EQUATORIAL AND TROPICAL WEATHERING OF RECENT BASALTS FROM CAMEROON: ALLOPHANES, HALLOYSITE, METAHALLOYSITE, KAOLINITE AND GIBBSITE

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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 which 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.

INTRODUCTION

Many areas of the Federal Republic of Cameroon are 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 the Cameroon Mountain.

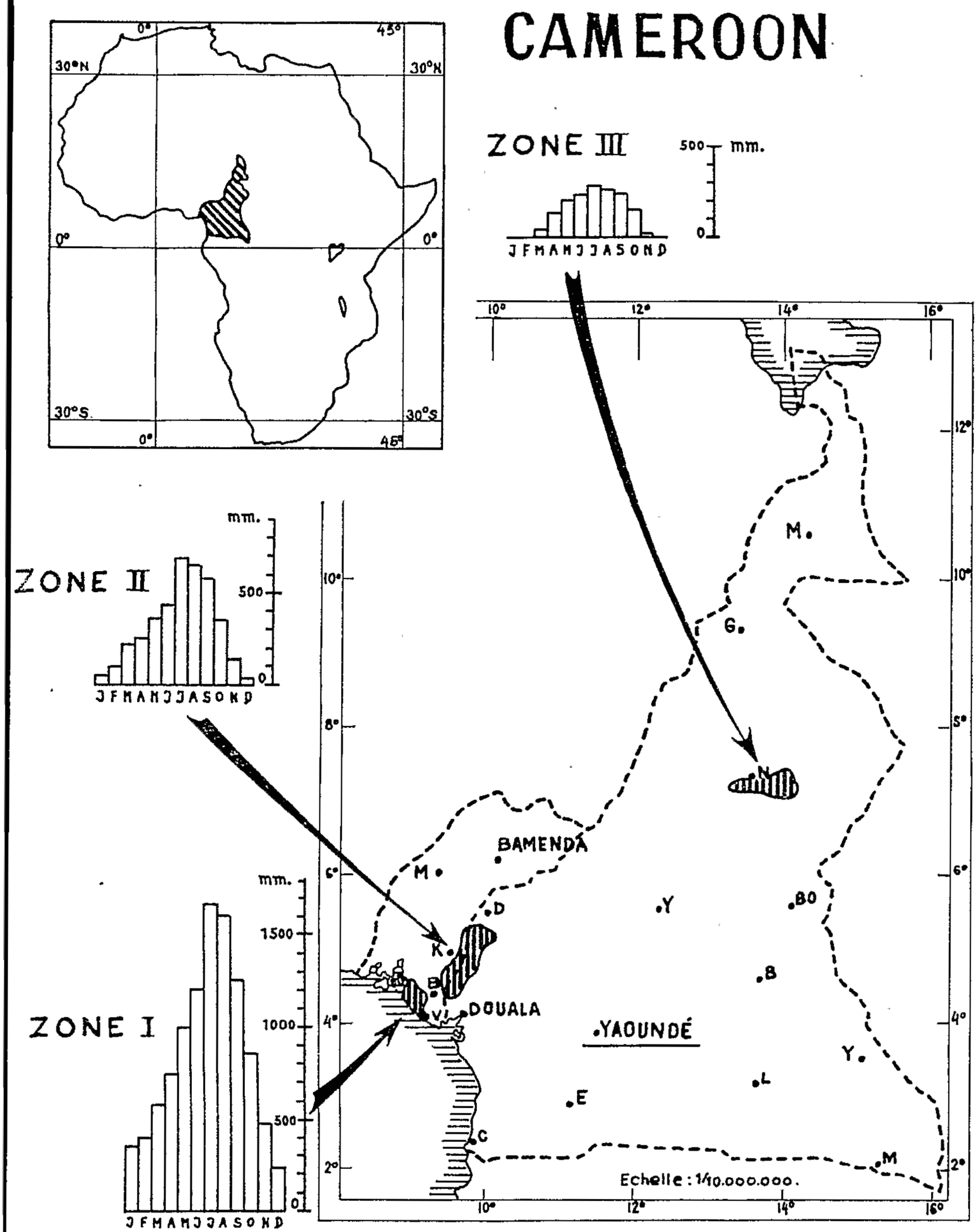


FIG. 1. Localization of the three climatic zones and annual rainfall distribution

Zone II —Equatorial climate, more moderate, with a dry season, on the south-eastern and eastern part of the Cameroon Mountain.

