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A STUDY OF AN EAST AFRICAN CATENA

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(*Soil Survey of Uganda*)

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Summary

The Buwekula catena occupies a tor landscape which was formed in two stages, as in Linton's two-cycle theory. Weathering under present conditions has been traced from the proportions of minerals. Feldspar and magnetite show weathering trends and among non-opaque heavy minerals there is an order of weatherability in the series biotite, muscovite, and epidote.

The soil sequence from summit to valley is as follows. Buwekula Shallow occurs on the upper slopes and is a comparatively youthful soil. Buwekula Red occurs on the upper and middle sections of pediments and is a deeply and thoroughly weathered soil the parent material of which has sustained more than one cycle of weathering. Buwekula Brown is a topohydric variant of Buwekula Red and occurs in the lower sections of the pediments. Two alluvial series (Buwekula Yellow-Brown and Buwekula Grey) are derived from weathering and erosion products of the deeply weathered upland associates.

Mineralogical and geomorphic evidence indicates that much weathering took place before the present land surface evolved and that the upland soils are being formed to a large extent on pre-weathered material. Since the formation of the present land surface further weathering has given rise to the present soil profiles which appear to be in equilibrium with their environment, so that the development of soil horizons is keeping pace with all the processes responsible for their removal.

The distribution of individual soil series of this catena has a considerable influence on the land-use pattern of the area. Despite the ample and favourably distributed rainfall the Buwekula soils are not as productive agriculturally as some other soils in Uganda under similar climate. The main reasons for this are their high acidity associated with extremely low percentages of base saturation and their liability to accelerated erosion.

Introduction

SINCE Uganda can be claimed as the type locality of soil catenas (Milne, 1935 and 1936), these natural mapping units have been used wherever possible in the reconnaissance soil survey of the Protectorate. In this paper we describe the whole of the Buwekula catena, which occurs over an area of about 1,100 square miles in south-western Uganda (Fig. 1).

Geology and Geomorphology

The Buwekula catena covers a region of rugged topograpy with an average altitude of about 4,000 ft. with a relative relief around 300 ft. The area is underlain by post-Karagwe-Ankolean granite. Where exposed this is often a very coarse rock consisting of large feldspar and quartz crystals, with subsidiary muscovite. Biotite is uncommon and all other minerals very rare. Many tors are composed of giant porphyry granite, but it is possible that the inter-tor areas, now occupied by weathered rock, were originally of finer grain than the outcropping fresh rock.

Granite outcrops as rounded hills and tors all over the district and quite a high proportion of the land surface is bare rock. Most of the rock exposures are on ridge tops, but they are also frequent on lower slopes. The general appearance of the country is shown in Plate I.

FIG. 1

Between the outcrops there is intensely weathered rock, often to a great depth. Quartz veins traverse the rotted rock, showing that it is *in situ*, and there are other features to show that the original rock structure is retained, although weathering has altered many of the original minerals. The quartz is less weatherable than other minerals and consequently the weathered rock always contains much angular quartz of fine gravel size.

There is a remarkably sharp junction between weathered and fresh rock, extending over only a few inches. Boulders or 'core stones' are sometimes detached from the main rock mass, and these too have a very sharp junction with the surrounding rotten rock. Such a sharp junction is shown in Plate II.

The weathered rock can be divided into zones. The lower one retains much rock structure, and may contain unweathered core stones. The zone above is uniformly red, and although there is evidence from quartz bands, &c., to show that it is *in situ*, this is not apparent in all sections.

Modern hypotheses for the formation of tor landscapes (Linton, 1955; Waters, 1958) can be applied to the Buwekula area. Briefly its geomorphic history appears to be as follows: The granite was planated by the Gondwana erosion surface, which was very well developed and existed for a very long time with little change. Weathering went on beneath this senile erosion level and picked out the structures, attacking especially the finer grained, well-jointed, and most fissile parts. It seems to be a characteristic of such deep weathering to form a sharp junction between fresh and weathered rock and this junction has been called the 'basal surface of weathering' (Ruxton and Berry, 1958). It also seems to be typically irregular.

