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Physical, chemical, micromorphological and field characteristics of three soils developed in volcanic mudflows of the Cameroon mountain and their classification

by

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PHYSICAL, CHEMICAL, MICROMORPHOLOGICAL AND FIELD CHARACTERISTICS OF THREE SOILS DEVELOPED IN VOLCANIC MUDFLOWS OF THE CAMEROON MOUNTAIN AND THEIR CLASSIFICATION

Major thesis presented in partial fulfilment of the requirements for the degree of Master of Science .

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Emmanuel T. Awah
Wageningen, June 1979

SUMMARY

This study deals with the physical, chemical, micromorphological and field characteristics of three profiles in a soil catena from the volcanic region of the Cameroon mountain and their classification. Each of the profiles belongs to one of the three soil series (Molyko, Ekona and Mussaka series) found in the area.

The general aspects of the area are described in Chapter 1., the methods of investigation in Chapter 2. and the data obtained in Chapters 3. and 4. From these data it appears that the Molyko series (Profile EB 63), at a height of about 700 m above M.S.L., is the youngest, while the Mussaka series (Profile EB 65), at a height of about 425 m above M.S.L., is the oldest soil in the catena. The Ekona series (Profile EB 66), at a height of about 550 m above M.S.L., is of intermediate age. Detailed micromorphological studies also confirm this sequence and the presence of argillic horizons in both the Mussaka and Ekona series.

The classification of the soils is discussed in Chapter 5. The Molyko soils are dominated by allophane and are classified as Udic Eutrandepts, thixotropic, isohyperthermic (USDA Soil Taxonomy), Mollic Andosols (Legend of the FAO Soil Map of the World) and Typic Haplotropands (Guy D. Smith's proposal for the reclassification of Andepts and some Andic subgroups). The Ekona soils are classified as Typic Tropohumults, very fine clayey, halloysitic, isohyperthermic (Soil Taxonomy), and Humic Acrisols (Legend of the FAO Soil Map of the World). The Mussaka soils are classified as Orthoxic Tropohumults, very fine clayey, halloysitic, isohyperthermic (Soil Taxonomy), and Humic Nitosols (Legend of the FAO Soil Map of the World).

The USDA Soil Taxonomy is a satisfactory system of classification for these soils. Also, placing these soils in the Legend of the FAO Soil Map of the World gives no major difficulty. The system proposed by Guy D. Smith (1978) for the reclassification of Andepts is applicable to the Molyko soil (the only andosol in the catena), but it was not possible to use the "variable charge

method" as defined in this system. Probably at the pH of these soils (5.2-6.0) the exchangeable bases were partly held at pH dependent negative charges. The "variable charge method" therefore is probably workable only when the soil pH is low ($\pm$ 5.0 in water).

Another problem with this system concerns the great group Haplotropands. There is no provision for Haplotropands with an Udic moisture regime like the Molyko soils have. Moreover the high base status of these soils is not expressed at the subgroup level.

INTRODUCTION

Not much is known about soils developed in volcanic mudflows in Cameroon. Work done by Segalen (1967), Hasselo (1961), Laplante (1953, 1954),Sieffermann,(1973) and others has been on the volcanic soils of Cameroon in general, but not much has been said about mudflow soils characteristic of the Buea area[1)] of the Cameroon mountain.

This study concerns three soil profiles developed in volcanic mudflows of the Buea area. Each of the profiles belongs to a soil series in the area as follows:

Profile EB 63	Molyko Series
Profile EB 66	Ekona Series
Profile EB 65	Mussaka Series

These soil series together form a soil catena in which profile EB 63 is at 700 m above M.S.L., profile EB 66 at 550 m above M.L.S. and profile EB 65 at 425 m above M.S.L. The main interest of the study is directed towards the description and interpretation of the physical, chemical, micromorphological and field characteristics of the soils with the aim of classifying them according to the following systems:

USDA Soil Taxonomy, Legend of the FAO Soil Map of the World and "A preliminary proposal for reclassification of Andepts and some andic subgroups" (Guy D. Smith, 1978). During the description, especially of the micromorphology, the addition of some aspects of the genesis of the soils has been unavoidable. The reader should note, however, that the study does not aim at describing the genesis of these soils.

This work originated as a result of soil classification problems encoutered by Soil Scientists of the FAO/UNDP Soil Project, which is based at the Institute of Agricultural and Forestry Research, Ekona, Cameroon. They were not sure whether the Ekona and

1) The Buea area as used in this context refers to the area shown in Figure 1.1.

Mussaka series were Ultisols, Alfisols or Mollisols. They also wanted to know whether the Molyko soil, which is an Andept, met all the requirements for Andepts as specified in the various classification systems.

The field work and most of the standard laboratory analyses were done at the laboratory of that Institute. Determinations to check the dominance of amorphous material in the exchange complex and the micromorphological investigations were done by the author at the Agricultural University of Wageningen.

This study has been done with the knowledge that the classification of soils can be of great practical value because it enables soil scientists and other interested parties to transfer knowledge (e.g. knowledge about management properties) about similar soils from one area to another. It is also an important medium of communication about soils.

1. GENERAL ASPECTS OF THE AREA

1.1. Location

The three soil profiles studied are situated on the eastern slope of the Cameroon mountain, in the Buea area of the South-West Province of Cameroon. The area lies around latitude 4°10'N and longitude 9°20'E (see Fig. 1.1.) and can easily be reached by road from Douala and Victoria. The exact locations of the profile pits are shown in Fig. 1.1.

1.2. Relief and topography

The dominant feature in the landscape of the Buea area is the Cameroon mountain (see plate 1.) which rises to about 4000 metres above M.S.L. The Buea area shown in Fig. 1.1. lies on the lower eastern slopes of this mountain. A longitudinal section of the landscape is shown in Fig. 1.2. It can be seen that the slope from the Molyko profile to the Mussaka profile is rather regular, but broken up by excarpments (slope breaks). The slope from the Molyko profile to the Ekona profile is steep whereas at the Mussaka profile the area is flat to gently sloping. The Molyko, Ekona and

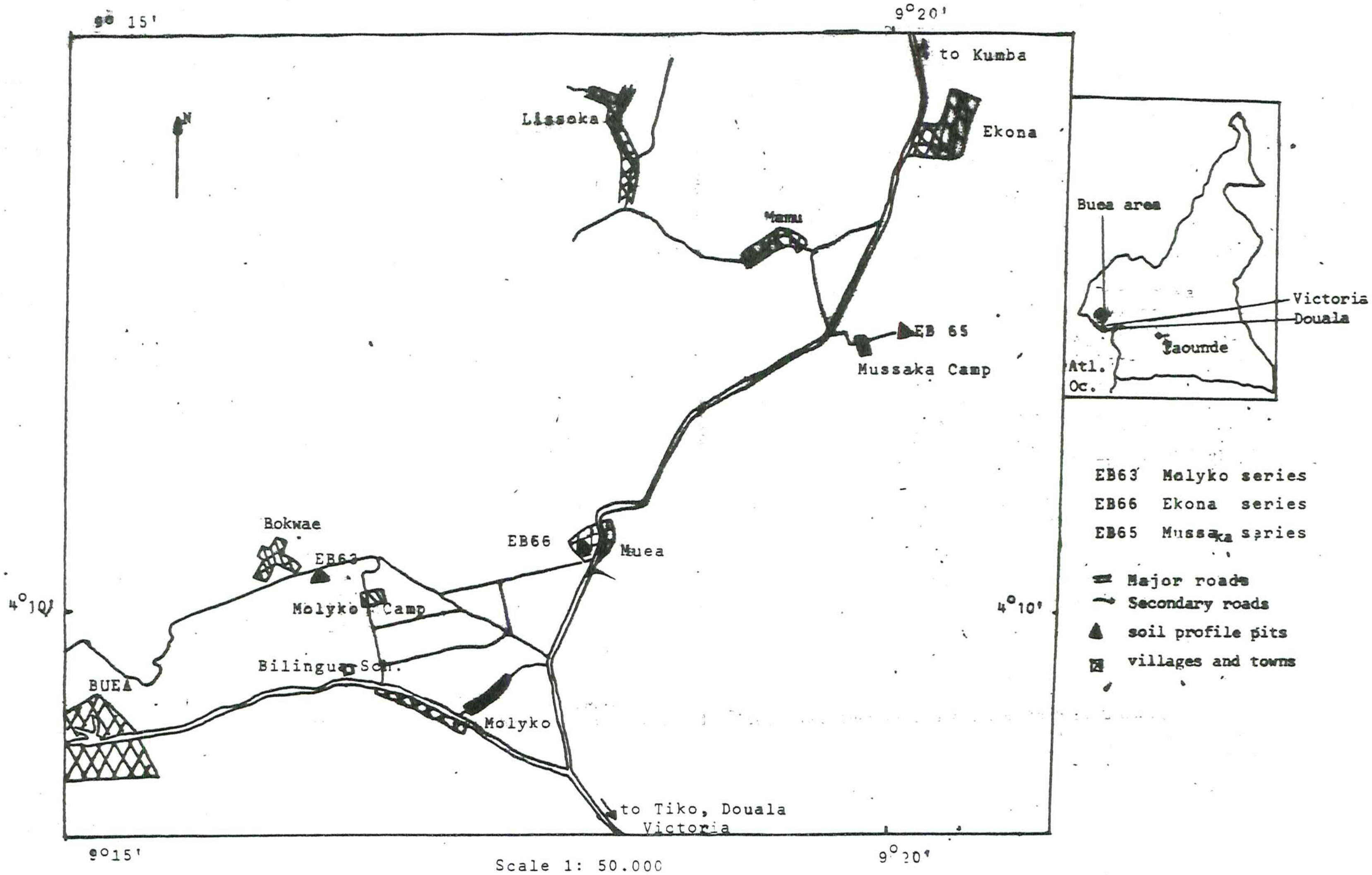


FIGURE 1.1. Location map of profiles EB 63, EB 65 and EB 66

Plate 1. The landscape of the Buea area with the Cameroon mountains in the background.

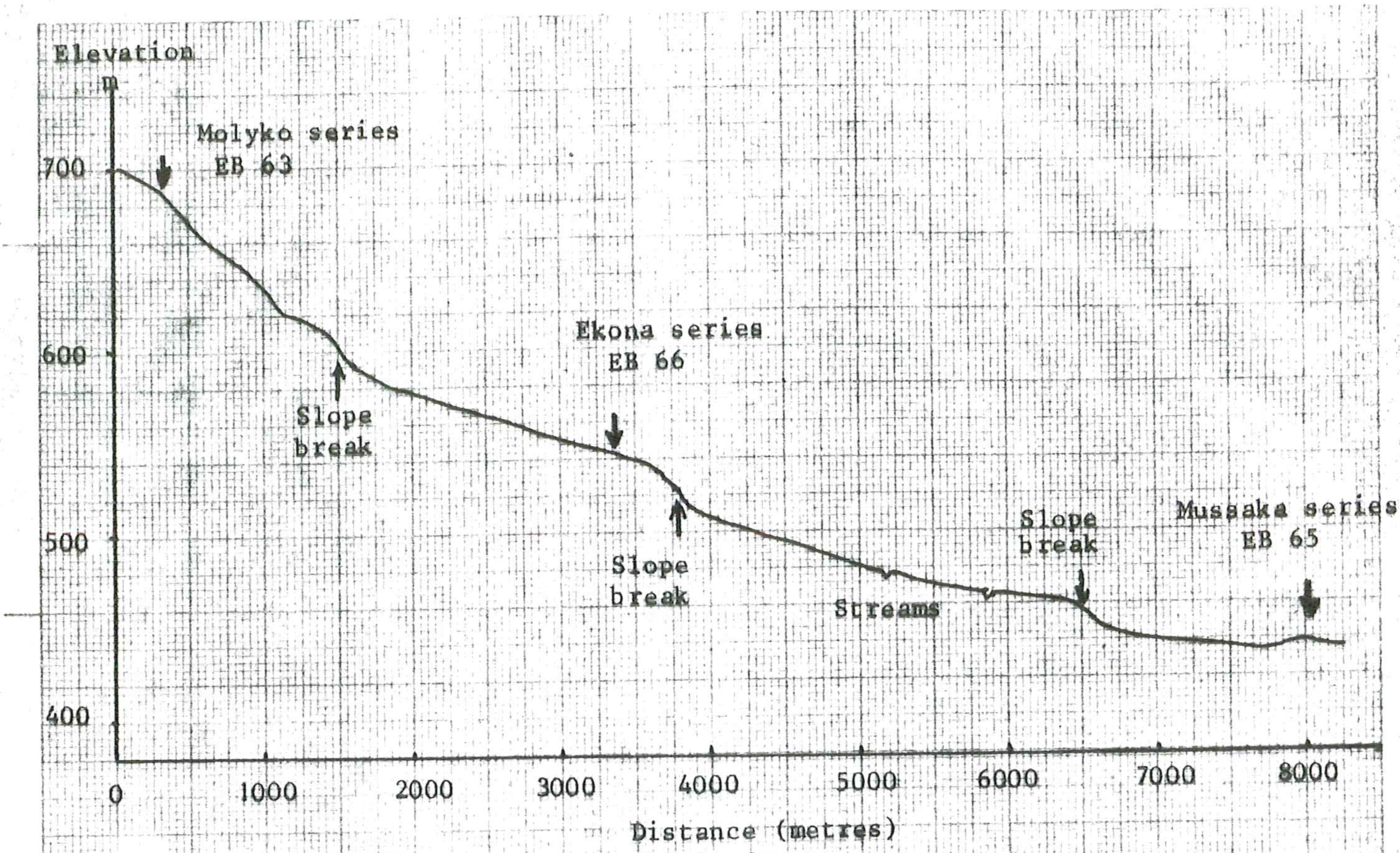


Fig. 1.2 Longitudinal section of the landscape.

Mussaka profiles lie at about 700, 550 and 425 meters above M.S.L. respectively. Generally when ascending from the Mussaka profile in the direction of the Ekona profile the land rises gently up to 500 m above M.S.L., then rather steeply to 600 m and then steeply towards the Molyko profile.

1.3. Geology and parent material

The Cameroon mountain is an active volcano of the Hawaiian type[1]. Geze (1943) recognized three phases of volcanic activity of the mountain.

The first phase, which occurred in the Cretaceous period, consisted of basalt ("la serie noire inférieure"). This basalt covered most of the eastern slopes of the Cameroon mountain, but it has been weathered and its presence in the Buea area is hardly noticed except for a few outcrops here and there. Elsewhere, however, soils developed on these old basalts are on the surface.

The second phase occurred towards the end of the Neogene period ("la serie blanche moyenne") and consisted of acid rocks (trachytes, phonolytes, etc.). This phase was of no consequence to the Buea area as most of the material was deposited elsewhere.

The third phase, ("la serie noire supérieure") which consisted of basaltic rocks, occurred in the Quaternary era. In the Buea area these basalts covered the deposits of the first volcanic phase. The last eruption of the volcano was in 1959 and the lava flowed right up to Ekona.

The origin of the parent material of the three soil profiles under study is connected with the third phase of volcanic activity. It is not a lava flow, however. It appears that during the third volcanic phase there was some ejection of pyroclastic material. This material was washed down the slope in the form of mudflows by heavy rains.

1) A Hawaiian type of volcano is a volcano in which the eruptions are not explosive. The lava which is poured out is usually basic. The effusion of lava is the dominant characteristic and takes place quietly. Mauna Loa, in Hawaii forms the classic example (Robinson, 1973).

A mudflow is formed when heavy rains transport loose material formed after a volcanic eruption from bare slopes into valleys and down the slope. The loose material consists not only of ash deposits but also of any material that the mudflow picks up during its downward flow. Thus a mudflow may carry boulders which ultimately block it. The front of a mudflow (i.e. the furthest point reached by the mudflow) consists of a pile of rocks. In the Buea area such a pile of rocks is found around N'Sonne Molive (which lies to the south-west of Muea). The parent material of the three soil profiles consists of one or more layers of mudflow in which basaltic rocks are present. It is only in the Buea area that mudflows are important. It appears that the oldest mudflow travelled furthest, because the soils become younger and less deep as one goes higher up the slope of the mountain.

1.4. Climate

As the area is situated near the equator its climate is equatorial. Rainfall and potential evapotranspiration data are given in Fig. 1.3. and Table 1.1. These show that there are two distinct seasons: the rainy and the dry season. The rainy season starts in March and ends in October, with July, August and September being the wettest months. These three months account for more than 50% of the total rainfall of 2275 mm per year. The existence of the dry season from November to February is very important for soil genesis and agriculture. In this season the rather shallow and well-drained soils (Molyko series) become dry while the deep soils with high clay content do not dry out completely except in the top 50 cm especially in cases where there is no vegetation cover. There is a large surplus of moisture in the rainy season and a deficit in the dry season (see Fig. 1.3.). Many crops growing in the area suffer from this moisture deficit. The moisture regime of all the soils is udic, however. This is because the moisture control section of the soil is not dry for more than 90 days.