Zone III —Tropical climate, with a well-marked dry season, on the Central Adamawa Plateau of Cameroon.

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).

ZONE I. ANDOSOLS DEVELOPED FROM RECENT BASALTIC ROCKS ON THE WESTERN PART OF THE CAMEROON MOUNTAIN

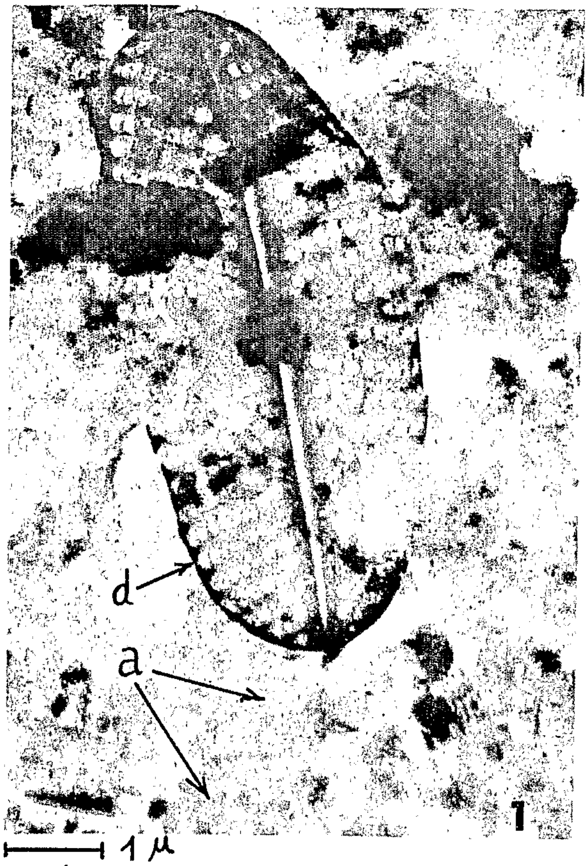
The climate is equatorial, with a mean annual precipitation of about 10 m (400″) and without a dry season. Mean annual temperature is 29°C. Drainage is good.

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./100 g at the bottom and between 1 and 4 meq./100 g at the top. Base exchange capacity is between 20 and 32 meq./100 g. Base saturation (ratio of the sum of exchangeable bases to base exchange capacity) is low: 5%. The pH varies between 6.4 and 5 from bottom to top.

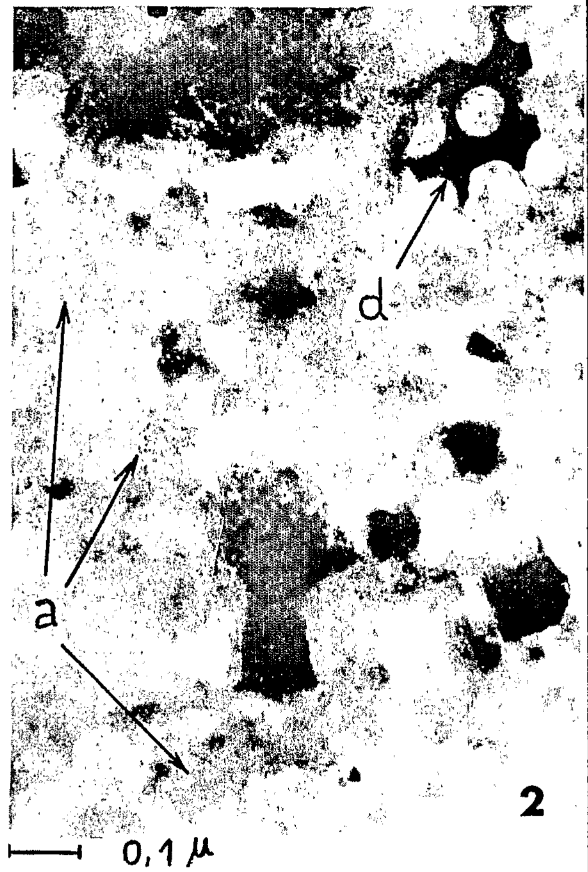
The clay fraction ($< 2\ \mu$) is characterized by a SiO_2/Al_2O_3 molecular ratio between 1–1.3. Thermal analysis and X-ray diffraction reveal predominance of allophane with a small admixture of gibbsite and well-crystallized kaolinite. The composition of the amorphous fraction, analysed by the method of Segalen (1968), is as follows: 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 $< 2\ \mu$ fraction, and this occurs down to 50 cm in depth (Plate I).