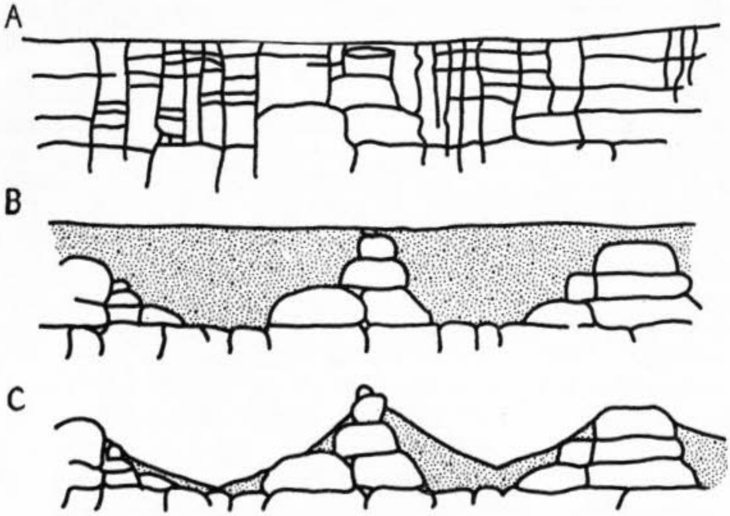

FIG. 2

Eventually a new cycle of erosion was initiated and a dendritic drainage system flowing west was incised on to the old surface. This drainage system became adjusted to structure and eroded the most weathered rock, leaving fresh rock to outcrop as tors and the present landscape of granite hills with a cover of rotten rock on slopes. Such a surface may be regarded as a kind of 'etchplain' (Wayland, 1934). The hills tend to reach the same approximate altitude but there are very few certain remnants of the original Gondwana peneplain. The sequence of events is shown diagrammatically in Fig. 2, A–C.

From a pedological point of view the most important feature of this history is that the weathered rock is a remnant of a previous cycle of weathering. The weathering which formed the parent materials for the present-day soils took place in Tertiary times. Weathering in the current cycle could only take place after the formation of the present-day slopes.

There is, of course, no evidence for any break in weathering, but there is a distinct break in the erosional history—the very perfect Gondwana surface existed for a very long time before its dissection by the later cycle of erosion. It is simply maintained that most of the weathering which converted the parent rock into soil material took place before erosion formed the present land surface, although there is mineralogical evidence, given later, for some contemporary weathering.

The angles of hill slopes seem to be partly controlled by the basal surface of weathering and partly by the processes which formed them. The cross-section shown in Fig. 3 bears out an impression gained in the field that most of the slopes are almost straight. The slope angle is about 9–10°. Pallister, in his study of Buganda slopes (1957), reported similar straight slopes. He found that hill slopes (*sensu stricto*) had gradients of 20–28° and pediments 5–8°. The main part of the slopes described here appear to be unusually steep pediments rather than free-face hill slopes.

The lower part of the catena may or may not have an alluvial member or members, and the distribution of these alluvial patches results from a rather complex later geomorphic history of the area. At the time of rift valley formation there was upwarping along the boundary of the western rift, which caused back-damming and reversal of the old westerly drainage (Wayland, 1921). The minor streams still flow west, but their flatter portions have been aggraded to form terraces, since cut through by later erosion. The steeper portions of the old valleys were never aggraded and now have very little alluvium in the narrow valley bottoms. This accounts for the irregular distribution of swamp and alluvium that is found along the valleys, as shown in Fig. 4.

With variations in rock outcrops, depth of weathered rock, and presence or absence of the alluvial soils, there is obviously quite a variation in the possible form of the catena, but the one described in detail in this paper is the simplest and most complete.

Climate

The average annual rainfall is about 45 in. in the west, increasing to just over 50 in. in the east of the area. There are two rainy peaks, in March–May, and in October–November, with the intervening short dry season in June–July and a long one in December–February. Light showers are common in the dry season with the average monthly falls seldom less than 2 in. The average annual temperature as recorded on Mubende Hill (5,000 ft.) is 66·8° F. with the maximum of 82·2° F. at the peak of the dry season and minimum of 58·2° F. in the rainy season. The relative humidity of the air at 8.30 a.m. is fairly constant, the average being 80 per cent. At 2.30 p.m. it drops to an average of 65 per cent.