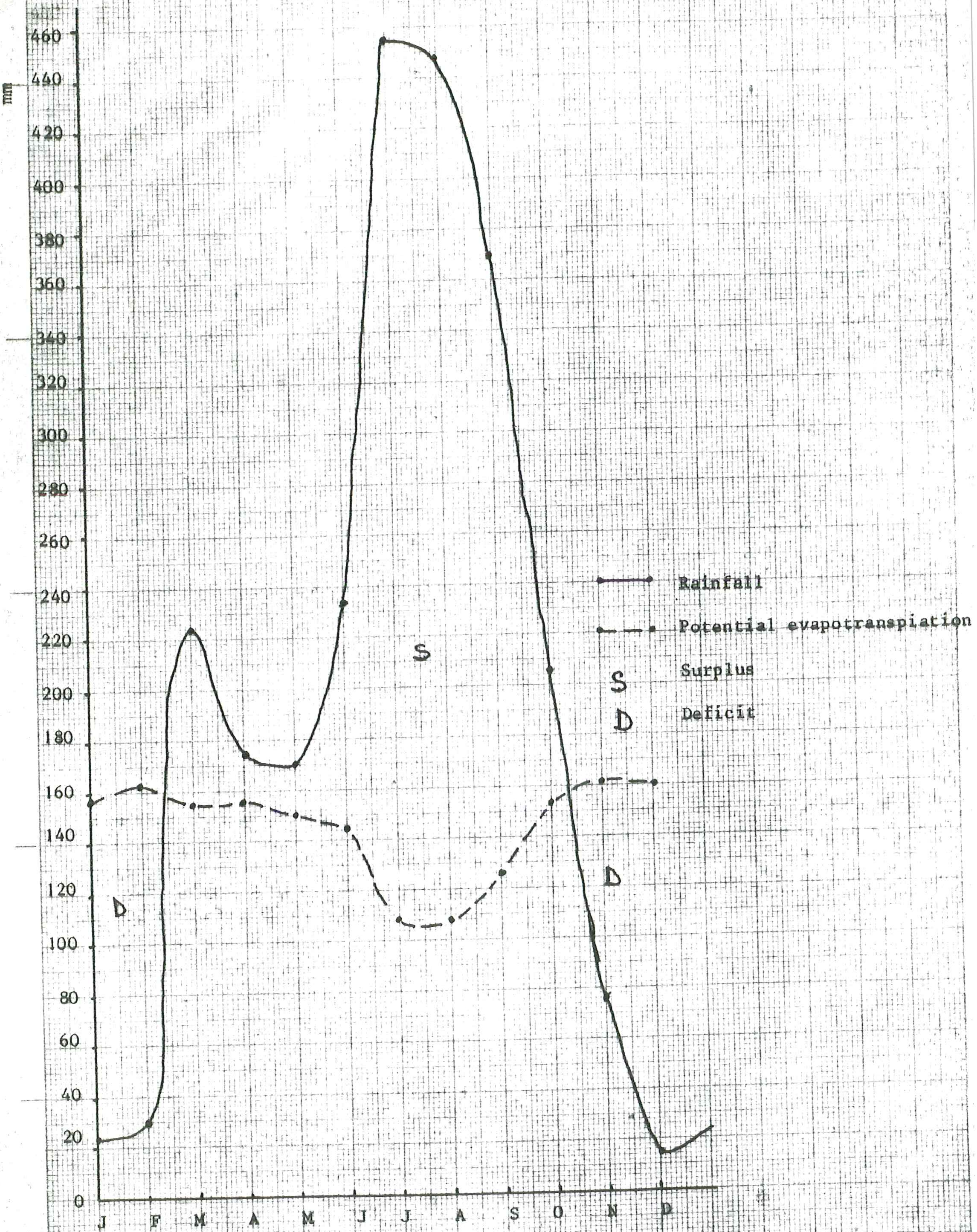


Fig. 1.3 Variation of rainfall and potential evapotranspiration during the year.

	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
Rainfall (mm)	23	27	224	173	169	232	458	448	347	204	74	13	2275
Sunshine hours	145	150	138	153	152	109	47	33	57	113	148	146	1385
Potential evapotranspiration (mm)[2]	156	161	155	156	150	144	108	108	126	153	162	160	1739
Air temperature													
- max.	28.7	29.4	29.3	28.9	28.8	26.9	25.0	24.8	26.2	27.7	27.9	28.4	27.7
- min.	19.7	19.7	19.8	20.8	20.7	19.8	19.8	19.4	19.6	19.5	19.2	19.2	20.3
- mean	24.2	24.9	24.7	24.6	24.7	24.3	22.4	21.6	22.9	23.7	23.6	23.8	24.0

TABLE 1.1. Climatic data of Ekona, Mussaka and Molyko[1].

1. Summaries of the meteorological stations at Ekona IRAF, Ekona CDC, Mussaka, Lysoka and Molyko (1954-1974).

2. Calculated according to TURC.

Fig. 1.4 Monthly variation of maximum and minimum temperatures.

The mean average monthly temperature in the area is 24°C. The difference in air temperature between the rainy and the dry season is about 3°C (see Fig. 1.4.). Assuming that the soil temperatures are also in the same order the soil temperature regime is isohyperthermic. Despite the rather high temperatures the total amount of sunshine (average: 1384 hours per year) is rather low (see Table 1.1.). This is a problem for certain crops (oil palm).

1.5. Land use and management

Subsistence farming for cocoyams, maize, plantains, sugar-cane and vegetables using rather primitive management practices is the main land use type in the area. Bananas and oil palms are grown in plantations owned and operated by the Cameroon Development Corporation. In these plantations a high level of management including mechanization where feasible, fertilizers and chemical pest and disease control is maintained. The banana fertilizer policy is open to question, however. Only nitrogenous fertilizer in the form of ammonium sulphate is applied despite the fact that the parent material is low in potassium (Hasselo, 1961), and bananas, like oil palms need large amounts of potash. The vulnerability of bananas to the moisture shortage during the dry season is probably lower in cases where the bananas are amply supplied with potash than where they are not. The relatively high magnesium content of the soils might suppress the uptake of the small amounts of potassium available (K-Mg antagonism). Another cash crop is coffee, but this is grown by small holders using some fertilizers and pesticides.

2. METHODS OF INVESTIGATION

2.1. Field work

The work done in the field included the description of the soils in their natural environment and the collecting of samples for the various physical, chemical and micromorphological tests and observations. The description of the soils was done according to the Soil Survey Manual of the Soil Survey Staff (1951) and the FAO guidelines (1967).

2.2. Physical determinations

1. Particle size analysis

This was done according to the standard USDA sieve and pipette method using sodium hexametaphosphate as a dispersing agent. Air dry samples were used in the case of Mussaka and Ekona series and field moist samples in the case of the Molyko series. All results were based on oven-dry weight.

2. Bulk density

The bulk density of the soils was determined in core samples with a volume of 100 cm^3 at 1/3 bar moisture content. This was checked with the paraffin-coated method.

3. Moisture content

The moisture contents at 1/3 bar and 15 bar were determined by pressure extraction and pressure membrane extraction methods respectively. They were expressed on oven-dry (105^oC) weight basis.

2.3. Chemical determinations

1. Cation exchange capacity and exchangeable bases.

The cation exchange capacity (CEC) was determined by the ammonium acetate (NH_4OAc) at pH 7.0 leaching method. The exchangeable bases were determined in the leacheate by flame photometry (Ca^{++}, K^+, Na^+) and colorimetry (Mg^{++}).

2. Organic carbon content

This was determined by the Walkley-Black method involving wet combustion and colorimetric determination by an automatic analyser.

3. Total nitrogen content

The nitrogen content was determined by the Kjeldahl method.

4. Soil reaction (pH)

The pH of the soil was determined potentiometrically using a glass electrode in a mixture of one part soil to two and a half parts water for pH water and in a solution of potassium chloride 1N for pH KCl.

2.4. Other determinations

The determinations mentioned above are standard determinations carried out at the laboratory of the Institute of Agricultural and Forestry Research, Ekona, Cameroon. For the purpose of classifying these soils it was necessary to know whether the exchange complex of any of them is dominated by amorphous material. The following analyses were required (FAO, 1974, Soil Survey Staff, 1975, Smith, 1978) and were carried out at the laboratory of the Department of Soils and Geology of the Agricultural University of Wageningen.

1. Thermal analysis

This involved the differential thermal analysis (DTA) and thermo-gravimetric analysis (TGA) of the fine earth fraction of the soils.

2. pH in NaF

This pH was determined in a 1M. solution of sodium fluoride. A mixture of 1 g soil in 50 ml 1M. NaF was used. The pH was determined potentiometrically 2 minutes after mixing.

3. Percent variable charge

The amount of variable charge as defined in Smith (1978) is the difference between the cation exchange capacity obtained with barium chloride at pH 8.2 and the sum of exchangeable bases and aluminum. The CEC ($BaCl_2$ at pH 8.2) was determined by the sum of cations method (USDA, 1972). This method involves the determination of the extractable acidity by $BaCl_2$ - triethanolamine. The sum of cations (= CEC $BaCl_2$ at pH 8.2) is the sum of the extractable acidity, the exchangeable bases and extractable aluminum. The extractable aluminum was not determined, however. The reason for this will be clear later on.

4. Phosphate retention value

The phosphate retention value was determined according to the method proposed by Smith (1978), but with some minor alterations. The reagent used was that described by Jackson (1958), because the reagent for the "Smith method" was not available. The method involves the mixing of known quantities of phosphate representing certain P-retention values with a fixed amount of soil and measuring the phosphate which remains in solution after shaking the mixture for about 20 hours. The higher the P-retention ability of the soil (hence the higher the P-retention value), the lower the amount left in solution.

2.5. Micromorphology

Samples for micromorphology were impregnated in the laboratory using the method of Miedema et al. (1973). After six weeks they were cut and ground to a thickness of 25 microns. These were then studied under a polarizing microscope. The description was made according to Brewer (1964).

2.6. Soil classification

The soils were classified according to the three systems mentioned in the introduction.

3. SOIL CHARACTERISTICS

3.1. Profile descriptions

One soil profile of each of the three soil series was described in the field.

1. Profile EB 65

Soil Series	: Mussaka
Location	: around the field assistant's (Mussaka banana estate) house.
Elevation	: 430 m (see Fig. 1.2.).
Parent material	: mudflow
Drainage	: moderate
Vegetation	: mango orchard with grass under growth.
Topography	: gently undulating
Described by	: M. Ntamack and H.E. Verwey.
Date	: 31-7-1978

Soil was moist when described.

0-4 cm A11	: Very dark brown (10 YR 2.5/2) when moist, very dark grayish brown (10 YR 3/2) when dry; clay; medium moderate subangular to angular blocky structure; friable, slightly sticky and slightly plastic consistence; common fine and medium roots; many fine and few medium pores; clear smooth boundary.
4-20 cm A12	: Very dark brown (10 YR 2.5/2) when moist, dark brown (10 YR 3/3) when dry; clay; medium moderate angular blocky structure; friable, slightly sticky and slightly plastic consistence; common fine and medium roots; many fine and few medium pores; gradual smooth boundary.

20-40 cm
B1t

: Very dark grayish brown (10 YR 3/2) when moist, dark brown (10 YR 3/3) when dry; clay; medium moderate angular blocky structure; friable, sticky and plastic consistence; few fine faint mottles; few fine clay skins; few fine roots; many fine and few medium pores; gradual smooth boundary.

40-57 cm
B21t

: Very dark grayish brown to dark brown (10 YR 3/2.5) when moist, dark brown to brown (10 YR 4/3) when dry; clay; medium moderate angular blocky structure, with tendency to form prisms; friable, sticky and plastic consistence; common fine faint mottles; common fine clay skins; few fine roots; many fine and very fine pores; diffuse smooth boundary.

57-110 cm
B22t

: Dark brown (10 YR 3/3) when moist, dark brown to brown (10 YR 4/3) when dry; clay; medium weak compound prismatic structure, which breaks into medium moderate angular blocky; friable, sticky and plastic consistence; common fine faint mottles; many fine clay skins; very few fine roots; many fine and very fine pores; stones with diameters up to 7 cm take up 30% of soil volume; diffuse smooth boundary.

110-150 cm
B23t

: Dark brown to dark yellowish brown (10 YR 3/3.5) when moist, dark yellowish brown (10 YR 3/4) when dry; clay; medium moderate angular blocky structure; friable, sticky and plastic consistence; few fine faint mottles; few fine clay skins; very few fine roots; many fine and very fine pores; stones with diameters up to 10 cm take up 40-50% of soil volume.

2. Profile EB 66

Soil Series	: Ekona
Location	: Catholic mission, Muea.
Elevation	: 550 m (see Fig. 1.2.).
Parent material	: volcanic mudflow
Drainage	: moderate - well.
Vegetation	: grass
Topography	: sloping
Described by	: M. Ntamack and T. Nyobe
Date	: 27-12-78

Soil was dry in the topsoil and slightly humid in the subsoil when described.

0-11 cm A11 : Very dark grayish brown (10 YR 3/2) when moist, dark brown (10 YR 3/3) when dry; clay; medium moderate granular and subangular blocky structure; slightly hard, friable, slightly sticky and slightly plastic consistence; common fine and medium roots; many fine pores; rounded basalt stones with diameters up to 4 cm take up 5% of soil volume; clear smooth boundary.

11-28 cm A12 : Very dark grayish brown (10 YR 3/2) when moist, dark yellowish brown (10 YR 3/4) when dry; clay; medium moderate subangular and angular blocky structure; slightly hard, friable, sticky and slightly plastic consistence; common fine roots; many fine and very fine pores; rounded basalt stones with diameters up to 6 cm take up 5% of soil volume; gradual smooth boundary.

28-48 cm B1t : Dark yellowish brown (10 YR 3/4) when moist, and (10 YR 3/5) when dry; clay; medium moderate angular blocky structure; friable, sticky and plastic consistence; traces of clay skins; few fine roots; common fine pores; same amount of stones as in A12; diffuse smooth boundary.

48-120 cm B2t : Dark yellowish brown (10 YR 3/5) when humid; clay; medium moderate angular blocky structure; with tendency to prismatic; friable, sticky and plastic consistence; few fine clay skins; very few fine roots; many very fine and few fine pores; many stones with diameters over 20 cm below 93 cm.

3. Profile EB 63

Soil Series	: Molyko
Location	: around Bokwae village (behind bilingual school)
Elevation	: 700 m (see Fig. 1.2.).
Parent material	: I & II: volcanic mudflow.
Drainage	: well
Vegetation	: secondary forest
Topography	: rather steep
Described by	: T. Nyobe and H.E. Verwey.
Date	: 17-2-77

Soil was moist when described.

0-12 cm A1 : Very dark gray (10 YR 3/1) when moist, very dark grayish brown (10 YR 3/2) when dry; loam; medium weak granular and subangular blocky structure; friable, slightly sticky and slightly plastic consistence; many fine and medium roots; many fine and medium coarse pores; clear smooth boundary.

12-22 cm A3 : Dark brown (10 YR 3/3) when moist, brown to dark brown (10 YR 4/3) when dry; loam; medium moderate subangular and medium weak angular blocky structure; friable, slightly sticky and slightly plastic consistence; common fine and medium roots; many fine and medium coarse pores; gradual smooth boundary.

22-66 cm B21	:	Dark brown (10 YR 3/3) when moist, and (10 YR 4/4) when dry; clay loam; medium moderate angular blocky structure; friable, slightly sticky and slightly plastic; few fine roots; thixotropic; common fine and medium pores; a thin layer of stones (with diameter 3 cm) at boundary with lower horizon; clear smooth boundary.
66-107 cm II B22	:	Dark brown (10 YR 3/3) when moist, brown (10 YR 5/3) when dry; clay loam; medium moderate angular blocky structure; friable, slightly sticky and slightly plastic consistence; thixotropic; few fine roots; few fine and very fine pores; gradual smooth boundary.
107-150 cm II B23	:	Dark yellowish brown (10 YR 3/4) when moist; dark brown to brown (10 YR 4/3) when dry; clay loam; medium moderate to weak angular blocky structure; friable, sticky and slightly plastic; thixotropic, few fine roots; few fine and very fine pores; rounded stones with diameters up to 20 cm from 145 cm.

Conclusions from profile descriptions

There is not much difference between profiles EB 65 and EB 66. The only notable difference is the relative amount of clay skins: profile EB 65 has much more than profile EB 66. These soils would probably have an argillic horizon.

Profile EB 63 is quite different. It has a less fine texture and is thixotropic. It has no clay skins. This soil is probably an Inceptisol (Andept). The horizon from 22-66 cm has been named B21 because of the angular blocky structure, but according to the organic matter content (see section 3.3.), it could as well be an A-horizon. Thus the nomenclature of this horizon is arbitrary.

3.2. Physical characteristics

3.2.1. Particle size

The results of the particle size analysis are given in Table 3.1. Profiles EB 65 and EB 66 have very high clay contents throughout and the clay content initially increases with depth, then decreases afterwards. This suggests an argillic horizon. The results for profile EB 63 should be interpreted with caution because the dispersion might not have been adequate (young volcanic soils). The subsoil has almost no clay despite the clay loam texture mentioned in the profile description.

3.2.2. Bulk density (see Table 3.1.).

The bulk density values are for a moisture content at 1/3 bar. The values in profiles EB 65 and EB 66 are not as high as would be expected of soils with such high clay contents. This is possibly due to the presence of some allophane (to be seen later on) or a reasonably high organic matter content or both. Profile EB 63 has bulk densities lower than 0.85 g/cm^3 which means that the exchange complex might be dominated by amorphous material.

3.2.3. Moisture content

The moisture contents of these soils tend to increase with depth. They are given in Table 3.1. Profile EB 63 holds more moisture at both 1/3 and 15 bar than the other profiles. This is probably due to a higher amount of amorphous material (as will be seen later on).