Electron micrographs show fuzzy flakes which can be considered to be allophanes (Plate 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 (1962a); Alonso et al. (1963); Chukhrov et al. (1963, 1964); Guiseppetti et al. (1963); Robertson (1963); Kirkman, Mitchell and Mackenzie (1966); Colmet-Daage et al. (1967); Sieffermann, Yehl and Millot (1968). But one must

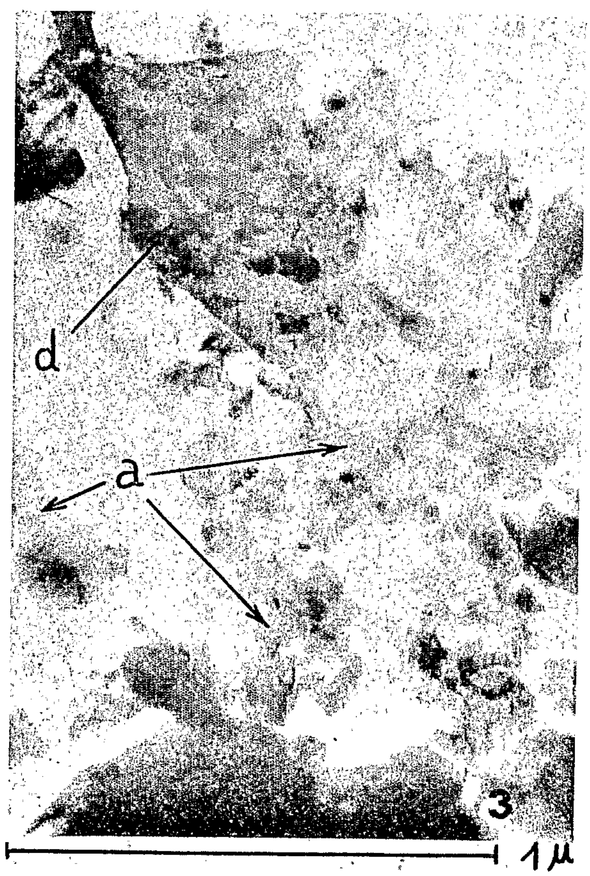


1. Test of diatom (d) coated with allophane (a)— × 14,000

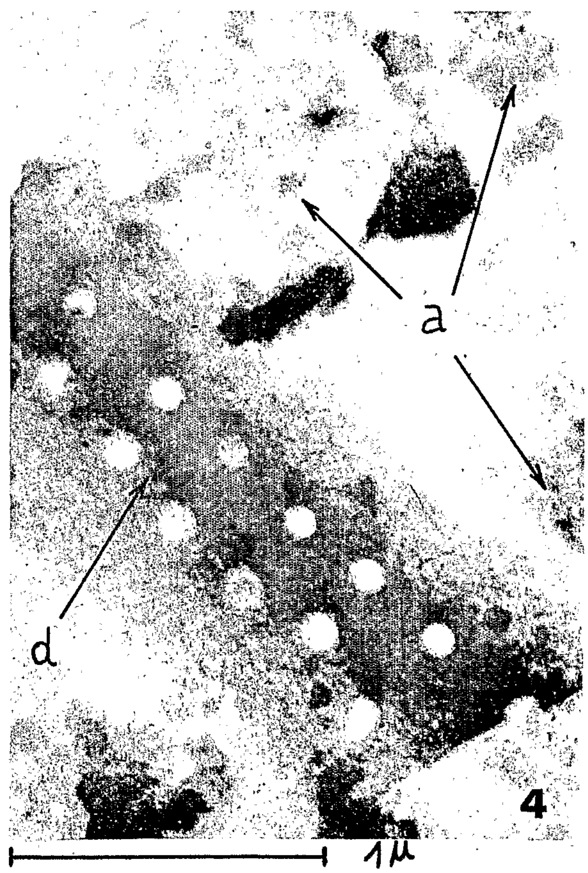


