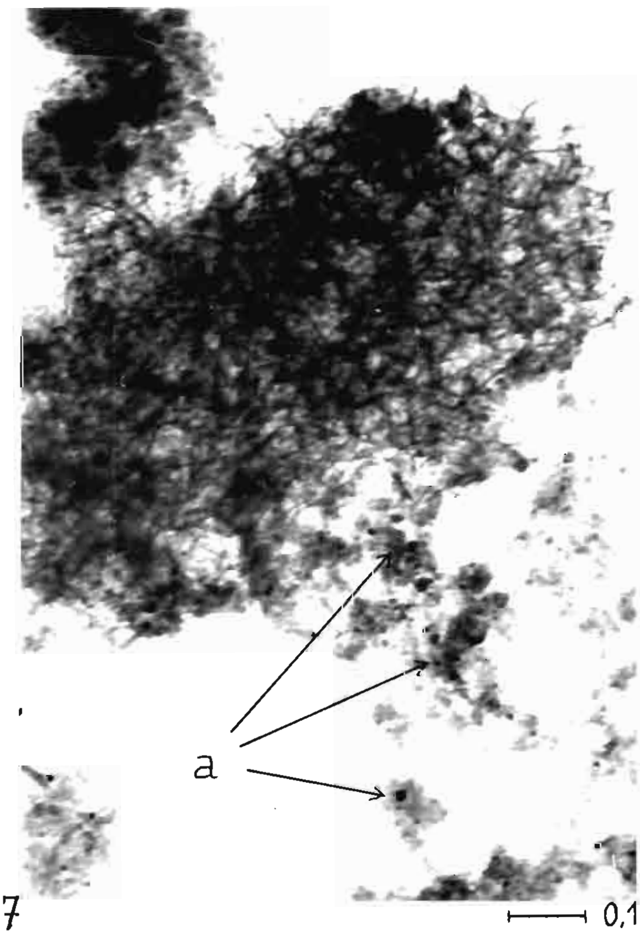

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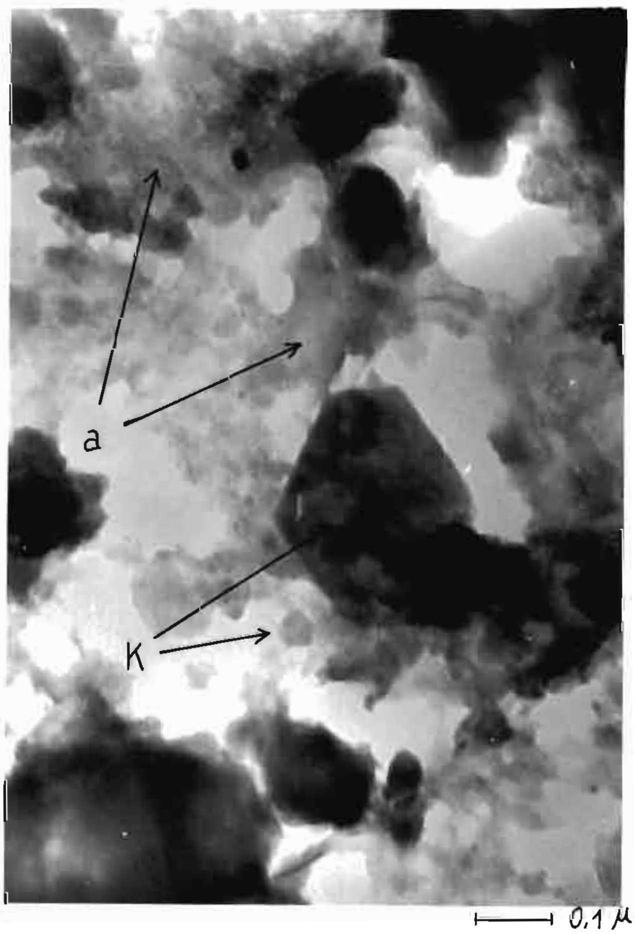