3.3. Chemical characteristics

3.3.1. Adsorption complex

1. Cation exchange capacity (CEC)

The CEC is given in Fig. 3.1. and Table 3.2. from which it can be seen that, in general, the cation exchange capacity obtained in NH_4OAc at pH 7 is high in the topsoil and slightly lower in the subsoil for all the profiles. This is most

Profile	Horizon	Depth (cm)	Bulk density g/cm^3	< 2μ (clay) %	2 -50μ (silt) %	50-2000μ (sand) %	1/3 bar moisture %	15 bar moisture %
EB 63	A1	0- 12	0.78	20.8	52.2	26.9	51.7	35.7
	A3	12- 22	0.78	21.5	53.4	25.2	49.7	37.9
	B21	22- 66	0.62	11.5	62.3	26.3	52.6	42.1
	II B22	66-107	0.62	1.6	58.8	39.6	62.7	48.4
	II B23	107-150	0.66	2.4	43.7	54.6	67.4	49.9
EB 66	A11	0- 11	1.01	65.5	32.0	2.6	47.0	34.3
	A12	11- 28	1.05	72.1	25.8	2.1	53.6	40.1
	B1t	28- 48	1.10	74.1	24.4	1.5	52.0	43.4
	B21t	48- 80	1.12	75.2	23.1	1.7	60.0	43.9
	B22t	80-100	1.15	82.1	16.3	1.6	ND	ND
	B23	100-120	ND	60.0	36.9	3.1	ND	ND
EB 65	A11	0- 4	1.10	59.7	31.1	4.2	25.5	8.1
	A12	4- 20	1.10	70.0	22.1	7.9	28.8	11.5
	B1t	20- 40	1.07	79.8	15.6	4.7	29.8	13.1
	B21t	40- 57	1.07	80.7	14.8	4.6	29.3	16.9
	B22t	57-110	1.04	78.5	16.7	4.8	33.5	22.5
	B23t	110-150	ND	79.3	17.3	5.4	34.2	ND

TABLE 3.1. Physical characteristics (Bulk density, % moisture at 1/3 bar and 15 bar, % clay, sand and silt of the profiles.

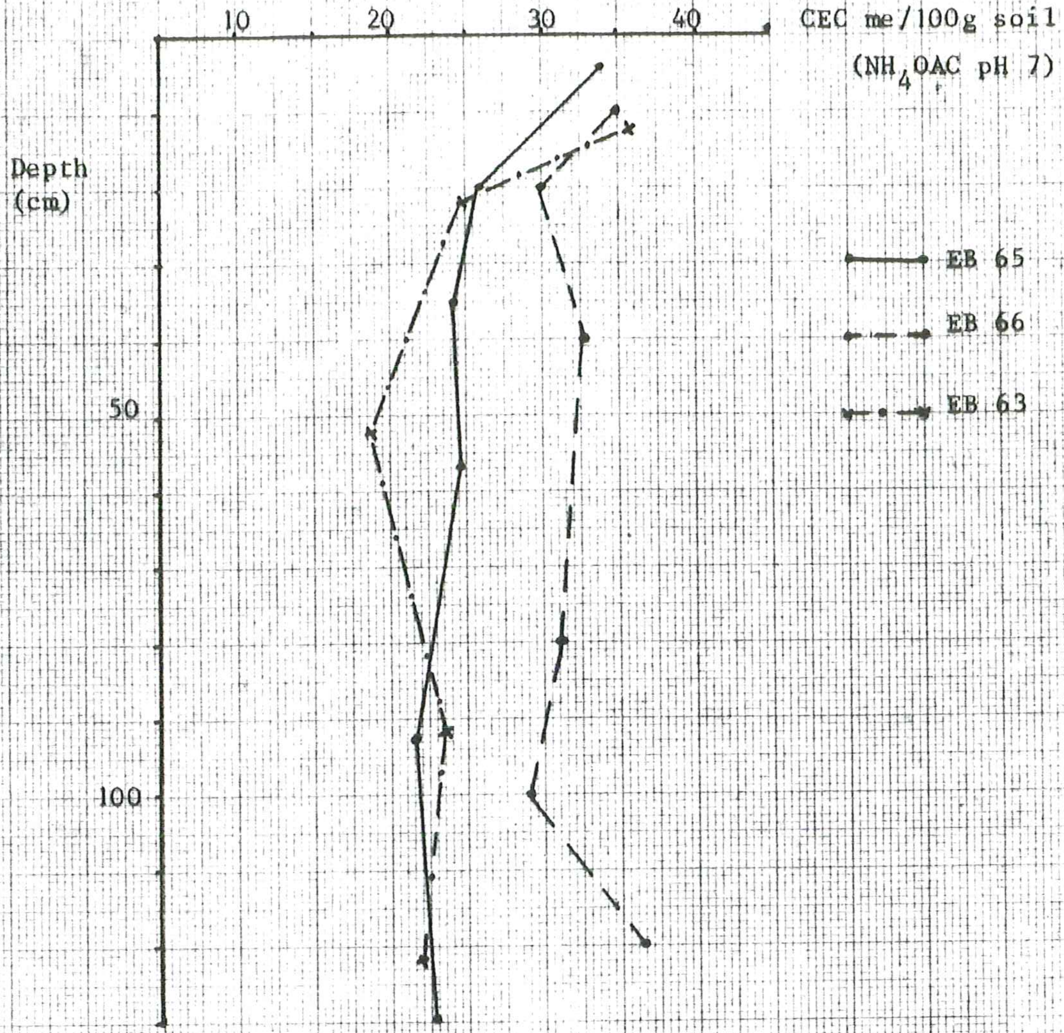


Fig. 3.1 Variations of CEC with depth.

probably due to the higher organic matter content of the topsoil.

If the CEC obtained in NH_4OAc at pH 7 is calculated per 100 g clay and plotted against the organic carbon content also calculated per 100 g clay, graphs as shown in Fig. 3.2. would be obtained. These graphs show that for profile EB 65, the CEC/100 g clay is about 26 milliequivalents while the CEC/g carbon is about 5 milliequivalents. For profile EB 66 these values are 30 milliequivalents and 7 milliequivalents respectively. This indicates that the clay mineralogy in these soils is not dominated by kaolinite (kaolinite has a much lower CEC). The most probable clay minerals in these soils are halloysite, metahalloysite and kaolinite in decreasing order of importance (Sieffermann et al., 1969, and Sieffermann, 1973). Such graphs could not be produced for profile EB 63 because of its very low (measured) clay content.

2. Exchangeable cations and base saturation (see Table 3.2.).

The total exchangeable bases (TEB) and base saturation are high to very high in profile EB 63 and moderate in profiles EB 65 and EB 66. These values decrease with depth. Calcium and magnesium are the most important bases in all the profiles, accounting for more than 75% and 50% of the TEB in the topsoil and subsoil respectively. Potassium and sodium are usually very low. The fact that magnesium is high may lead to a physiological depression of potassium (K-Mg antagonism). This means that crops growing in this soil would need more K-fertilizer than in soils where the Mg-content is not high. This is especially true for bananas and oil palm which generally need an ample supply of potash.

3.3.2. Soil reaction (pH)

The pH obtained in water and in KCl solution are presented in Table 3.2. and Fig. 3.3. The pH of the soils are good. They lie between 5.2. and 6.2. (in water), with a concentration around 6.0 The pH measured in KCl is usually one unit less than the pH obtained in water.

Profile	Horizon	Sample depth (cm)	milliequivalents/100 g soil CEC	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	Base saturation %	pH H_2O	pH KCl
EB 63	A1	0- 12	36.0	22.9	11.5	1.39	0.32	36.11	100	6.0	5.1
	A3	12- 22	25.1	11.3	4.2	0.39	0.38	16.27	64.82	5.9	4.7
	B21	33- 52	19.1	5.7	2.6	0.45	0.32	9.07	47.49	6.0	4.8
	II B22	75- 92	23.8	8.9	4.6	0.70	0.54	14.74	61.93	6.2	4.8
	II B23	106-122	22.4	8.3	3.9	0.69	0.55	13.44	60.00	6.2	4.9
EB 66	A11	0- 10	35.1	9.0	3.1	2.33	0.02	14.45	41.57	5.6	4.8
	A12	15- 20	29.9	5.9	1.8	1.30	0.0	9.00	30.10	5.7	4.8
	B1t	30- 40	32.9	5.7	3.6	0.43	0.06	9.79	29.76	6.0	5.0
	B21t	60- 80	31.6	5.6	3.7	0.52	0.10	9.92	31.39	6.0	5.0
	B22t	80-100	29.6	6.5	1.9	0.93	0.02	9.35	31.59	5.9	4.8
	B23	100-120	37.2	6.6	1.2	0.53	0.10	8.43	22.66	6.2	5.1
EB 65	A11	0- 4	34	15.3	3.2	1.58	0.03	20.11	59.15	6.2	5.2
	A12	4- 20	26.3	7.3	2.3	1.45	0.01	11.06	42.05	6.0	4.8
	B1t	21- 35	24.6	3.0	1.7	1.68	0.02	6.40	26.02	5.4	4.4
	B21t	40- 52	25.2	2.2	1.4	2.15	0.02	5.77	22.90	4.4	4.6
	B22t	72- 93	22.2	1.7	1.2	2.51	0.02	5.43	24.46	4.4	4.5
	B23t	130-142	23.5	1.2	0.9	2.23	0.01	4.37	18.60	5.2	4.2

TABLE 3.2. CEC (NH_4O Ac pH 7), exchangeable bases, TEB, base saturation and pH in the three profiles.

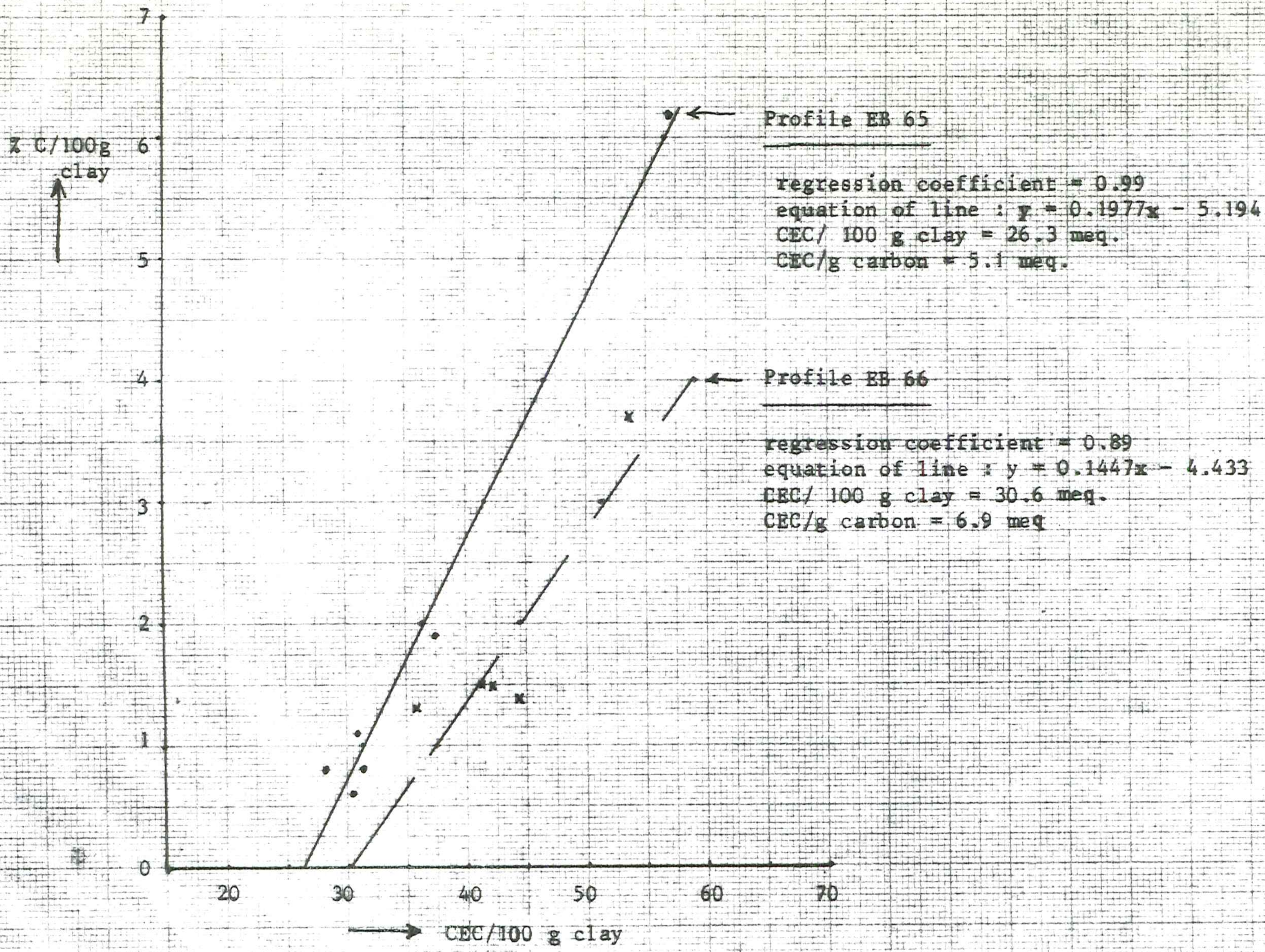


Fig. 3.2 CEC (NaOAc pH 7) per gram organic carbon and per 100 g clay of profiles EB 65 and EB 66.

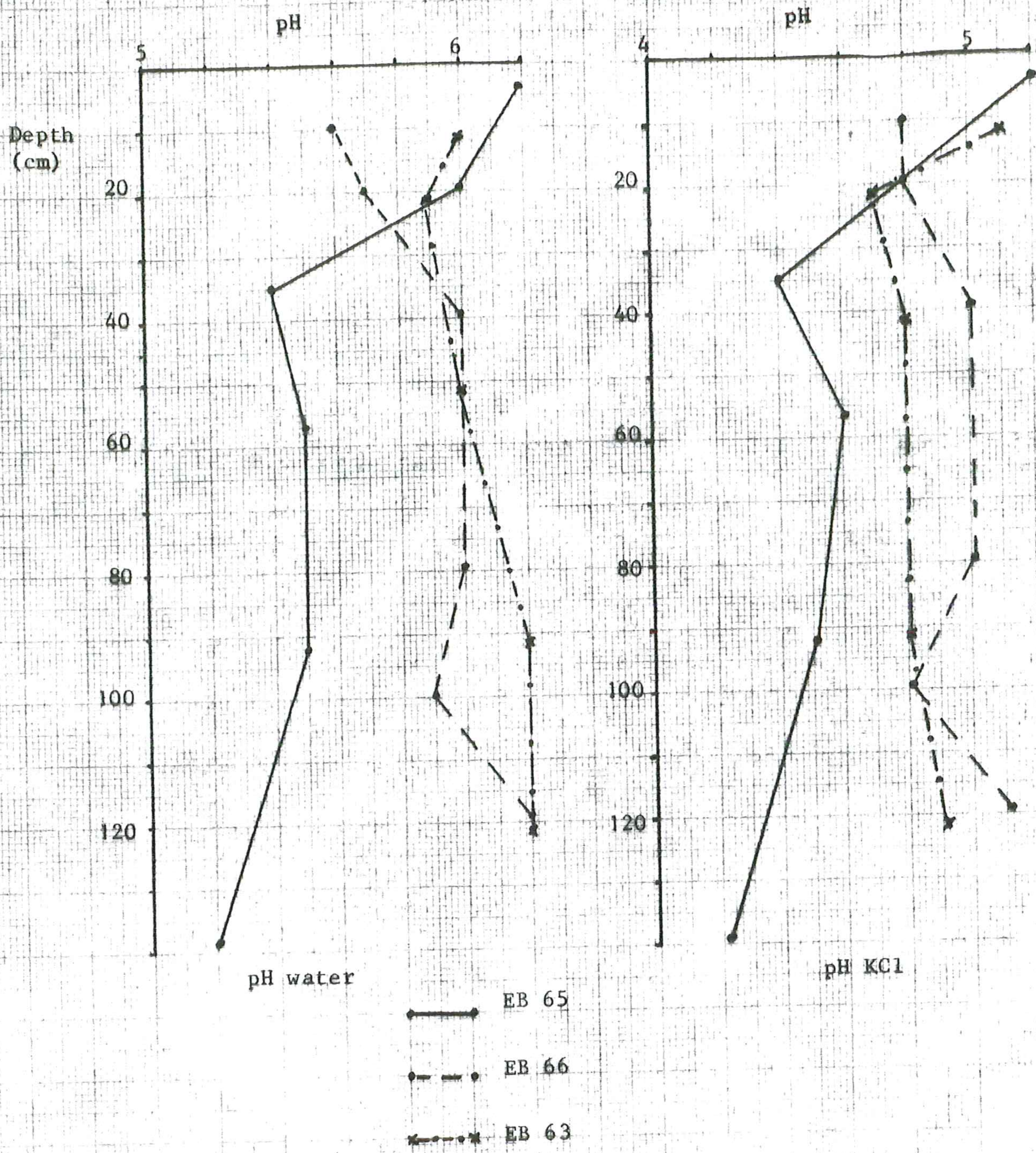


Fig. 3.3 Variation of pH with depth in the three profiles.

Table 3.3 % organic carbon, % organic matter and total nitrogen content of the soils.