2. Fragment of diatom $< 0.2\mu$ (d) in an allophanic mass (a) — × 100,000

PLATE I. Samples from Zone I

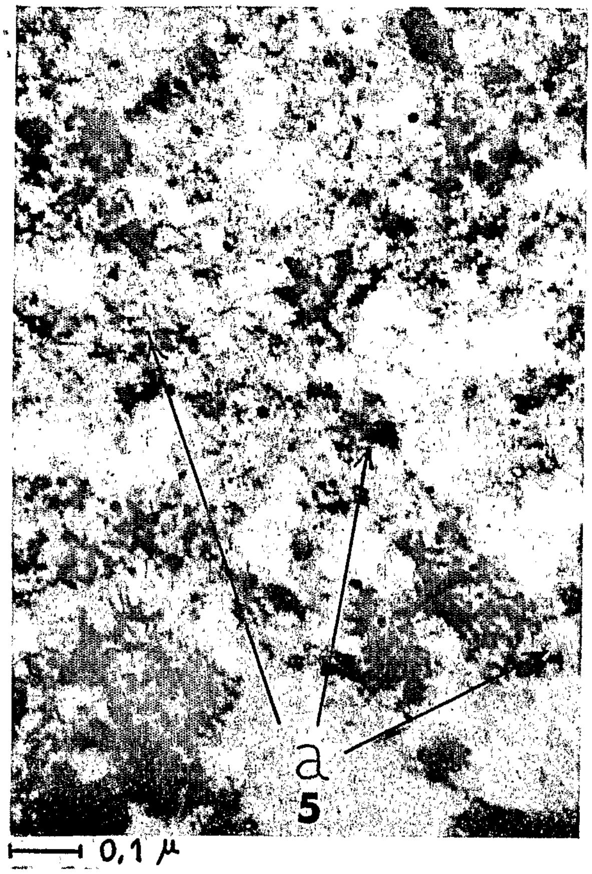


3. Unperforated fragment of diatom (d) coated with allophane (a)— × 70,000

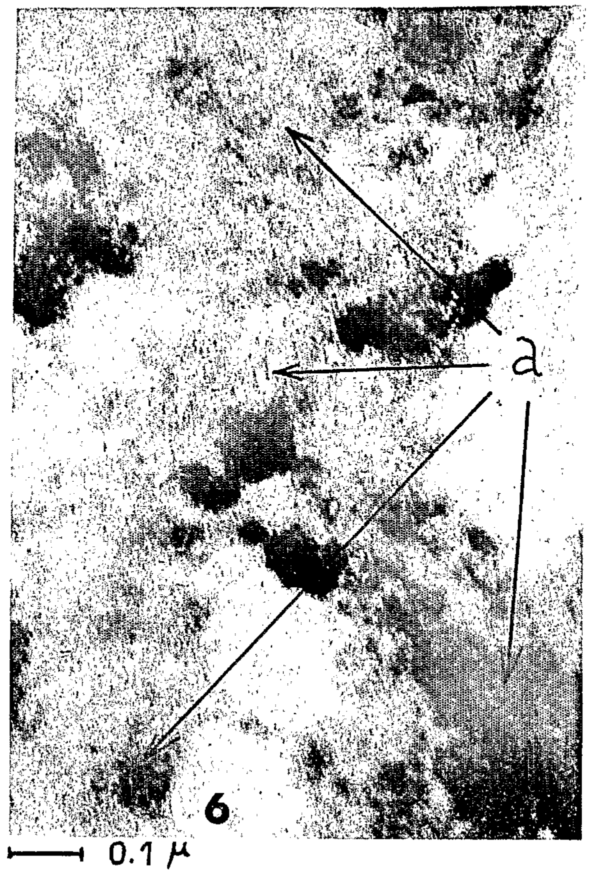


4. Fragment of diatom in process of dissolution (d) coated with allophane (a) — × 45,000

PLATE I. Samples from Zone I

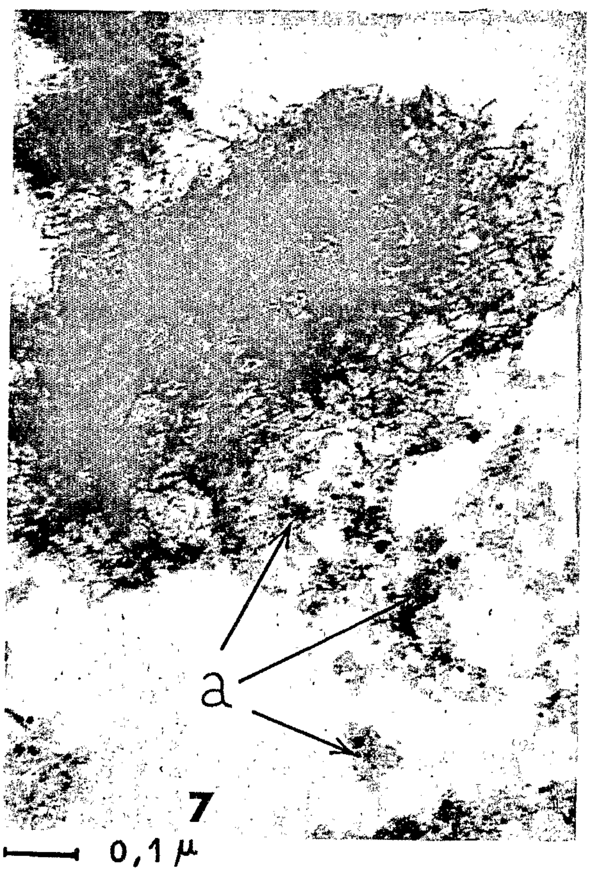


5. Felt-like facies of allophane (a)— × 100,000