Vegetation

The present natural vegetation consists of savanna with scattered trees and shrubs. In more remote and rarely cultivated areas there is a tendency to forest regrowth with the resulting invasion of thicket or young secondary forest. The latter usually occurs along valley fringes and, if undisturbed, extends gradually into the upland soils. Swamp communities consisting of papyrus (*Cyperus papyrus* L.) or *Miscanthidium violaceum*, K. Schum. (Robyns) are commonly found on the floors of larger river valleys.

On the transect line along which soil pits were dug there was a narrow belt of *Themeda triandra* Forsk., surrounding the rocky outcrop on the hill summit and followed by a grass savanna with frequent scattered shrubs extending down to the valley bottom. The dominant grasses were *Cymbopogon excavatus*, Stapf., *Brachiara soluta*, Stapf., and *Brachiara brizantha*, Stapf. The most numerous species of shrubs were *Vernonia amygdalina*, Del. and *Vernonia uniflora*, Hutch. & Dalz. There was no marked change in the dominant plant species between the hill slope and valley bottom, owing, presumably, to the fact that the adjoining valley was relatively narrow and possessed an intermittent stream capable of only occasional flooding for short periods. Together with the species already mentioned, scattered *Loudetia kagarensis* Hubbard ex Hutch. and some unidentified sedges were found in the valley bottom.

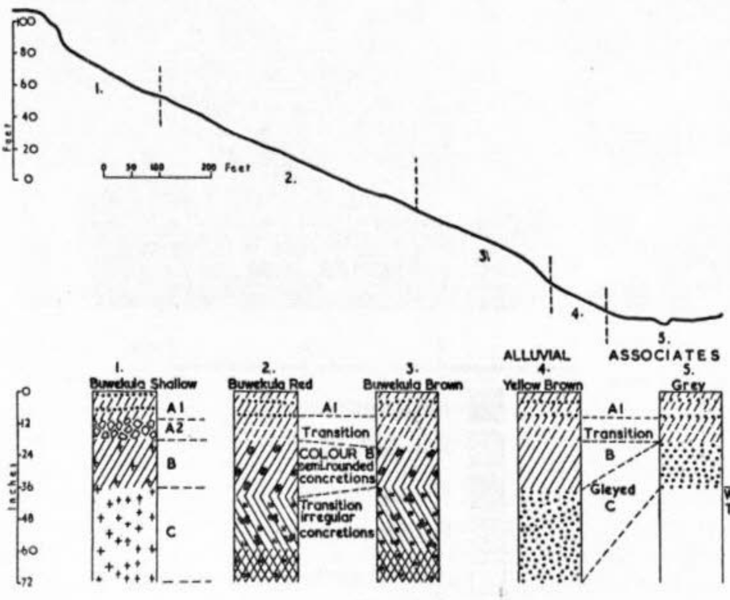

FIG. 3.

The Buwekula Catena

Fig. 3 represents a full topographic soil sequence from summit to valley. There are three upland- and two lowland-alluvial components in this catena each distinguished at the soil series level. These series are classified according to their present topographic site and the resulting profile morphology. A compound soil series name is used, consisting of the catena name with an adjective describing an outstanding characteristic of the soil series. By applying this system the usage of a number of local names is reduced and each soil name is made to convey something of its actual character in the field.

Each profile diagram represents an individual soil profile as found on a given topographic site. The boundaries between the soil series vary considerably in their sharpness. There is usually a fairly sharp boundary between Buwekula Shallow and Buwekula Red, but the latter merges in Buwekula Brown through a number of intergrades. Again, the boundary between Buwekula Brown and the alluvial soils is clearly defined by topography, but the two alluvial members gradually merge into each other.