Profile	Horizon	Sample Depth (cm)	Organic C. %	Organic matter %	Total N %	C/N
EB 63	A_1	00-12	6.68	11.5	0.67	10
	A_3	12-22	3.72	6.4	0.39	9.5
	B21	33-52	2.51	4.32	0.27	9.3
	II B_{22}	79-92	1.70	2.93	0.19	8.9
	II B_{23}	106-122	1.38	2.38	0.14	9.9
EB 66	A_{11}	00-10	2.43	4.18	0.18	13.5
	A_{12}	15-20	1.05	1.81	0.10	10.5
	B_1t	30-40	1.0	1.72	0.08	12.5
	$B_{21}t$	60-80	1.13	1.92	0.10	11.3
	$B_{22}t$	80-100	1.07	1.84	0.11	9.7
	B_{23}	100-120	1.25	2.15	0.10	12.5
EB 65	A11	00-04	3.70	6.36	0.35	10.6
	A_{12}	04-20	1.33	2.29	0.17	7.8
	B_1t	21-35	0.90	1.55	0.09	10.0
	$B_{21}t$	40-57	0.67	1.15	0.08	8.4
	$B_{22}t$	72-93	0.62	1.07	0.08	7.7
	$B_{23}t$	130-142	0.49	0.84	0.86	8.1

3.3.3. Organic matter content

The organic matter content in the surface horizons varies between 4 and 12% and decreases rather sharply with depth thereafter. Profile EB 63 has much more organic matter content at all depths than the other profiles (probably because it is an Andept, as proved later on). Profile EB 66 does not show a decrease with depth in the B-horizon. This is probably due to some allophane in the subsoil of this profile (see thermal analysis).

The C/N ratios lie between 9 and 14 (see Table 3.3.).

3.4. Adsorption complex dominated by amorphous material

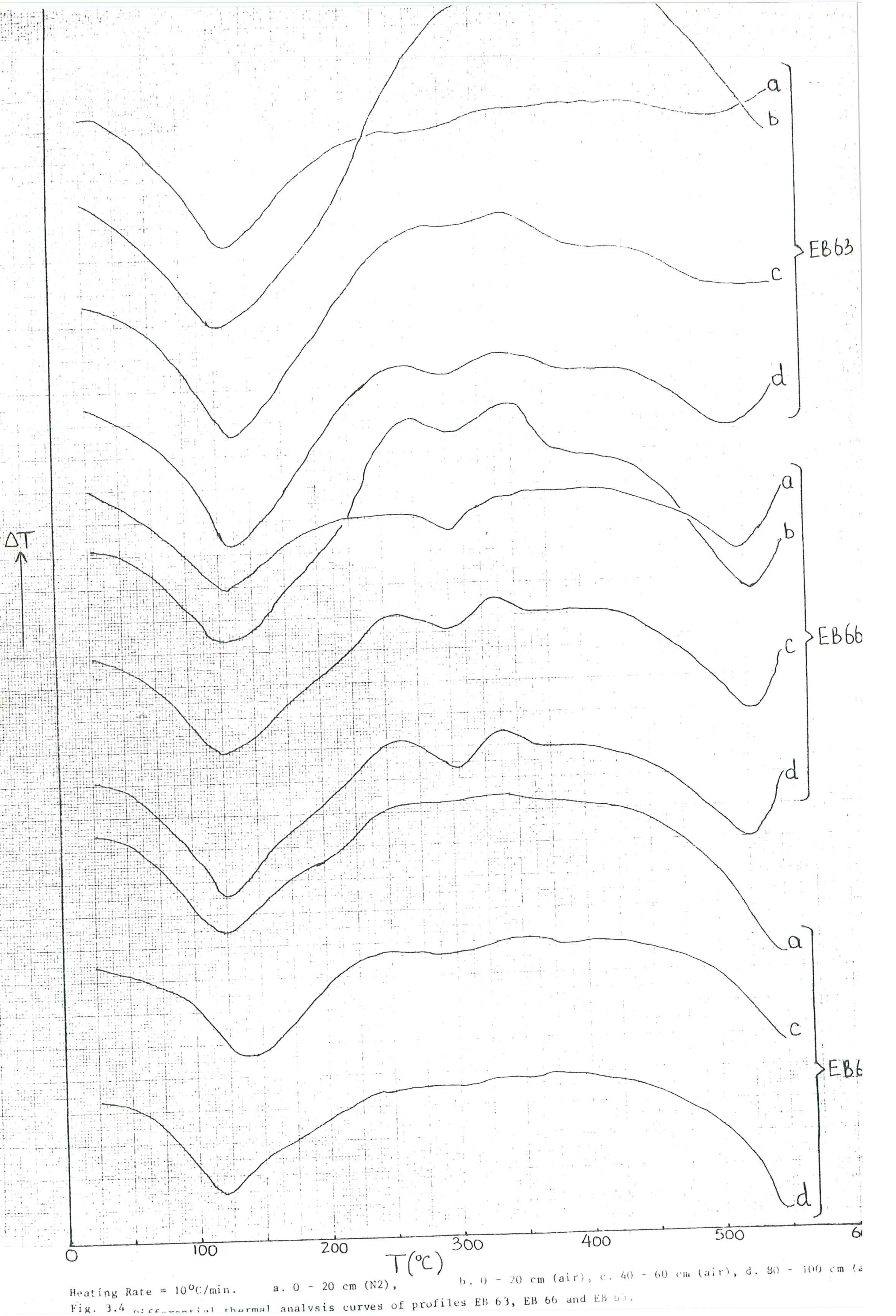
It has already been established (see Chapter 1.) that the parent material of the three soils is of volcanic origin and that these were deposited in recent times. For the purpose of classification it was necessary to carry out special tests in order to see whether or not the exchange complex of any of the soils was dominated by amorphous material. The methods of these tests were mentioned in Chapter 2. The results are discussed in this section.

3.4.1. Thermal analysis

1. Differential thermal analysis

Fig. 3.4. groups the differential thermal analysis curves of the three profiles. All the soils show a low temperature endothermic peak between 125 and 150^{o}C which satisfies the requirement for Andepts and Andosols specified by the various classification systems. In the absence of X-ray data of the clay fraction, it cannot be definitely established whether the cause of the low temperature endotherm is allophane. Montmorillonite also produces the same effect. However, in view of the fact that the soils are well drained and the high rainfall and temperatures do not favour the accumulation of montmorillonite, it is very unlikely that there is any significant amount of montmorillonite in these soils.

From the relative steepness of the endothermic peaks, it can be said that there is much more amorphous material



Heating Rate = 10°C/min. a. 0 - 20 cm (N2), b. 0 - 20 cm (air), c. 40 - 60 cm (air), d. 80 - 100 cm (a

Fig. 3.4 Differential thermal analysis curves of profiles EB 63, EB 66 and EB 6[illegible].

(allophane) in the youngest and highest profile (EB 63) than in the other profiles. The intermediate profile (EB 66) seems to contain more of this material, especially in the subsoil, than the oldest and lowest profile (EB 65).

Profile EB 66 shows a small endothermic peak around 325^{o}C which could be attributed to small amounts of gibbsite. The endothermic peaks between 525 and 600^{o}C shown by profiles EB 65 and EB 66 could be attributed to appreciable amounts of kaolinitic clay minerals (halloysite, metahalloysite and kaolinite). The absence of this peak in profile EB 63 is further confirmation of the dominance of allophane in this profile if the chronological sequence of weathering (parent rock - allophane - halloysite - metahalloysite - kaolinite - gibbsite) discussed by Sieffermann et al. (1969) is correct.

2. Thermogravimetric analysis (TGA)

The thermogravimetric analysis curves of the three profiles are given in Fig. 3.5. The reader's attention is drawn to two aspects of the curves. The first is the percent loss of weight due to water loss below 200^{o}C. Profile EB 63 loses more water than the other profiles. This suggests that profile EB 63 holds more water, which is less strongly bound than the other two profiles. Amorphous material has a loosely bound structure so water held by it is also loosely bound (Grim, 1968).

The other aspect is the curves themselves. The curves of profile EB 63 (especially of the 40-60 cm layer) is rather smooth, without any prominent flexures, whereas the curves of profiles EB 65 and EB 66 show a prominent increase in weight loss between 400 and 500^{o}C. According to curves shown by Grim (1968) the smooth curve is characteristic of allophane while the curve with a prominent flexure at 400-500^{o}C is characteristic of halloysite. Thus profile EB 63 is dominated by amorphous material while profiles EB 65 and EB 66 are dominated by halloysite.

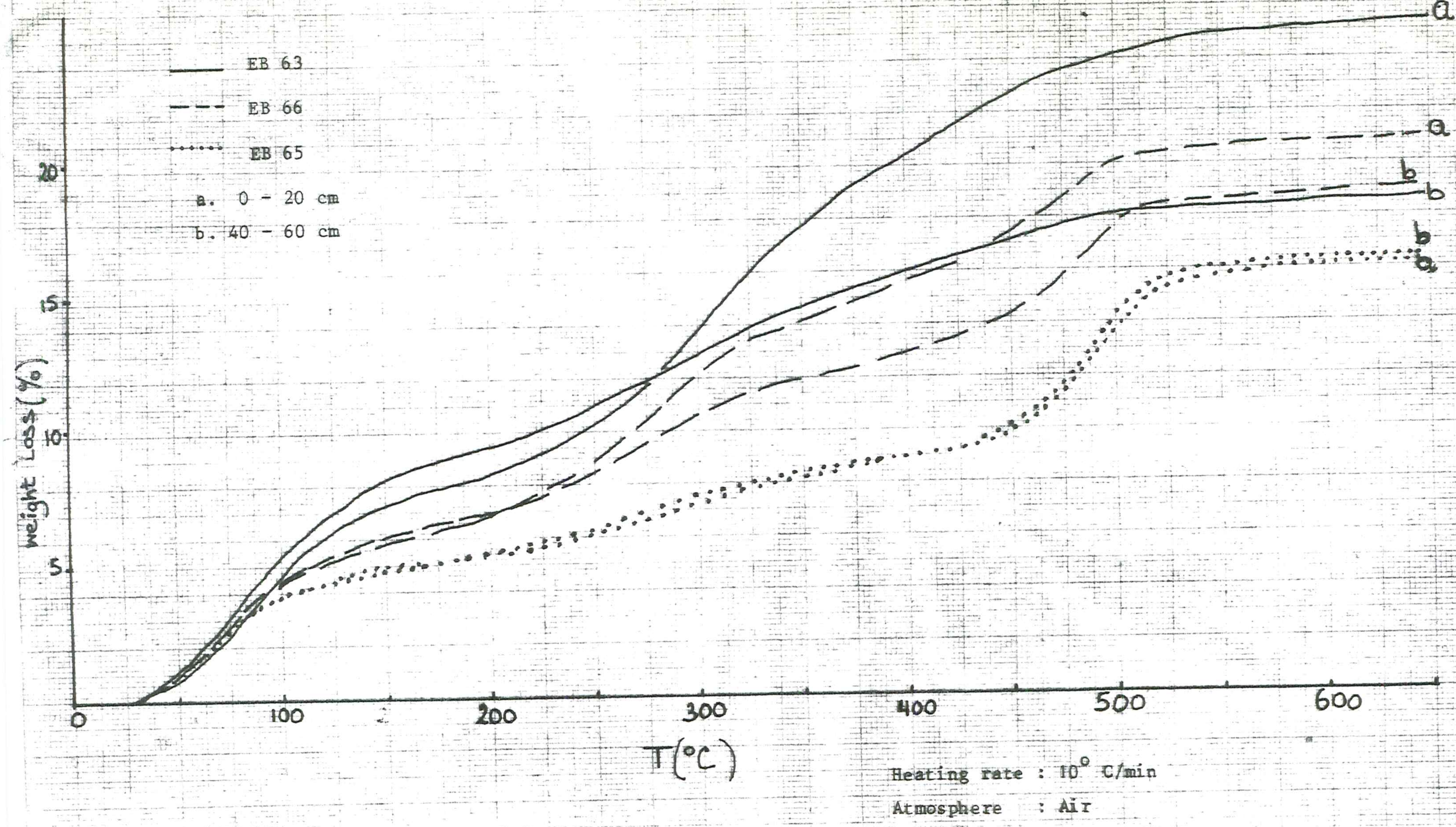


Fig. 3.5 Thermogravimetric analysis curves of profiles EB 63, EB 65 and EB 66.

3.4.2. pH in 1N NaF

The theory surrounding the use of this pH in detecting allophane centres on the fact that the fluoride ion (F^-) forms strong complexes with cations of high valence. When the cations are present in hydroxylated forms the OH^- is released during the reaction (for example: $Al(OH)_3 + 3F^- \rightarrow AlF_3 + 3OH^-$) giving rise to an increase in alkalinity. Now the reactivity of the cations depends on the degree of organisation of the material in which they are present. If the material is a well crystallized mineral F^- is unable to extract the cations and release the OH^-. In case of a loosely bound structure F^- can extract some of the cations and release OH^- (Perrott et al., 1970). Thus the amount of alkalinity released is an indirect expression of the degree of organisation present in the treated material.

The hydroxylated cations (Al, Si and Fe) in allophane are much more loosely bounded together than in crystalline clay. Thus it is possible to estimate the presence of large amounts of allophane in the soil by this test. The critical pH is 9.4: when the pH in NaF after 2 minutes is more than 9.4, the adsorption complex is probably dominated by amorphous material.

The results are shown in Table 3.4 and Fig. 3.6. The pH is mostly more than 9.4 in profile EB 63 and always less than 9.4 in profiles EB 65 and EB 66. Thus the adsorption complex in profile EB 63 is probably dominated by amorphous material. Profiles EB 65 and EB 66 have more crystalline clays.

3.4.3. Phosphate retention value

This property reflects the anion exchange ability of the soil. A soil with a high anion exchange ability will have a higher phosphate retention value than one with a low ability to exchange anions. Hydroxylated cations, with their ability to be both positively and negatively charged, possess a higher anion exchange potential than crystalline clay minerals.

Profile	Horizon (approx.)	Sample depth (cm)	pH in 1N NaF (2 min.)	P-retention value %
EB 63	A1	0- 20	9.10	75.0
	B21	20- 40	9.70	88.5
		40- 60	9.95	92.5
	II B22	60- 80	9.80	91.0
		80-100	9.55	87.5
	II B23	100-120	9.63	91.0
		120-140	9.75	91.0
EB 66	A1	0- 20	7.95	68.0
	B1t	20- 40	7.90	77.0
	B21t	40- 60	8.10	77.5
		60- 80	8.60	83.5
	B22t	80-100	9.0	85.5
	B23	100-120	9.20	85.5
EB 65	A1	0- 20	8.10	52.5
	B1t	20- 40	7.80	41.5
	B21t	40- 60	8.60	57.0
	B22t	60- 80	8.80	58.0
		80-100	8.90	62.5
		100-120	9.0	61.0
	B23t	120-140	8.90	61.0

TABLE 3.4. pH (NaF) and phosphate retention values in the three profiles.

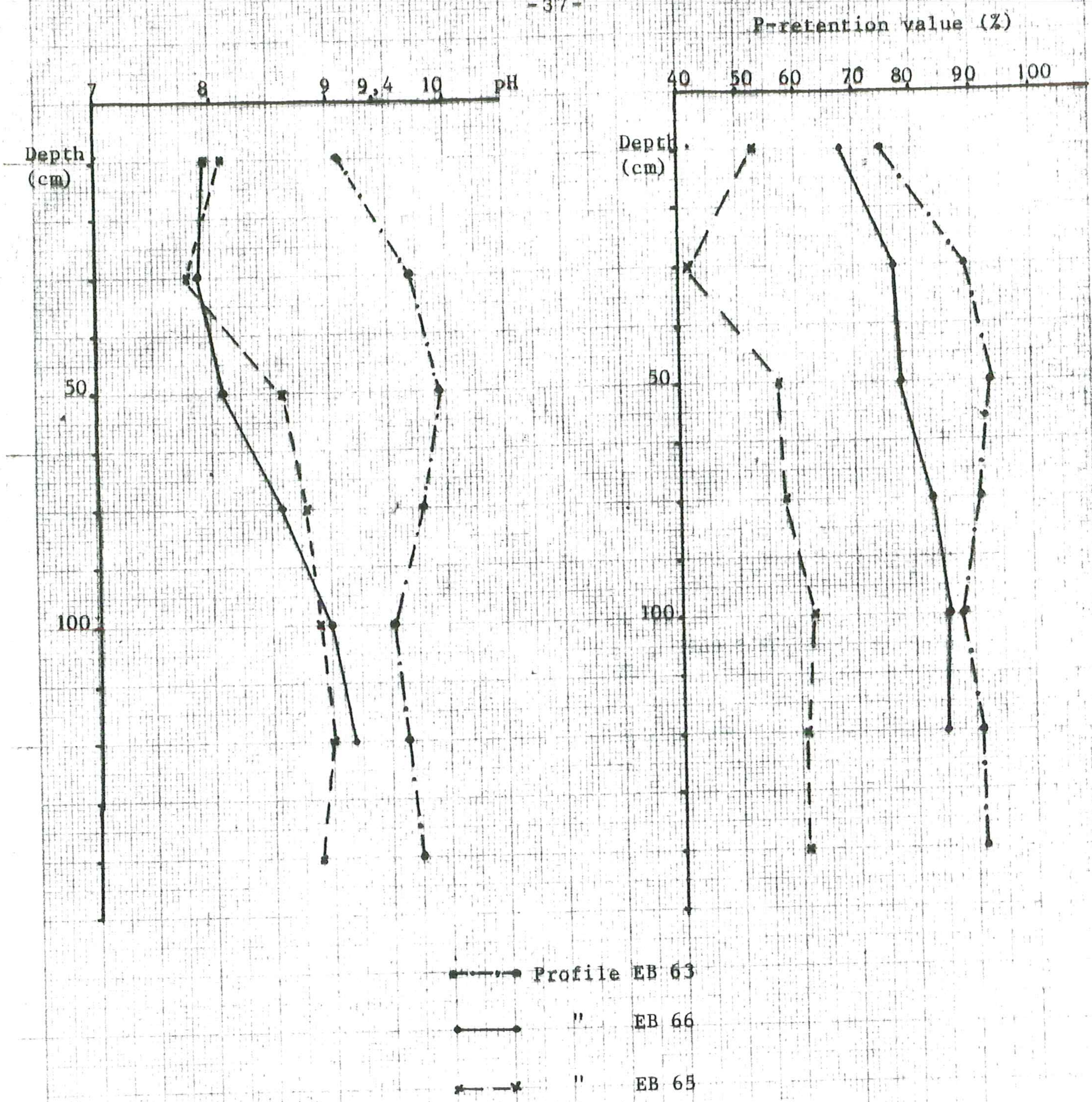


Fig. 3.6 Variation of pH(NaF) with depth in profiles EB 63, EB 65 and EB 66

Fig. 3.7 Variation of phosphate retention value with depth in profiles EB 63, EB 65 and EB 66

Allphane contains more hydroxylated cations than crystalline clays. Thus it is possible to detect the presence of allophane from the phosphate retention value. The critical value according to Smith (1978) is 90% of the added phosphate. A soil with a P-retention value of more than 90% probably has its exchange complex dominated by amorphous material.