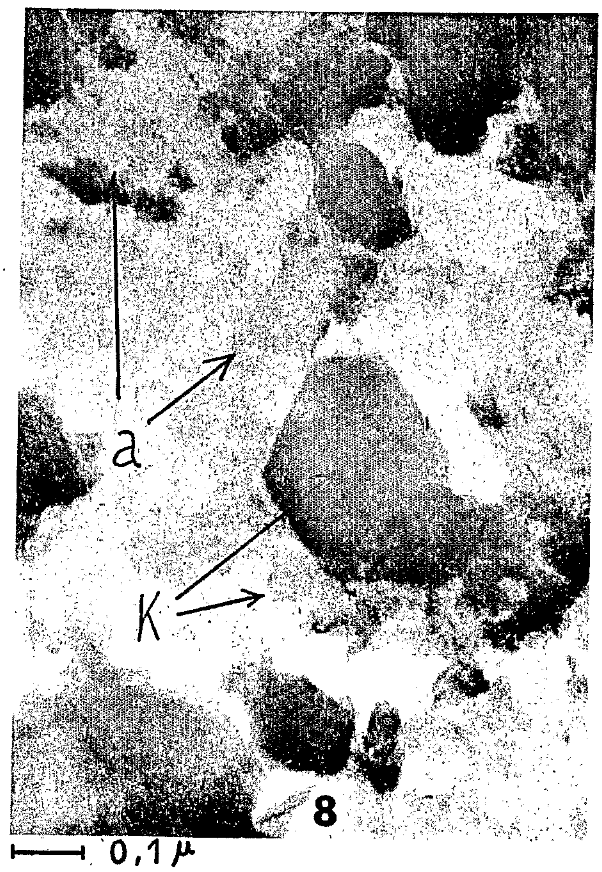


6. Fuzzy flakes of allophane (a)— × 100,000

PLATE II. Facies of allophanes of Zone I



7. Allophane (a) and unidentified mass in process of organization— × 100,000



8. Allophane (a) and kaolinite (k)— × 100,000

PLATE II. Facies of allophanes of Zone I note in addition the presence of well-crystallized kaolinite (Plate II, 8 and Plate III, 9) and gibbsite. Neither tubular- nor globular-shaped halloysite, nor fibrous allophane were observed.