Fig. 4 (a generalized portion of the soil map) shows the areal expanse

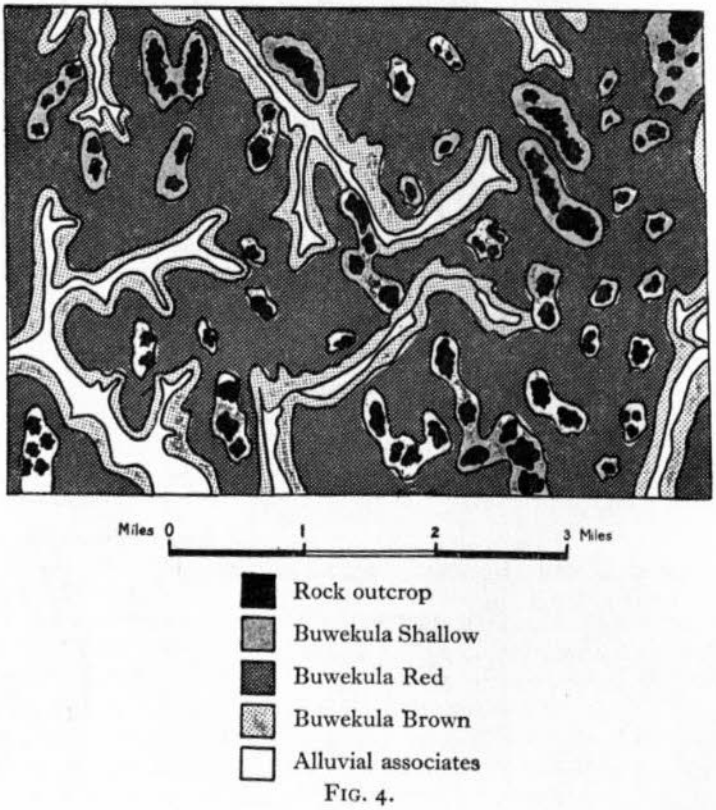

FIG. 4.

of the component soil series originally mapped at the scale of 1:50,000. The two alluvials are mapped together since the extra field work involved in separating them would not have been justified on the present scale.

The full catenary sequence as shown in Fig. 3 has not developed uniformly over the whole area and quite frequently one or more of its component soil series are absent. The reasons for such irregularity must be sought in the composition of the parent rock, which shows a varying degree of resistance to weathering, and in the complicated geomorphic history already described.

In the following sections the individual soil series will be described in detail and their morphological and analytical properties discussed from the point of view of pedogenesis. These are actual profiles from a transect studied in the field.

Buwekula Shallow. This series occurs on the upper slopes of hills and forms a relatively narrow belt surrounding the rocky summits. The term 'shallow' refers to the presence of incompletely weathered rock at shallow depths though the upper horizons are usually well developed but not sharply defined. The profile is described below:

0–3″ Dark grey (10 YR 4/1).* Humose, loamy sand with frequent coarse angular quartz gravel. Weakly crumbly and loose. Frequent roots.

3–10″ Dark brown (7·5 YR 4/2) less humose, loamy sand with very frequent coarse angular quartz gravel and frequent stones. Weakly crumbly and firm. Frequent roots.

10–18″ Light brown (7·5 YR 6/4) slightly stained with humus, loamy sand with abundant coarse angular quartz gravel. Frequent stones. Structureless and firm.

18–36″ Reddish-yellow (7·5 YR 6/6) loam + frequent quartz gravel and stones + occasional small fragments of feldspar + occasional minute flakes of muscovite. Slightly compact. Breaks into subangular blocks of varying stability.

36–60″ Yellow-red (5 YR 5/6) gravelly clay-loam + abundant angular quartz stones + frequent fragments of feldspar and flakes of muscovite. Structureless and compact.

60–72″ Yellow-red (5 YR 5/8) similar to the above + more frequent fragments of partially weathered rock.

Applying the standard horizon nomenclature, the first 0–3-in. layer would correspond to the A_1 horizon in which humus is intimately mixed with mineral matter. The second 3–10-in. layer may be regarded as an extension of the A_1 horizon. It is essentially similar to the overlying layer in its high content of humus and represents a transition into the 10–18-in. layer corresponding to the A_2 horizon, which is lighter-coloured and shows the highest concentration of quartz gravel (see Table 1). The 18–36-in. layer may represent an incipient B horizon at a very early stage of development. The presence of scattered small fragments of feldspar and minute flakes of muscovite indicates a close genetic relationship to the underlying C horizon. On the other hand this layer differs from the rest of the profile in its tendency to form subangular blocky peds and its orange colour. There is also a sharp rise in the content of clay and a reduction in quartz gravel when compared with the overlying A_2 horizon.