The results are presented in Table 3.4. and Fig. 3.7. from which it can be seen that only profile EB 63 has P-retention values over 90%. This again confirms the presence of large amounts of amorphous material in this profile. Profile EB 66 has higher P-retention values than profile EB 65 suggesting the presence of more amorphous material in the former.

3.4. 4. Percent variable charge

The percent "variable charge" as defined by Smith (1978) is given by:

% variable charge =

$$100 \times \frac{\text{CEC } (BaCl_2 \text{ pH } 8.2) - (\text{sum of bases} + \text{extractable } Al^{3+},)}{\text{CEC } (BaCl_2 \text{ pH } 8.2)}$$

In general soils with a high amount of amorphous material have a high proportion of their total charge which is variable with pH. According to the proposals of Smith (1978) the variable charge in such soils is greater than 70% of the total charge.

In this study the CEC obtained in $BaCl_2$ at pH 8.2 was determined by the sum of cations method (USDA, 1972) which involves the determination of the extractable acidity in $BaCl_2$ - triethanolamine at pH 8.2 and the extractable aluminum in 1N KCl solution. The extractable aluminum of the soils studied was not determined, however. Generally aluminum becomes important in the adsorption complex of a soil when the pH in water is less than about 5.2., which is not the case with these soils. The pH (water) of the soils is high enough to preclude the accumulation of exchangeable aluminum. Thus in this study the percent "variable charge" was got from:

% variable charge =

$$100 \times \frac{\text{sum of cations } (= \text{CEC } BaCl_2 \text{ pH } 8.2) - \text{sum of bases}}{\text{sum of cations}}$$

The results obtained are shown in Table 3.5. Al the soils have "variable charges" of over 70%, which suggests the presence of appreciable amounts of allophane or organic matter (organic matter produces the same effect) or both. It has been seen, however, that only profile EB 63 satisfies all the other conditions for high amorphous material content so one might think that the cause of the high percent "variable charge" in profiles EB 65 and EB 66 is organic matter. This is not the case. Profile EB 63 contains more organic matter than the other profiles so the effect on the "variable charge" should have been much more than in the other profiles. Moreover, the percent "variable charge" in profiles EB 65 and EB 66 do not decrease with depths as does the organic matter content.

The amount of extractable acidity is also given in Table 3.5. The extractable acidity is much higher in profile EB 63 than in profile EB 66 or EB 65, and profile EB 66 has a higher amount than profile EB 65. This sequence is in agreement with the results of the other determinations (pH NaF, P-retention, thermal analysis). Apparently the amount of extractable acidity is a better indicator if the amount of amorphous material in this case than the percent "variable charge" as defined by Smith (1978).

The determination of the variable charge as defined by Smith (1978) assumes that all the exchangeable bases is accounted for by the permanent charge of the soil. This may be correct if the pH (in water) of the soil is low (5.0). The three soils in this study have pH (water) values of over 5.2 , and mostly around 6.0. There is nothing to stop bases from being held at pH-dependent exchange sites in such soils. Thus what Smith (1978) assumes to be

Profile & horizon	Depth (cm)	% clay / 100 g soil	sum of bases (meq.)	EA (meq/ 100 g soil)	CEC pH 8.2 (meq/100 g soil)	CEC pH 8.2 (meq/100 g clay)	" Variable charge "%	% 15 bar H_2O per 100 g clay	% 15 bar H_2O / % clay
EB 63: A1	0- 12	20.8	36.11	51.1	87.21	419.3	58.6	171.6	1.7
A3	12- 20	21.5	16.27	51.1	67.37	313.3	75.9	176.3	1.8
B21	20- 66	11.5	9.07	61.2	70.27	611.0	87.1	366.1	3.7
II B22	66-107	1.6	19.74	57.0	71.74	4483.8	79.5	3025.0	30.2
II B23	107-150	2.4	13.44	55.0	68.44	2851.7	80.4	2079.2	20.8
EB 66: A11	0- 11	65.5	14.45	44.1	58.55	89.4	75.3	52.4	0.52
A12	11- 28	72.1	9.0	40.3	49.30	68.4	81.7	55.6	0.56
B1t	28- 48	74.1	9.79	40.0	49.79	67.4	80.3	58.6	0.59
B21t	48- 80	75.2	9.92	40.8	50.72	67.4	80.4	58.4	0.58
B22t	80-100	82.1	9.35	40.8	50.15	61.1	81.3	-	-
B23	100-120	60.0	8.43	44.8	53.23	88.7	84.2	-	-
EB 65: A11	0- 4	59.7	20.11	23.6	43.61	62.6	54.1	13.6	0.14
A12	4- 20	70.0	11.06	23.6	34.66	49.5	68.1	16.4	0.16
B1t	20- 40	79.8	6.40	25.5	31.90	40.0	79.9	16.4	0.16
B21t	40- 57	80.7	5.77	26.4	32.17	39.9	82.0	20.9	0.21
B22t	57-110	78.5	5.43	26.5	31.98	40.7	83.0	28.7	0.28
B23t	110-150	79.3	4.37	28.3	32.67	42.3	86.0	-	-

TABLE 3.5: % variable charge, extractable acidity (EA), CEC ($BaCl_2$ pH 8.2) / 100 g soil and / 100 g clay, % 15 bar moisture / 100 g measured clay and 15 bar moisture/g measured clay of the three profiles.

the permanent charge (sum of bases + extractable Al^{3+}) might be partly made up of the pH-dependent charge. The percent "variable charge" as defined for New Zealand soils by Smith (1978) needs checking, especially in Cameroon. The percent "variable charge" might be a good indicator of the presence or absence of allophane, but one has to be sure that the bases and extractable aluminum occupy permanent exchange sites only.

The CEC ($BaCl_2$) at pH 8.2 expressed per 100 g measured clay is also given in Table 3.5. The difference between profiles EB 63 and EB 65 is very high. Profile EB 63, with a high allophane content, has extremely high values whereas profile EB 65 (and EB 66), with little or no allophane has much lower values. This and the percent moisture at 15 bar expressed per 100 g measured clay (or per 1 g measured clay) offer more possibilities of distinguishing between allophane soils and non-allophane soils.

4. MICROMORPHOLOGICAL CHARACTERISTICS

A summary of the level of processes as deduced from micromorphological observations is shown in Fig. 4.1. Details about each profile are given below.

4.1. Profile EB 65 (Mussaka series)

The micromorphological observations and interpretation concerning this profile are summarized in Fig. 4.2.

4.1.1. Groundmass

The groundmass of this profile is not as dense as one would expect from the high clay contents. This is probably due to the moderate level of biological activity which results in many biogeneic voids.

The skeleton grains are for a large part made up of volcanic material, the most common being pyroxene and plagioclase with a high amount of magnetite. Volcanic rock (amdesitic basalt) fragments were observed in the lower horizons. The presence of manganese in the groundmass and within the rock fragments was confirmed by the metallic lustre produced when observed under a stereomicroscope with incident light, and the production of gas bubbles (oxygen) when H_2O_2 was applied to the suspected spots. Manganese catalyses the dissociation of H_2O_2 into $H_2O_{(l)}$ and $O_{2(g)}$, but it is not the only element which can perform this function.

The magnetite grains vary in size between 10 and 50 microns while the other minerals are up to 200 and even 1000 microns. The rock fragments are usually up to 2 cm in diameter. The grains are angular, with low sphericity and randomly distributed.

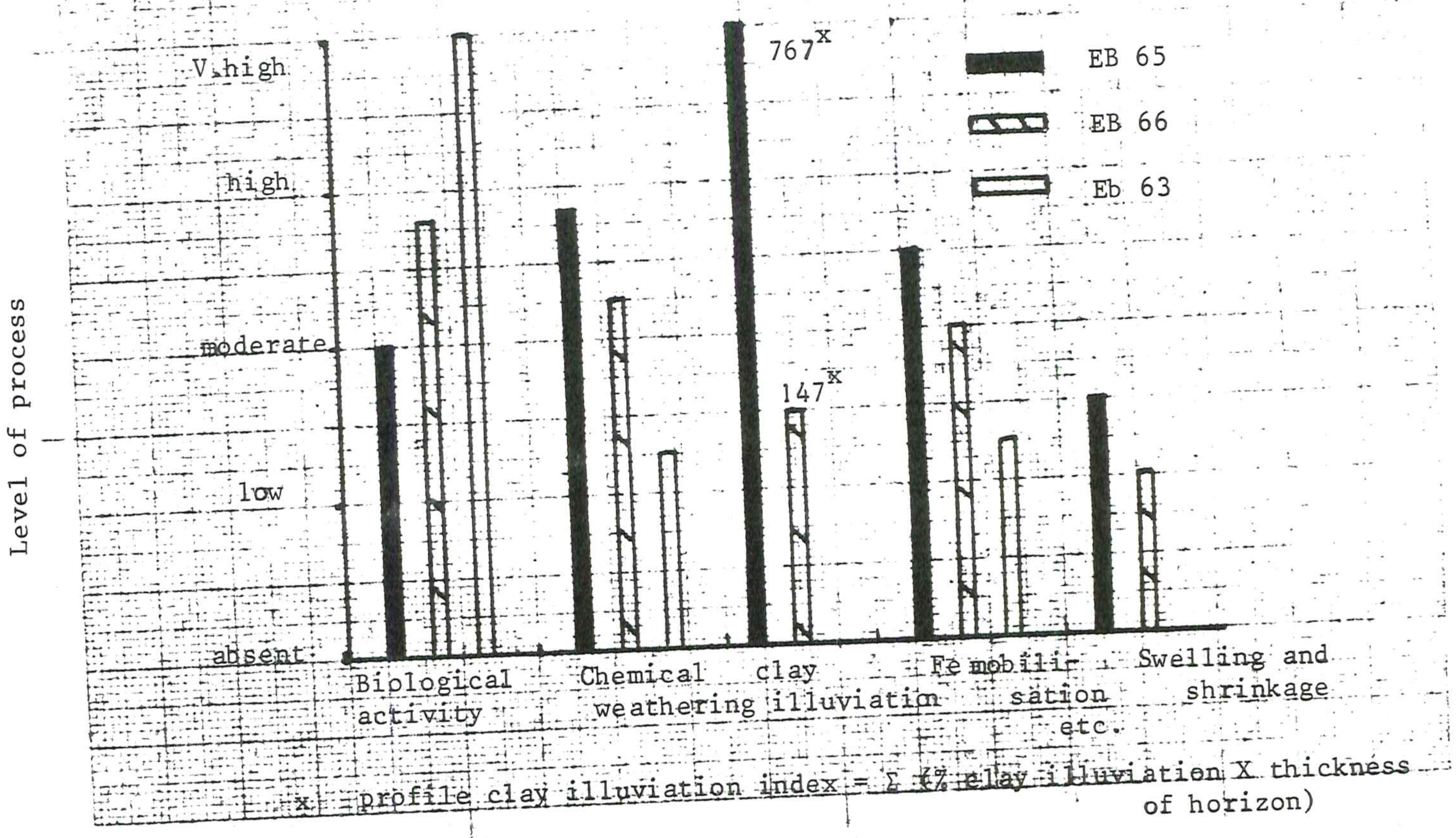


Fig. 4.1 Relative level of processes in the three soils.

The amount of grains is not more than common and decreases with depth.

The plasma is composed of clay minerals and iron (and organic matter in the topsoil). The plasmic fabric is mostly undulic, but there are a few spots with masepic (in the B-horizon) and isotic where there is a concentration of iron. The amount of plasma is abundant in the subsoil and decreases towards the surface.

There are many biogenic voids (vughs, interconnected vughs, channels, compound packing voids) in the profile. The amount of vughs and interconnected vughs is almost constant, while that of channels and compound packing voids decreases with depth. There are also some craze and skew planes in the B-horizon.

4.1.2. Special features

The observed special features in this profile were probably caused by the following processes:

1. clay illuviation
2. biological activity
3. mobilization, translocation and immobilization of iron
4. swelling and shrinkage
5. chemical weathering of rocks and minerals.

1. Clay illuviation (Plates 2a., 2b., and 3.)

The amount of ferriargillans and papules is very low in the topsoil and very high in the subsoil. These ferriargillans are associated with all the types of voids in this profile, but there are more normal voids (vughs, interconnected vughs) than channel or planar ferriargillans. The ferriargillans are usually well developed with high birefringence and showing extinction in bonds. They are mostly 30-100 microns thick and a few are up to 200 microns thick. Some ferriargillans and most of the papules, however, have a low birefringence. This is probably due to coarse textured clay which was also translocated by the high rainfall characteristic of the Buea area.

The percentage of clay illuviation features (ferriargillans and papules) ranges from 0.6 in the A-horizon to an average of about 10 in the B-horizon. As can be seen in Table 4.1a. there are more ferriargillans than papules in the B-horizon and almost no ferriargillans in the A-horizon. This indicates that there is almost a total disturbance of the ferriargillans in the A-horizon by biological activity.

The profile clay illuviation index (Miedema et al., 1972) is about 760, which is very high. Thus the level of clay illuviation is very high and the B-horizon, having more than 1% clay illuviation features, meets the micro-morphological requirements for an argillic horizon. The argillic horizon is more strongly expressed than in profile EB 66 (see Fig. 4.3.).

2. Biological activity

There are many aggrotubules and fecal pellets in the upper 50 cm of the profile and less in the subsoil. These features indicate the presence of faunal pedo-turbation.

The biogeneic voids mentioned before also indicate the presence of plant and animal **activity.** There are a few biorelicts, sometimes filled with fecal pellets (plate 4.), and papules in the topsoil. These features indicate the presence of faunal pedoturbation and root action.

The level of this activity is moderate in the top-soil and lower in the subsoil.

3. Mobilization, translocation and immobilization of iron

This process involves the reduction of Fe^{+++} oxides when the soil is saturated with water, the trans-location of Fe^{++} and the concentration of Fe^{+++} oxides when the soil is aerated. Iron concentrations and cutans may be formed in the process.

There are many large (100-300μ thick) distinct and common faint diffuse ferric nodules below a depth of 30 cm (see Plates 2a., 2b., and 5.). There are few to common faint diffuse ferric nodules in the top 30 cm of the soil. These features indicate that the process is concentratedin the B-horizon.

Other features observed in the B-horizon include a few normal void and channel neo-ferrans and neo-mangano-ferrans (see Plate 6.). There is also an uneven distribution of iron within the groundmass with the result that some parts are more reddish brown than others.

In conclusion it can be said that this soil is subjected to periodic excess of water leading to mild (pseudo) gleying..Although no bleached spots were observed, it cannot be established whether the absence of such spots was due to a good drainage or a very high iron content.

The level of this activity is higher than in profiles EB 66 and EB 63.

4. Swelling and shrinkage

Evidence of swelling and shrinkage of the soil upon wetting and drying is provided by the plasma re-orientations in the form of masepic and glaesepic (glaesepics in association with ferric nodules etc.) below a depth of 30 cm (see Plate 7.). The broken form of some skew planes in the B2-horizon provides further evidence.

The level of the process is quite low.