ZONE II. ANDOSOLS DEVELOPED FROM RECENT BASALTIC ROCKS ON THE EASTERN AND SOUTHEASTERN PART OF THE CAMEROON MOUNTAIN

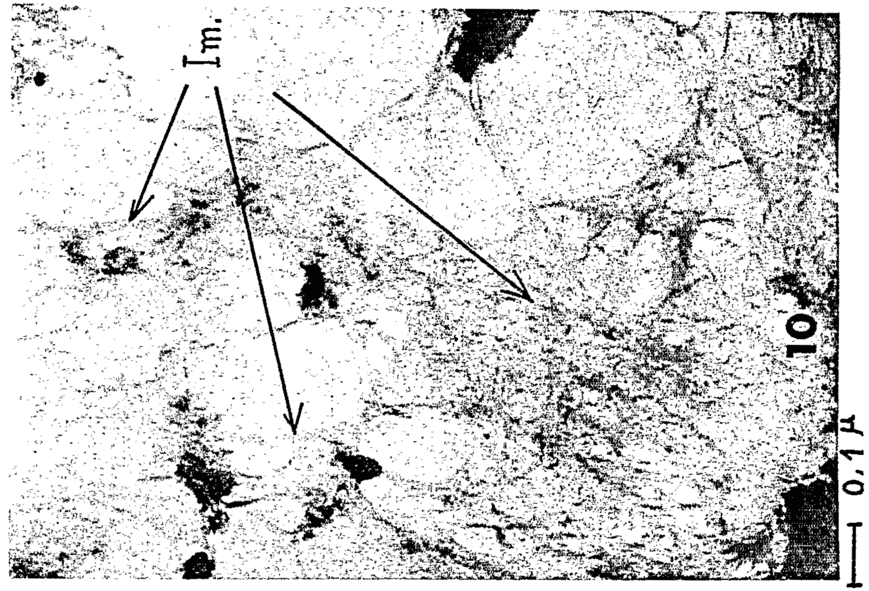
The climate here is equatorial, with a mean annual precipitation between 2.5 and 6 m (90–250″). A moderate dry season occurs three months of the year. The mean annual temperature is between 27–29°C. Drainage is good.

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./100 g 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 ranges from 6 at the bottom to 5 at the top.

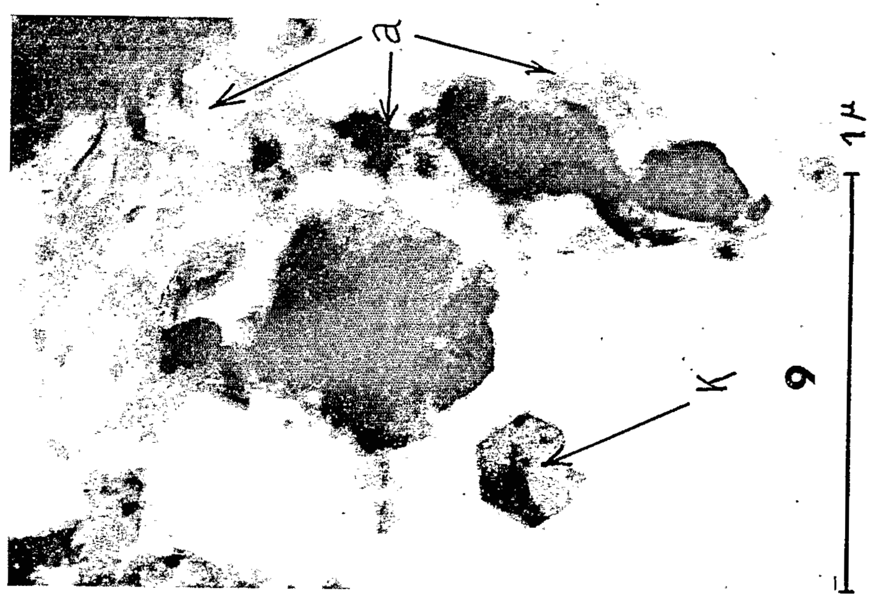
The $< 2\mu$ fraction is characterized by a SiO_2/Al_2O_3 molecular ratio between 0.9–2 at the bottom and between 1.6–2 at the top. The amorphous fraction analysed by the method of Segalen shows, as previously, a SiO_2/Al_2O_3 molecular ratio close to 1, but with a smaller percentage of iron hydroxides 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 (Plate III, 10) [Yoshinaga and Aomine (1962b); 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 (Plate III, 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.