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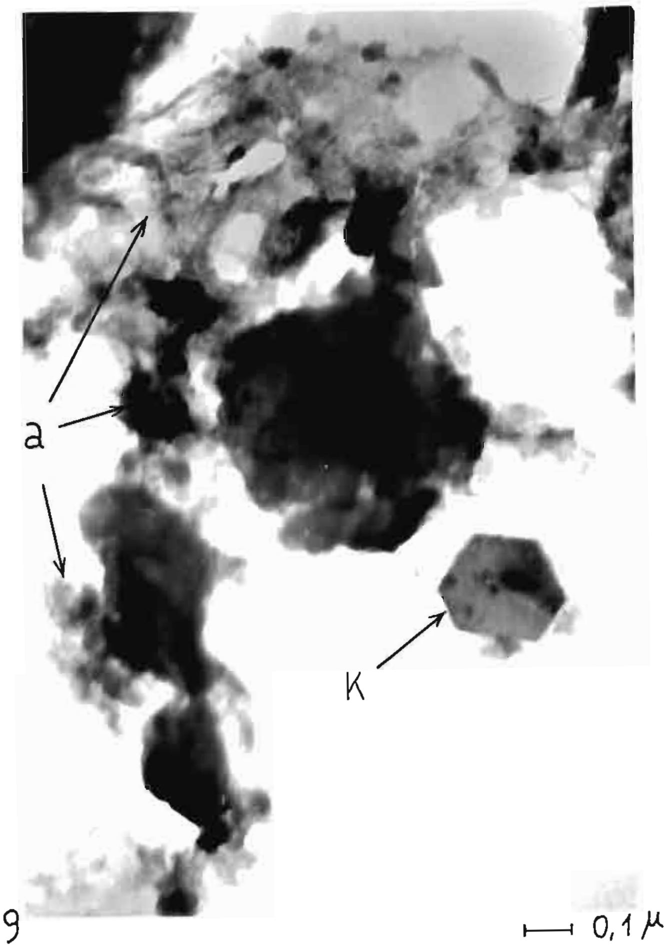

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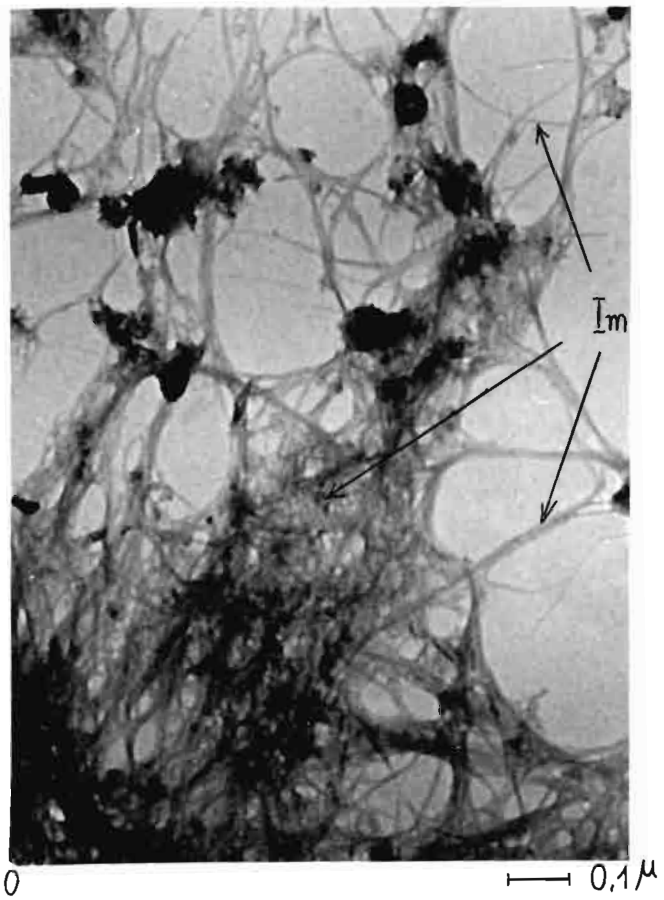