5. Weathering of rocks and minerals (see Plate 7.)

Remnants of andesitic basalt rocks were observed in the subsoil. These rocks contain plagioclase and pyroxene phenocrysts within a groundmass of plagioclase and magnetite. In some cases the magnetite is also present as

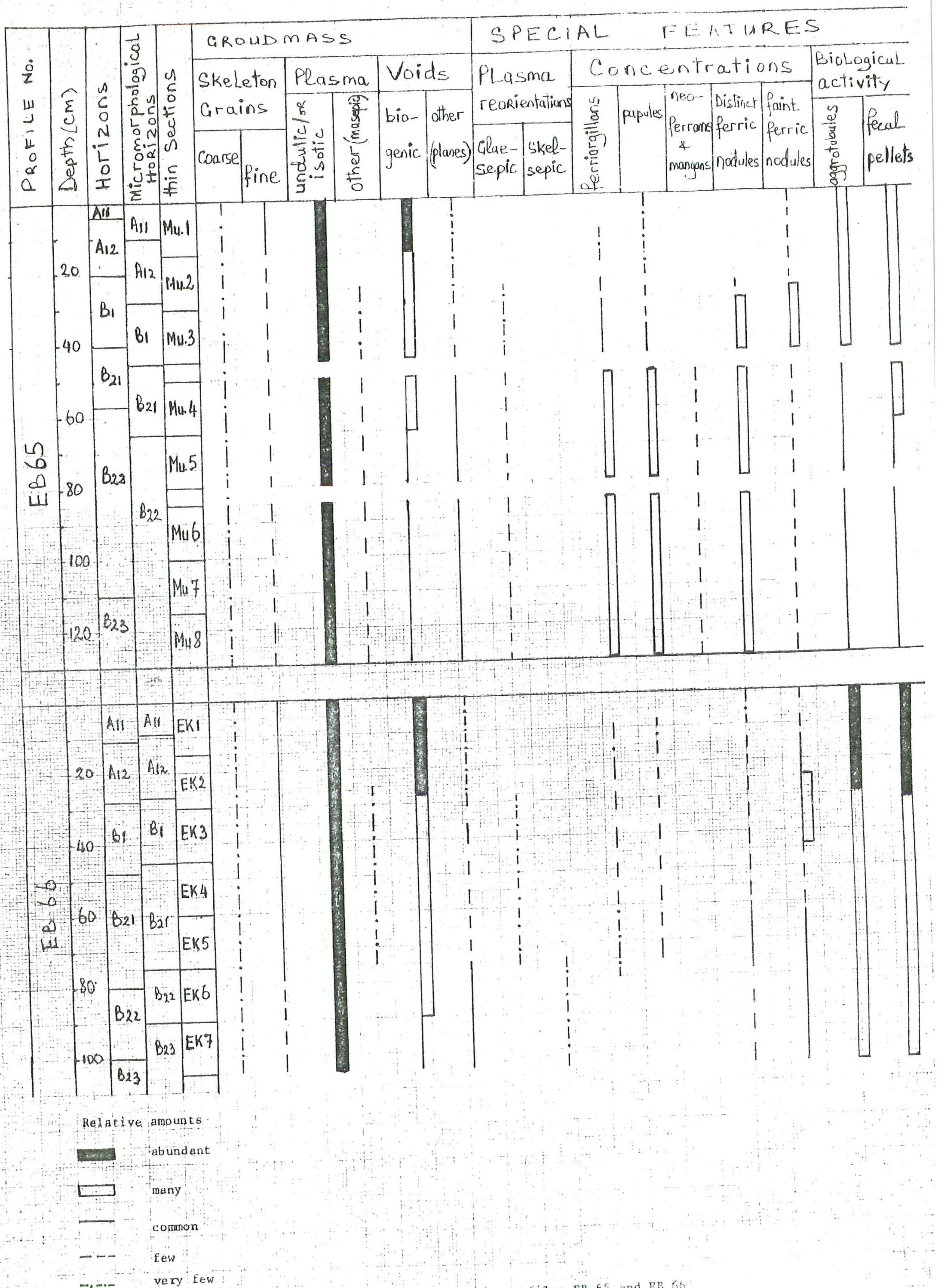


Fig. 4.2 Summary of micromorphological observations in profiles EB 65 and EB 66

phenocrysts. Chemical weathering of some of the pyroxene and plagioclase has taken place with the release of iron. Within the groundmass there are a lot of magnetite, some plagioclase and few pyroxene minerals. This indicates that the weathering of pyroxene is in a more advanced stage than that of plagioclase. Evidence of liberation of iron during the weathering is provided by the iron concentrations within cracks in the rocks and minerals.

Gibbsite crystals lining the walls of some voids within the rock fragments were observed (only under crossed polarizers). The stage of weathering is more advanced in this profile than in the other two profiles.

4.2. Profile EB 66 (Ekona series)

The micromorphological observations and interpretation concerning this profile are summarized in Fig. 4.2.

4.2.1. Groundmass

The groundmass in this profile is essentially similar to that of profile EB 65.

The skeleton grains are also crystals of plagioclase and pyroxene, but there are more andesitic basalt rock fragments than in profile EB 65. There is also a lot of magnetite both within the groundmass and the rock fragments. Manganese present as black spots within the rock fragments and the groundmass, was confirmed as for profile EB 65.

Most of the grains are of silt and fine sand sizes, with very few in the coarse sand fraction. The rock fragments are larger (0.5-2 cm). The amount of fine grains is nearly constant within 80 cm of the soil surface and decreases with depth thereafter. All the grains are angular, with low sphericity, and randomly distributed.

The plasma is also composed of clay minerals and much iron (plus organic matter in the A-horizon). There are very few plasma re-orientations in the form of masepic. In general the plasmic fabric is undulic. The plasma is abundant.

There are many biogenic voids in the profile. As in the Mussaka profile the amount of vughs and interconnected vughs is almost constant while the number of channels and compound packing voids decreases with depth.

There are less skew and craze planes in the B-horizon of this profile than in profile EB 65.

4.2.2. Special features

The observed special features in this profile were probably caused by the same processes mentioned in section 4.1.2.

1. Clay illuviation

Like the Mussaka profile this profile shows evidence of clay illuviation, but to a much lower degree. There are a few ferriargillans and papules between a depth of 10 and 75 cm, with the highest amount between 25 and 60 cm. The ferriargillans here are mostly associated with normal voids (see Plate 1.) and occur more in clusters rather than at random like in profile EB 65. They are also thinner (10-30 microns) than in profile EB 65.

The percentage of clay illuviation features ranges from 0.6 in the topsoil to a maximum of 4.2 in the subsoil. The percent in-situ clay illuviation features (ferriargillans) and reworked clay illuviation features (papules) are given in Table 4.1b. It shows that there are more ferriargillans even in the topsoil than papules. This indicates that the topsoil of this profile might have been slightly eroded.

The profile clay illuviation index (Miedema et al., 1972) is about 150, which is low. Nevertheless the layer between 15 and 75 cm depth has more than 1% clay illuviation features which thus qualifies it as an

Profile & approx. horizon		Depth of sample (cm)	Total % clay illuviation[2]	Degree of illuviation[1]	% in-situ clay illuviation[2]	% clay illuviation reworked biologically[2]	Degree of biological reworking[1]
(a) EB 65 :	A	0- 15	0.66 ± 0.6[3]	weak	traces	0.56 ± 0.5	strong
	B1	15- 30	2.5 ± 1.0	moderate	1.6 ± 0.3	0.9 ± 0.7	moderate
		30- 45	4.8 ± 1.6	strong	3.8 ± 1.4	1.0 ± 0.7	weak
	B21	50- 65	5.1 ± 1.5	strong	4.2 ± 1.4	0.9 ± 0.7	weak
	B22	65- 80	10.5 ± 2.2	very strong	9.0 ± 2 0	1.5 ± 0.7	weak
		85-100	11.7 ± 2.3	very strong	10.2 ± 2.1	1.5 ± 0.9	weak
		100-115	7.9 ± 1.9	very strong	7.0 ± 1.8	0.9 ± 0.7	weak
	B23	115-130	7.9 ± 1.9	very strong	6.8 ± 1.8	1.1 ± 0.7	weak
(b) EB 66:	A11	0- 15	0.6 ± 0.5	weak	0.4 ± 0.4	traces	moderate
	A12	15- 30	1.6 ± 0.9	moderate	1.5 ± 0.9	traces	weak
	B1	30- 45	4.2 ± 1.4	strong	2.6 ± 1.1	1.6 ± 0.9	moderate
	B2	45- 60	2.5 ± 1.1	moderate	1.4 ± 0.8	1.1 ± 0.9	moderate
		60- 75	0.9 ± 0.7	weak	0.5 ± 0.4	0.4 ± 0.4	moderate
		75- 90	-	(none)	-	-	-

1. according to Miedema et al. (1972)
2. based on point counting of about 800 points using a 3 x 3 mm grid.
3. 2 x standard deviation using graphs proposed by Van der Plas et al. (1965).

TABLE 4.1. Data of clay illuviation (volume %), degree of clay illuviation and degree or reworking of illuviated clay in (a) profile EB 65, and (B) profile EB 66.

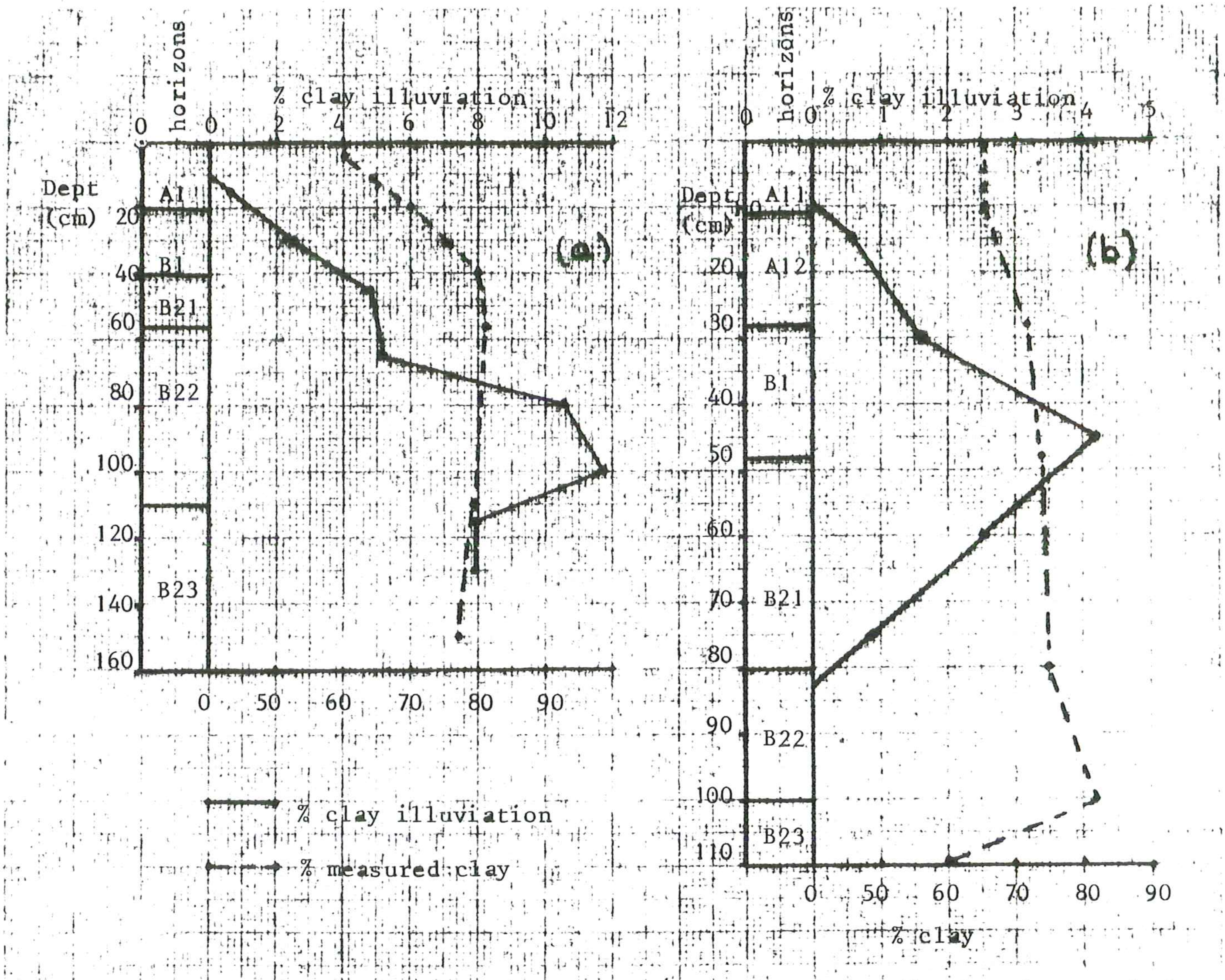


Fig. 4.3 Variation of percent clay illuviation (according to micromorphological observations) and % < 2 μ (granulometric analysis) with depth in (a) profile EB 65 and (b) profile EB 66

argillic horizon (as far as micromorphology is concerned). The relationship between % clay illuviation features and % measured clay is given in Fig. 4.3.

2. Biological activity

The main type of biological activity in this profile is faunal pedoturbation. Ants and earthworms are the most important fauna.

Although the amount of biogenic voids, aggrotubules (see Plate 8.) and fecal pellets is high in the topsoil and decreases with depth there are still many aggrotubules and fecal pellets at a depth of 100 cm. Some parts of the profile contain so many aggrotubules, fecal pellets and compound packing voids that the fabric could be named "a fecal fabric" (see Plate 9.). There are also some biorelicts in the topsoil.

In view of the higher amount of such features in this soil than in profile EB 65 the level of biological activity here is probably higher.

3. Mobilization, translocation and immobilization of iron

In comparison with profile EB 65 the period during which this soil is saturated with water is shorter. This implies that the level of this activity is lower in this profile than in profile EB 65.

There are common faint diffuse and few distinct ferric nodules throughout the profile, but more in the subsoil than in the topsoil. The ferric nodules usually have diameters between 50 and 300 microns (see Plate 4.).

It is doubtful whether any harmful effect is caused by the temporary excess of water.

4. Swelling and shrinkage

There are very few plasma re-orientations in the form of masepic, glaesepic and skelsepic (plasma re-orientation around skeleton grains) in the B-horizon.

These features were probably caused by swelling and shrinkage of clay minerals upon wetting and drying.

However, there are very few of these features, fewer than observed in profile EB 65. This leads to the conclusion that there is very little swelling in this profile, less than in profile EB 65.

5. Chemical weathering of rocks and minerals

The features observed in profile EB 65 were also found in this profile. But there are more pyroxene crystals and rock remnants here than in profile EB 65. So the stage of weathering is less advanced than in profile EB 65.

4.3. Profile EB 63 (Molyko series)

The micromorphological observations and interpretation concerning this profile are summarized in Fig. 4.4.

4.3.1. Groundmass

The groundmass in this profile is different from that of profiles EB 65 and EB 66, especially with respect to number and amount of voids and plasma.

The amount of coarse skeleton grains in the topsoil is higher than in any of the other profiles, and increases with depth. The amount of fine grains is almost the same. This soil thus contains more skeleton grains than the others.

The skeleton grains also consist of pyroxene, plagioclase and magnetite but there is more pyroxene than in the other profiles. There are also more rock (basaltic) remnants even at shallow depth in this profile.

The distribution pattern is random and the grains are angular, with low sphericity.

The plasma is composed of clay minerals, iron and organic matter. The amount of plasma is much less than in profiles EB 65 and EB 66. Here again the plasma is darker,

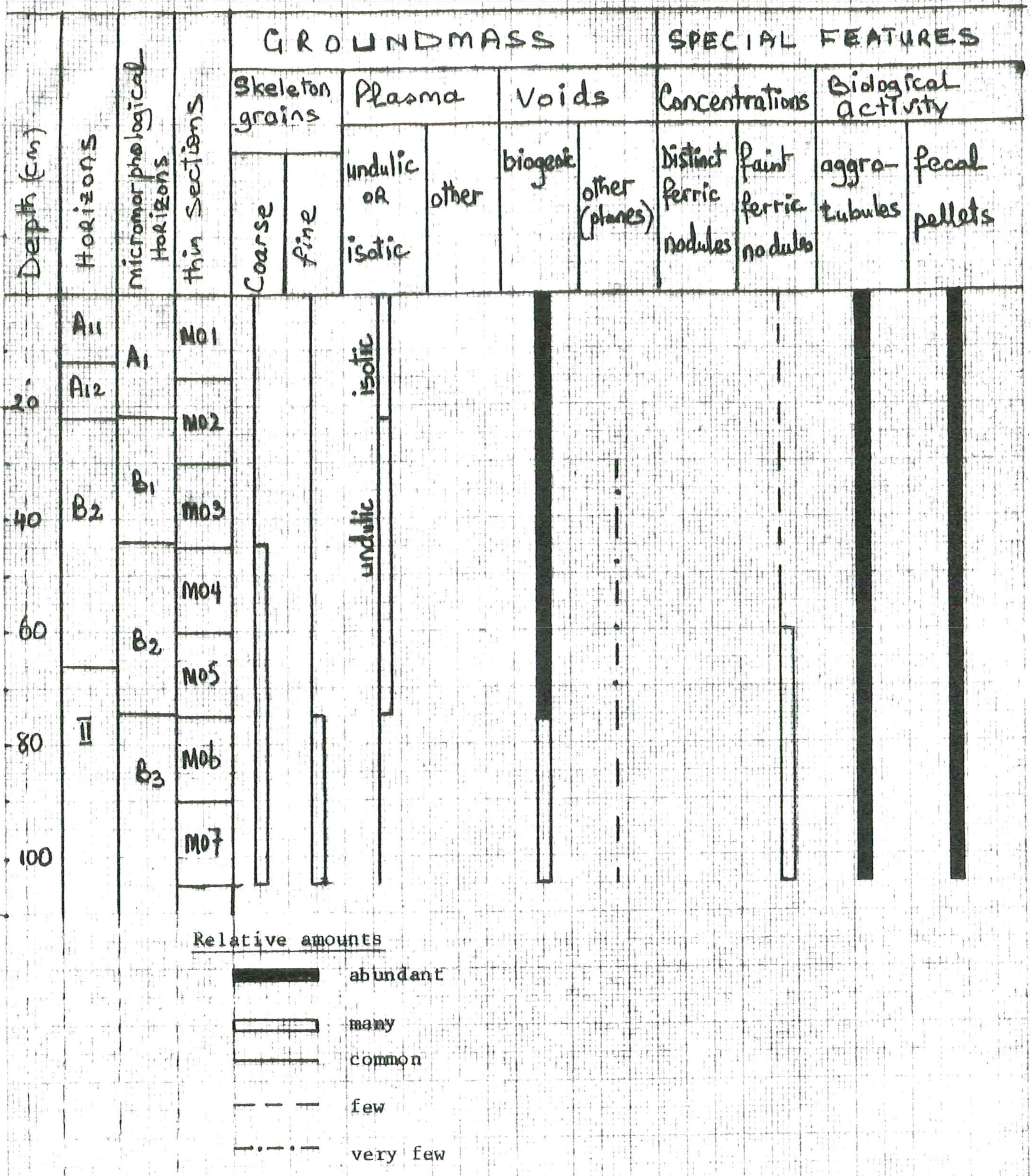


Fig. 4.4 Summary of micromorphological observations in profile EB 63.

creating an isotic plasmic fabric in the A-horizon and dark undulic fabrics in the subsoil.