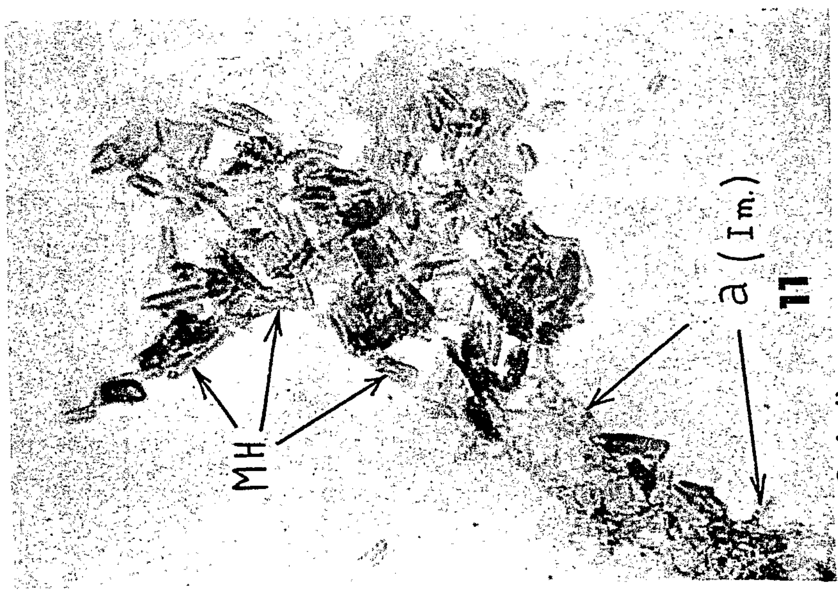
10. Imogolite (Im)— × 80,000—Zone II



9. Allophanic mass (a) and kaolinite (K)— × 60,000—Zone I

PLATE III

12. Globular- and tubular-shaped halloysite (Hall) and amorphous mass (a)— × 210,000—Zone III



11. Metahalloysite (MH) and thread-like fine fibrous particles (a) which may be imogolite— × 80,000—Zone II

PLATE III

ZONE III. SOILS DEVELOPED FROM RECENT BASALTIC ROCKS ON THE CENTRAL ADAMAWA PLATEAU OF CAMEROON

The climate is the tropical mountain climate of Adamawa. Mean annual precipitation is between 1.5 and 1.6 m, with a well-marked dry season lasting five months. The 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./100 g at the bottom, and from 15–24 meq./100 g at the top. Base exchange capacity is between 15–30 meq./100 g at the bottom and between 30–50 meq/100g at the top. Base saturation is between 50–80%, and the pH varies between 7.3–6 from bottom to top.

The clay fraction is characterized by a SiO_2/Al_2O_3 molecular ratio of 2–3 for the youngest soils, reaching 2 for the most advanced ones, and contains 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. Soils from the earlier Quaternary are similar, but gibbsite is even more highly developed at the top of these profiles.

INTERPRETATION

Allophanes

It is difficult to purify allophanes. In particular the presence of diatoms, constituting up to 20% of the clay fraction (Plate I, 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 minerals. (Plate I, 3 and 4).

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

Kaolinite and Gibbsite in Andosols

In Zone I, which is equatorial and permanently humid, allophanes are always present in the form of amorphous fuzzy flakes, never as imogolites (Plate 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 (Plate III, 9) and up to 20% gibbsite, especially at the bottom of the profiles.

Local desaturation permits direct crystallization of kaolinite, particularly using the silica of diatoms.

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

Halloysite and Metahalloysite

Halloysite can form in two habits: 1) as tubes only. In profiles, the exclusive occurrence of tubes often coincides with the presence of amorphous products rich in thread-like, fine, fibrous particles (Plate III, 10 and 11); 2) as globules with defined form and crystallinity. They occur in soils in which allophanes as amorphous flakes predominate (Plate III, 12). Subsequently, these globules give rise to tubes (Plate III, 12).

The genesis of halloysite takes place only in Zones 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 fast enough 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 is formed at the top of the profiles by degradation of metahalloysite (Sieffermann et al., 1968).

Evolution According to Climate and Time

Two weathering sequences can be discerned:

a) Parent rock → allophane + kaolinite *sensu stricto* + gibbsite (Zone I)

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 gibbsite formation under different conditions were reported in part 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.

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 permanently 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 desiccation.

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