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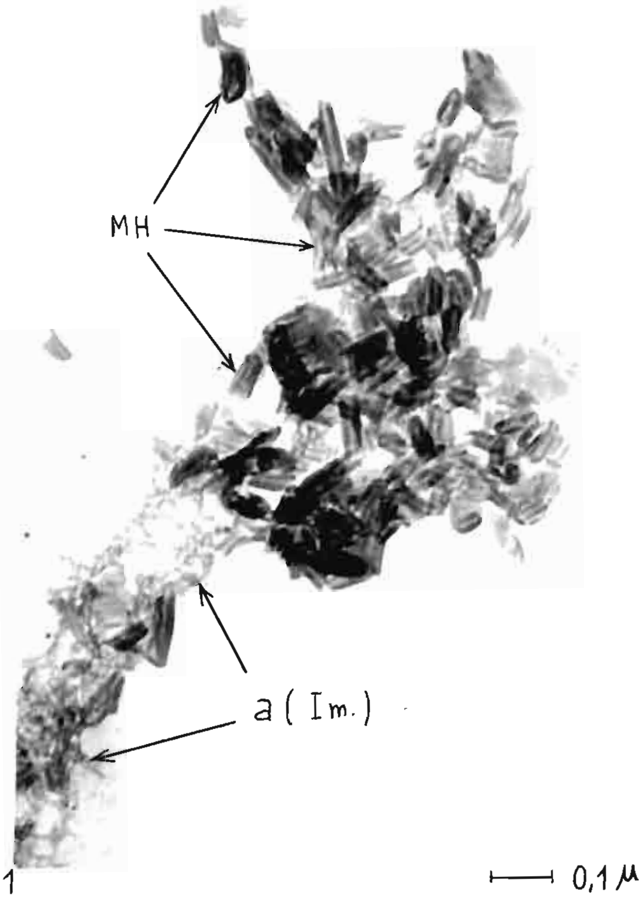

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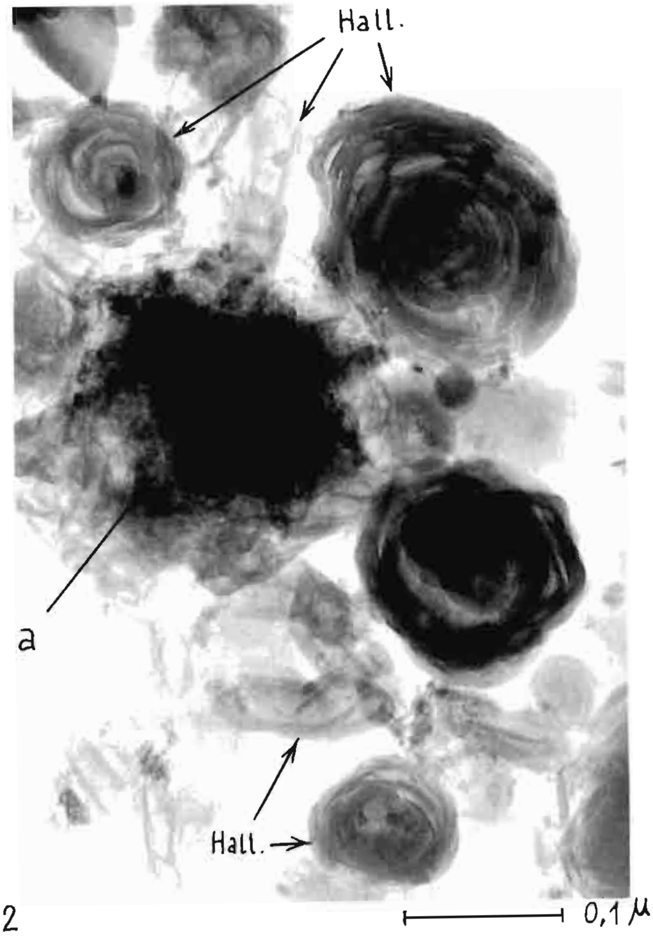

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