Compound packing voids and other biogenic voids are abundant even at a depth of 100 cm. The voids are the most dominant features in the groundmass, occupying more than 50% of the soil volume.

4.3.2. Special features

The observed special features in this profile were probably caused by the following processes:

- biological activity
- mobilization, translocation and immobilization of iron
- chemical weathering of minerals and rocks.

1. Biological activity

The amount of aggrotubules and fecal pellets in this profile is very high even at a depth of 100 cm. These aggrotubules and fecal pellets are probably the result of faunal pedoturbation (earthworms and ants).

The many biogenic voids in the profile and bio-relicts in the topsoil are further evidence of biological activity. Some plant remains have been partly eaten up by the fauna which deposited fecal pellets in them (see Plate 3.). There is also what has been referred to earlier as "fecal fabric" in this soil.

Thus the biological activity is very high in the topsoil and high in the subsoil. This profile has the highest level of biological activity in the sequence.

2. Mobilization, translocation and immobilization of iron

The faint diffuse ferric nodules (few in the topsoil and many in the subsoil) provide evidence that there is temporary excess of water in this profile during the months of heavy rainfall.

As there are no distinct nodules of iron or ferrans as observed in profiles EB 66 and EB 65 it can be concluded that the gleying process is very mild, milder than in profiles EB 65 and EB 66. This soil is probably well-drained.

3. Chemical weathering of rocks and minerals

As mentioned before the type of rock fragments in the three profiles is andestic basalt with phenocrysts of pyroxene, plagioclase and magnetite in a fine-textured groundmass of plagioclase and magnetite. There are more of these fragments in this profile than in the others. There are also more crystals of pyroxene and plagioclase (as skeleton grains) in the groundmass.

Chemical weathering of the rocks and minerals results in the liberation of iron which was observed as concentrations in cracks in the minerals. Most of the plagioclase has not been affected, however, unlike in the Mussaka profile.

The fact that there are more rock fragments and more pyroxene and plagioclase in this profile leads to the conclusion that the stage of weathering is less advanced than in profiles EB 66 and EB 65.

4.4. Conclusions based on micromorphology

From the foregoing the following conclusions have been drawn:

1. Considering that the three profiles represent a soil catena , the Mussaka profile is the oldest, the Molyko profile is the youngest and the Ekona profile is of intermediate age but closer to the Mussaka profile.

2. The parent material of the three soils is the same but the Mussaka soil, being the oldest has had more time for weathering of some primary minerals to proceed with the release of iron, silica and other products. Secondary minerals (clay minerals) have been formed from these products and a high amount of clay illuviation has taken place. Since it has been shown that

the soil has an argillic horizon it must be either an Alfisol or Ultisol (Soil Taxonomy), or a Luvisol, Nitosol or an Acrisol (FAO Soil Map of the World).

3. The Ekona soil, although somewhat younger, has also been weathered to an appreciable degree. Clay minerals have also been formed and some clay illuviation has taken place. There is also an argillic horizon in this soil so the classification possibilities are the same as those for the Mussaka profile.

4. The Molyko soil has not been weathered as much as the other two. Not much clay has been formed from the weathering products. No clay illuviation exists. This soil is probably an Inceptisol (Soil Taxonomy).

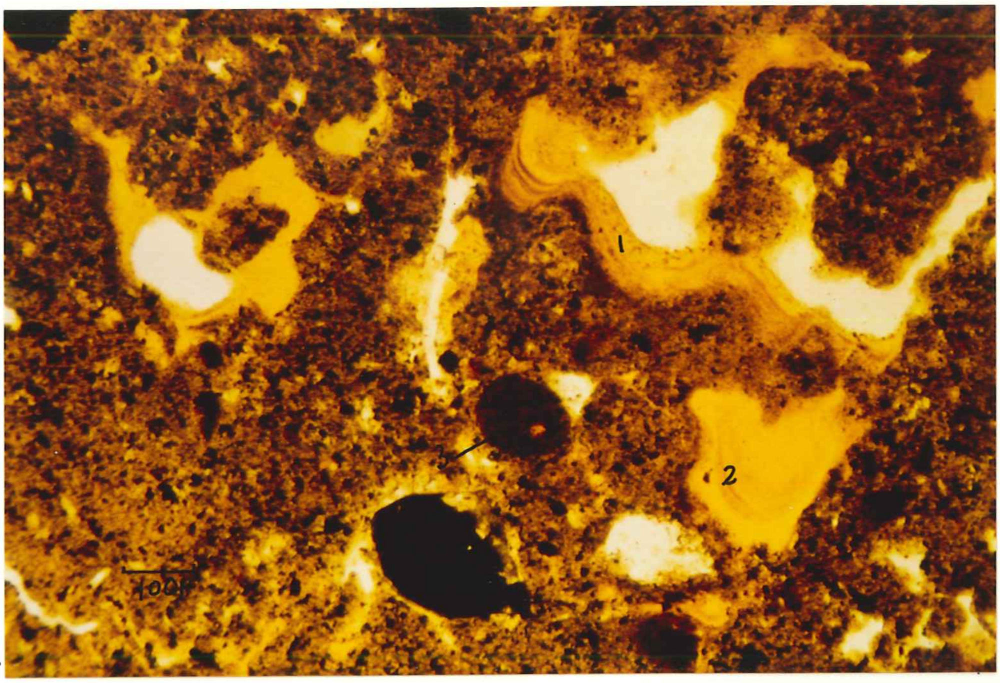


Plate 2a. Photograph of thin section showing 1. normal void ferriargillan, 2. papule, 3. distinct ferric nodule in the B-horizon of profile EB 65 (plain polarizer).

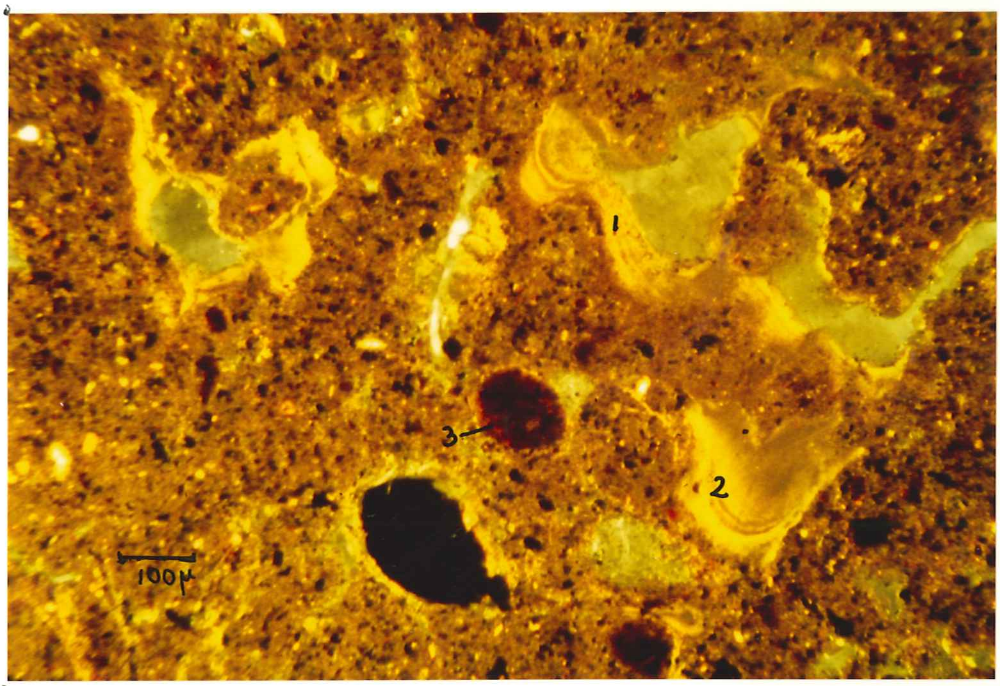


Plate 2b. Same as 2a. but seen under circular polarizers.

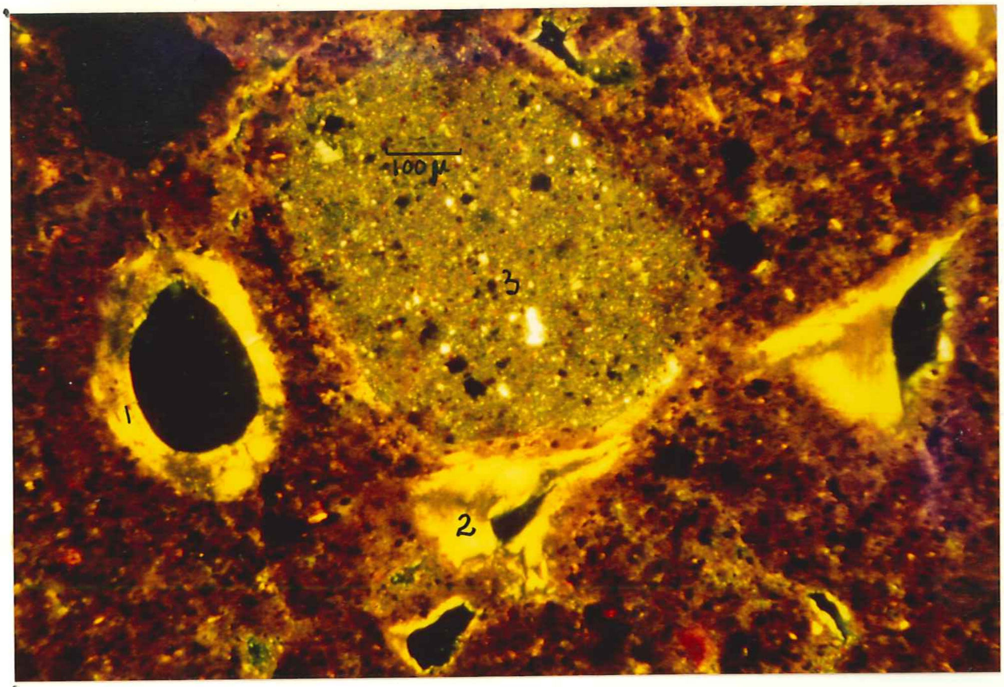


Plate 3. Photograph of thin section showing 1. high birefringent channel ferriargillan, 2. high birefringent normal void ferriargillan, 3. litho relict (crossed polarizers) in B-horizon of profile EB 65.

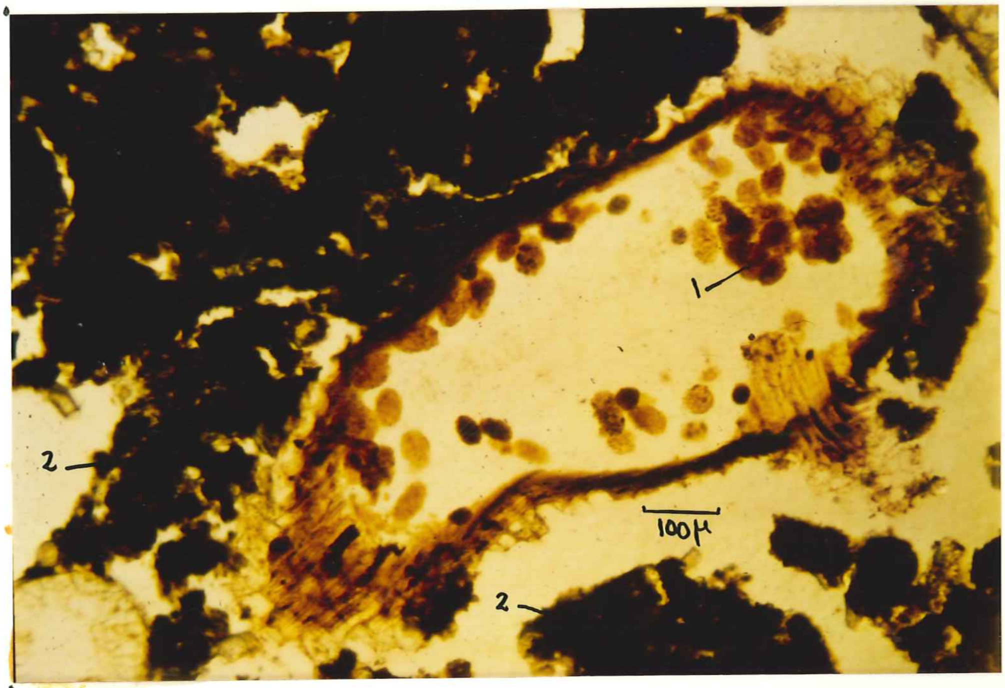


Plate 4. Photograph of thin section showing 1. fecal pellets in a biorelict, 2. isotic plasmic fabric, as seen in a A-horizon of profile EB 63 (plain polarizer).

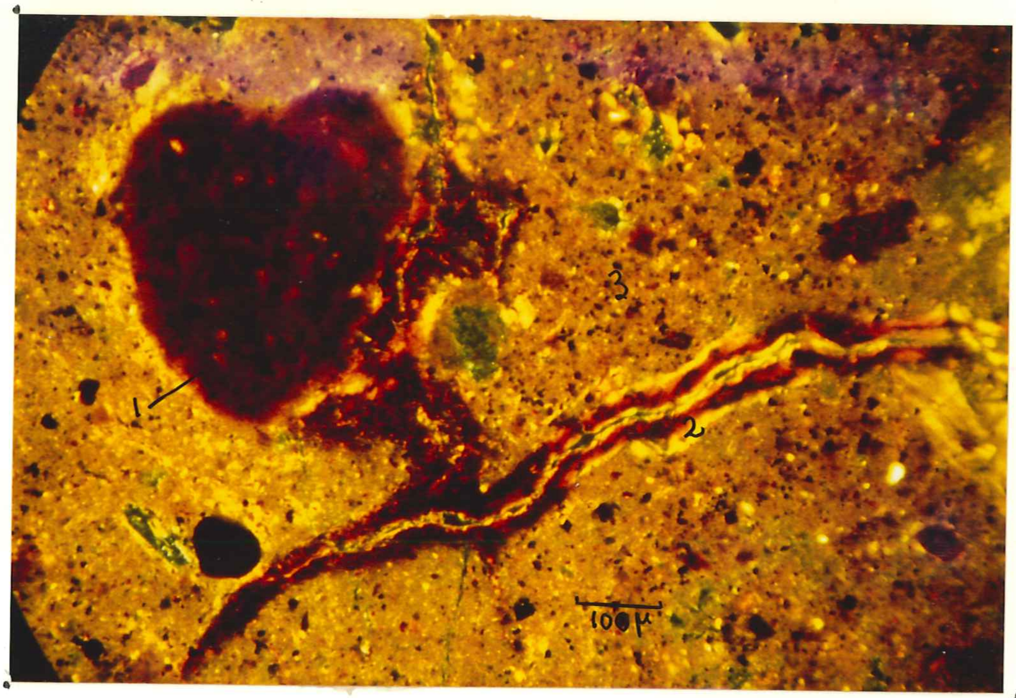


Plate 5. Photograph of thin section showing 1. distinct ferric nodule, 2. planar ferriargillan covered by a ferran, 3. undulic plasmic fabric in the B-horizon of profile EB 65 (crossed polarizers).

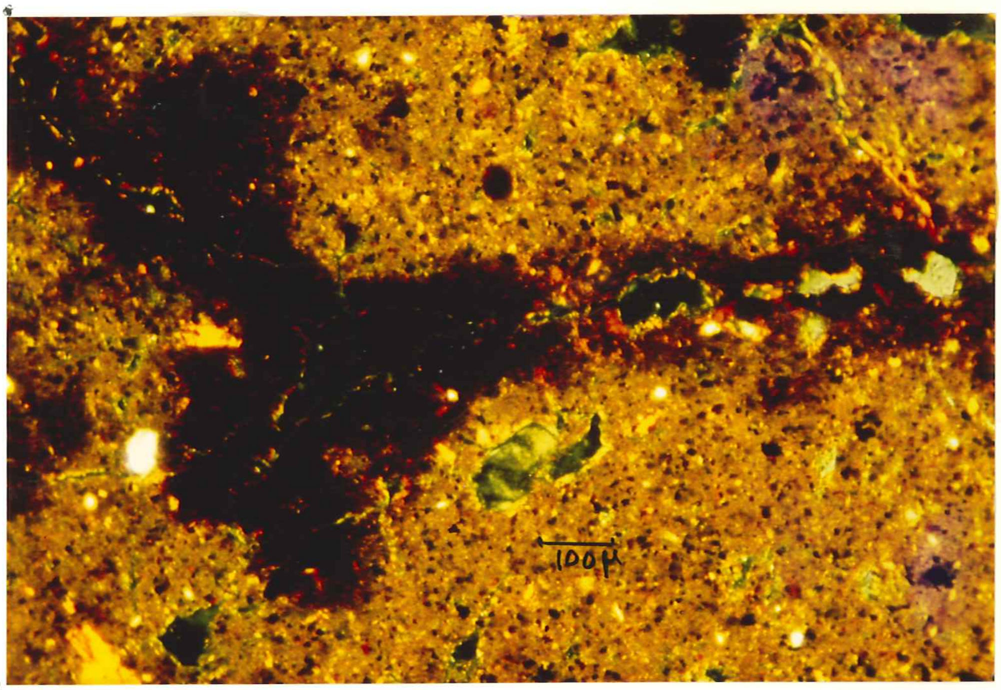


Plate 6. Photograph of thin section showing normal void neo-mangano ferran in B-horizon of profile EB 65 (crossed polarizers).

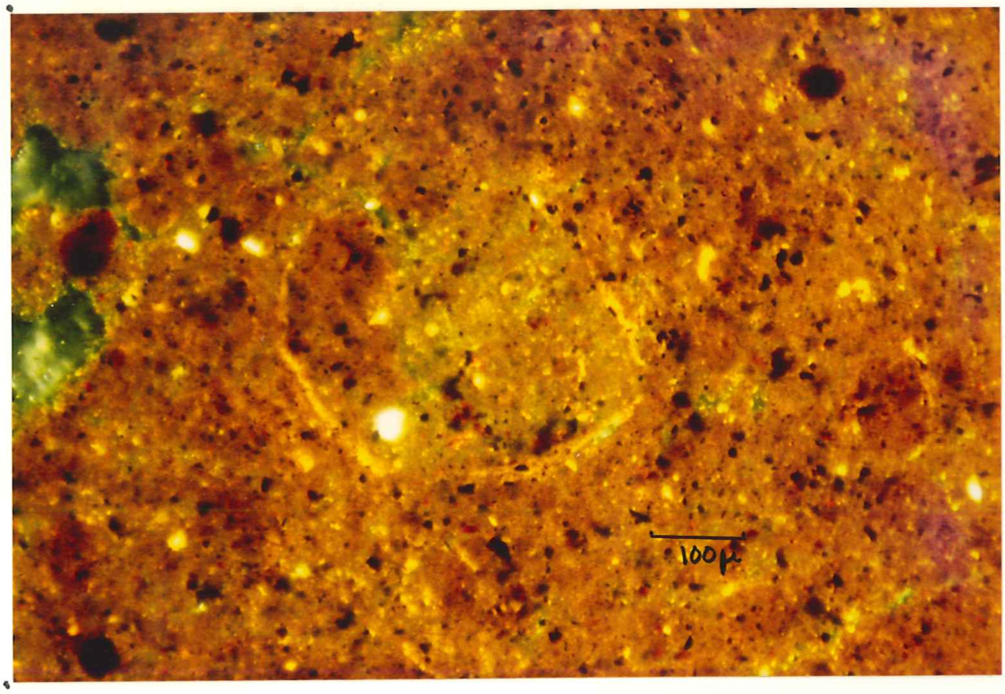


Plate 7. Photograph of thin section showing traces of plasma re-orientation around a glaebule (glaesepic) as seen in B-horizon of profile EB 66 (plain polarizer).

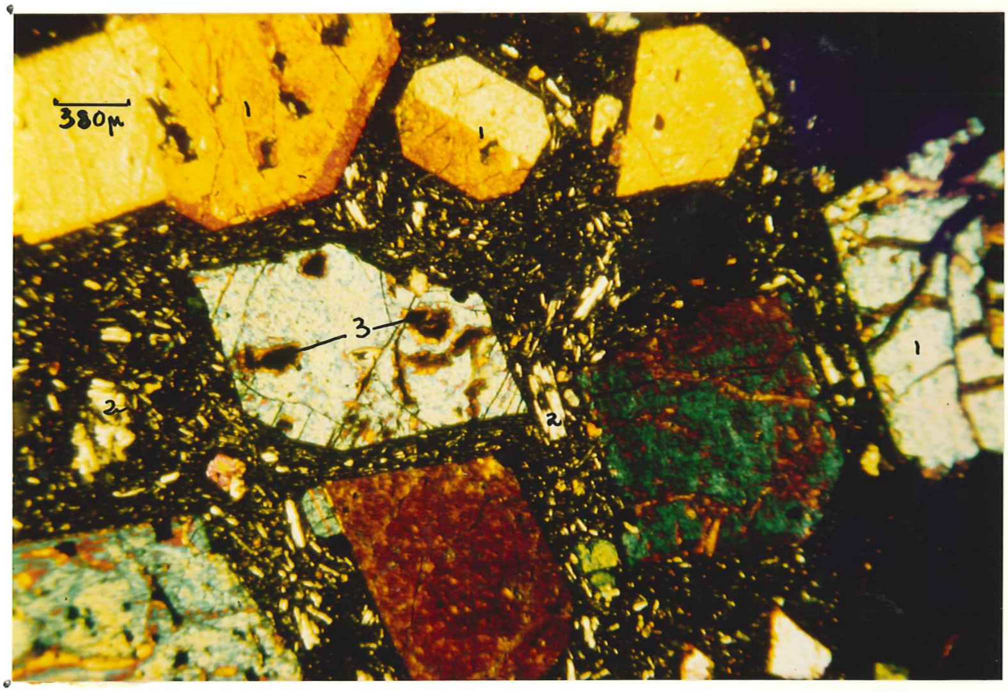


Plate 8. Photograph of thin section showing a litho relict with 1. pyroxene phenocrysts, 2. plagioclase phenocrysts, 3. Fe^{3+} concentrations in cracks,as seen in B-horizon of profile EB 66 (crossed polarizers).

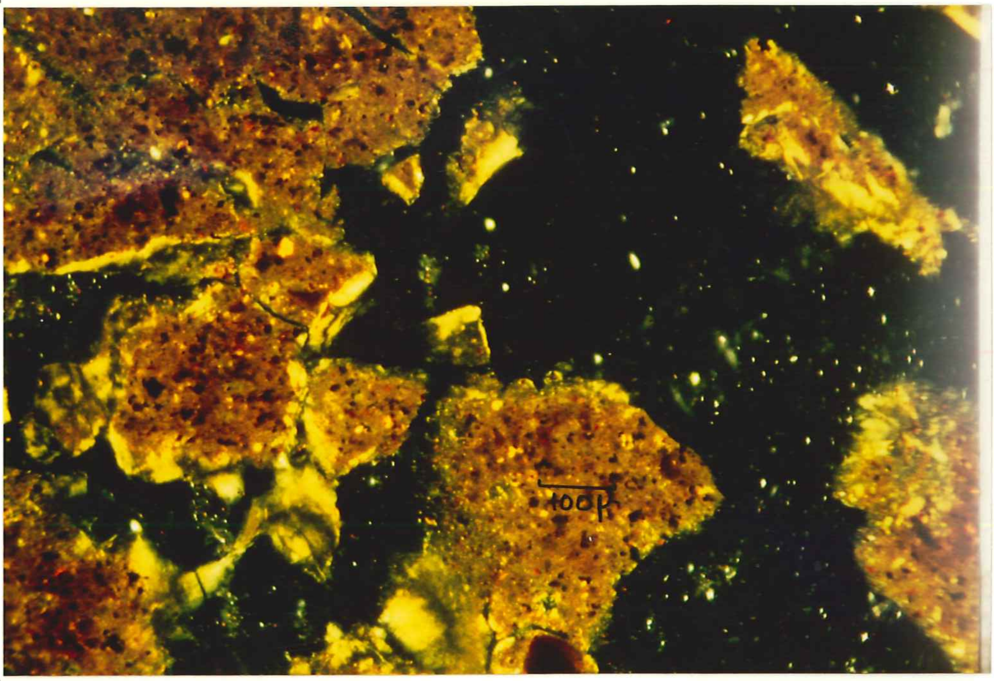


Plate 9. Photograph of thin section showing aggrotubules in B-horizon of profile EB 65 (crossed polarizers).

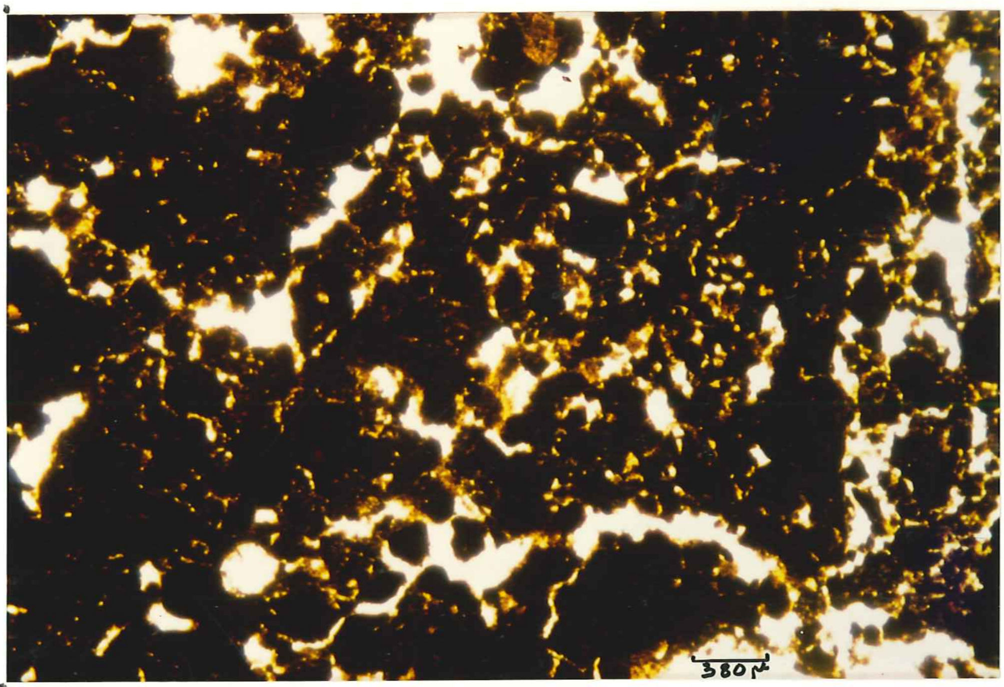


Plate 10. Photograph of thin section showing what has been referred to as a fecal fabric in profile EB 66 (plain polarizer).

5. CLASSIFICATION OF SOILS

The classification of the three soils was done according to the following systems:

1. U.S.D.A. Soil Taxonomy
2. Legend of the FAO Soil Map of the World
3. Guy D. Smith's proposal for reclassification of Andepts and some Andic subgroups (this system is applicable to Andepts only).

5.1. Profile EB 63

Most horizons in this profile meet the following requirements of the classification systems for an exchange complex dominated by amorphous material:

- Bulk density < 0.85 g/cc. (1, 2, 3)[1.]
- Differential thermal analysis shows a low temperature endotherm (1, 2)
- pH in 1N NaF after 2 minutes > 9.4 (1, 2, 3)
- Phosphate retention value > 90% (3)
- % variable charge > 70 (3)
- Cation exchange capacity (pH 8.2) /100 g clay > 150 meq (1, 2)
- Ratio of 15 bar moisture content to measured clay > 1.0 (1, 2)
- Amount of organic carbon > 0.6% (1, 2).

Thus this soil is an Andept according to system 1, Andosol according to system 2, and an Andisol according to system 3.

5.1.1. Diagnostic horizons

The whole soil up to a depth of 107 cm meets the requirements of a mollic epipedon as defined in the USDA Soil Taxonomy and the A-horizon (0-22 cm) meets the requirements of a mollic A-horizon as defined in the legend of FAO Soil Map of the World.

1. 1, 2, 3 refers to the classification system which has this requirement.

The mollic epipedon does not include the II B23 horizon because the latter does not meet the colour requirements.

The B21 horizon does not meet the requirements of a cambic horizon because it meets the requirements of a mollic epipedon. This is a classic example of the requirement of these two classification systems that a cambic horizon and a mollic epipedon are mutually exclusive.

5.1.2. Classification

1. Soil Taxonomy: Udic Eutrandept, thixotropic isohyperthermic
2. FAO Soil Map of the World: Mollic Andosol
3. Guy D. Smith's proposal: Typic Haplotropand, medial, isohyperthermic.

Comments on the classification

1. This soil is an Eutrandept because apart from the mollic epipedon it has base saturation (by NH_4OAc) that is more than 50% in the B-horizon and does not have clays that dehydrate irreversibly into aggregates of gravel and sand size. It is an Udic Eutrandept rather than a Typic Eutrandept because it has an udic moisture regime.

2. The classification according to USDA Soil Taxonomy satisfactorily expresses the major properties of the soil. This cannot be said of the classification according to Guy D. Smith's proposal, however. The high base content and the moisture regime of the soil cannot be deduced from the classification according to the latter system.

5.2. Profile EB 66

This profile, though derived from volcanic material, does not have the soil exchange complex dominated by amorphous material so it is no more an Andept or Andosol. The soil is obviously older than that of profile EB 63.

5.2.1. Diagnostic horizons and properties

The A-horizon (0-28 cm) meets the requirements of an umbric epipedon (Soil Taxonomy) and an umbric A-horizon (FAO Soil Map of the World). The base saturation is too low to qualify for a mollic epipedon

The B-horizon between a depth of 28-100 cm is an argillic horizon or an argillic B-horizon. It meets the macromorphological (clay skins) and granulometric requirements, but only the layer between 28-75 cm meets the micromorphological requirements. One could therefore argue that the argillic horizon is only the layer between 28-75 cm depth.

The soil has a high organic matter content in the B-horizon as defined in the legend of the FAO Soil Map of the World.

5.2.2. Classification

1. Soil Taxonomy: Typic Tropohumult, very fine clayey, Halloysitic, isohyperthermic
2. Soil Map of the World: Humid Acrisol.

Comments on the classification

1. This soil has a base saturation (by sum of cations) of less than 35% in the B-horizon so it is an Ultisol (Soil Taxonomy) rather than an Alfisol. It is a Humult rather than an Udult because it has

more than 0.9% organic carbon in the upper 15 cm of the argillic horizon (in fact, throughout the argillic horizon).

2. It is a Tropohumult rather than a Palehumult because of its clay distribution and because it is most likely that it has more than 10% weatherable minerals in the 20-2000 fraction (cf. micromorphology: the skeleton grains and rock fragments are weatherable).

3. It has been classified as Typic Tropohumult despite the absence of data about the cation retention in unbuffered 1N NH_4Cl because the sum of bases is more than 12 meq/100 g clay in the argillic horizon. The soil pH is too high to permit more than traces of aluminum on the exchange complex, so the cation retention capacity in unbuffered 1N NH_4Cl will not be significantly different from the sum of bases. In any case the cation retention capacity so determined will always be higher than the sum of bases.

4. The soil is an Acrisol (FAO Soil Map of the World) rather than a Nitosol because of its clay distribution. It is also a Humic Acrisol because it has an umbric A-horizon and a high organic matter content .organic matter content in the B-horizon($>$1.35% up to a depth of over 100 cm).

5. The mineralogy class "halloysitic" was arrived at by taking into consideration the CEC (by NH_4OAc) per 100 g clay, the TGA curves and the weathering sequence in these volcanic soils as constructed by Sieffermann et al. (1969). The CEC per 100 g clay is about 30 meq., which is typical for halloysite. Sieffermann et al. (1969) constructed the following chronological weathering sequence for volcanic soils in the Buea area: Allophane - halloysite - metahalloysite - kaolinite - gibbsite. TGA curves show a

prominent increase of water loss between 400 and 500°C., which is characteristic for halloysite.

5.3. Profile EB 65

This profile, like profile EB 66, is not an Andept or Andosol.

5.3.1. Diagnostic horizons

The A and B1t horizons meet the requirements of an umbric epipedon (Soil Taxonomy), and the A-horizon is an umbric A-horizon (FAO Soil Map of the World). The base saturation is too low to meet the requirements of a mollic epipedon.

The whole B-horizon is an argillic horizon (Soil Taxonomy) or an argillic B-horizon (FAO Soil Map of the World). It meets all the macromorphological, granulometric and micromorphological requirements of an argillic horizon.

5.3.2. Classification

1. Soil Taxonomy: Orthoxic Tropohumult, very fine clayey, halloysitic, isohyperthermic.
2. FAO Soil Map of the World: Humic Nitosol.

Comments on the classification

1. This soil has been classified as Tropohumult for the same reasons as profile EB 66 (except for the clay distribution).

2. It is, however, an Orthoxic Tropohumult rather than a Typic Tropohumult because the sum of bases in the argillic horizon is too low. As the pH (in water) of this soil is always equal to or more than 5.2. there would not be more than traces of Al^{3+} on the exchange

complex. This means that the cation retention capacity in unbuffered 1N NH_4Cl is unlikely to be up to 12 meq/100 g clay in the argillic horizon.

3. The mineralogy class is halloysitic for the same reasons as profile EB 66 (see comment 5 in section 5.2.2.).

4. This soil is a Humic Nitosol because among other properties it has an umbric epipedon and meets the clay distribution requirements of a Nitosol.

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