The two bottom layers constitute the C horizon, in which the clay content is much higher than in the upper part of the profile.

Buwekula Red. This series occurs on the upper middle and middle slopes of hills and is the most extensive member of the catena. If the concept of soil zonality were applied to the present soil sequence, Buwekula Red would be regarded as the 'normal soil' having its features in equilibrium with its present environment (U.S.D.A., 1951). The profile is as follows:

0–3″ Dark brown (7·5 YR 4/2) humose sandy loam + occasional quartz gravel. Frequent roots. Weakly crumbly and firm.

3–8″ Red-brown (5 YR 4/3) less humose, sandy clay-loam + frequent quartz gravel. Frequent roots. Weakly granular and slightly compact.

8–18″ Yellow-red (5 YR 4/6) slightly stained with humus, sandy clay-loam +

* All the Munsell colour determinations were made on air-dry soil samples.

frequent quartz gravel+occasional quartz stones. Weakly granular and slightly compact.

18–40″ Red (2·5 YR 5/8) sandy clay-loam+frequent humose streaks+frequent quartz gravel+occasional quartz stones+occasional, semi-rounded hard ironstone concretions ($\frac{1}{2}$–$1\frac{1}{2}$ cm.). Slightly compact. Breaks into subangular blocks of varying size.

40–60″ Red (2·5 YR 5/8) sandy clay-loam+faint humose streaks+frequent quartz gravel and stones+occasional grey, yellow, and red mottles+occasional dull brown and irregular ironstone concretions. Structureless and compact.

60–72″ Red (2·5 YR 5/8) strongly mottled grey, red, and yellow clay-loam+occasional soft ferruginous specks. Structureless and very compact.

The last whole depth of the horizon is several feet and gradually merges into loose, friable, and gritty rotten rock.

The A_1 horizon consists of two layers, 0–3 in. and 3–8 in., and is followed by the transitional 8–18-in. layer which merges into a weakly developed B horizon between 18 and 40 in. Concretions in this horizon are dark brown and semi-rounded. The 40–60-in. layer represents another transition into the mottled and slightly indurated horizon which appears to be enriched with iron compounds forming a discontinuous ferruginous network. Concretions in the 40–60-in. layer are irregular in shape and of dull brown colour closely resembling cemented clay fragments.

The middle layers of Buwekula Red may be irregularly streaked with dark humose material. This may be due to the action of soil fauna, or inwashed clay from the upper soil layers.

Buwekula Brown. This series occurs on the low middle and lower slopes and is generally far less extensive than Buwekula Red. It may be regarded as a topohydric variant of Buwekula Red which has been altered by drainage as influenced by topography. The profile is described as follows:

0–3″ Grey-brown (10 YR 5/2) humose sandy loam+frequent fine quartz gravel. Frequent roots. Weakly crumbly and loose.

3–8″ Red-brown (5 YR 5/3) less humose gravelly loam+occasional small quartz stones. Weakly granular to structureless. Frequent roots.

8–20″ Red-brown (5 YR 5/3) slightly stained with humus, gravelly loam+frequent coarse gravel and quartz stones. Weakly granular to structureless.

20–36″ Yellow-red (5 YR 5/6) gravelly clay-loam+frequent dark brown streaks+frequent coarse gravel and occasional stones+occasional ironstone concretions. Weak subangular blocky structure. Slightly compact.

36–60″ Yellow-red (5 YR 5/8) gravelly clay-loam+frequent dark yellow, dark grey, and brown mottles+some irregular ironstone concretions. Structureless and compact.

60–72″ Reddish-yellow (7·5 YR 6/8) indurated material, strongly mottled dark yellow, dark grey, and brown+occasional semi-hard ferruginous specks. Very compact and structureless.

The arrangement of the main horizons in this series is very similar to that of its red associate. The light-textured A horizon, including a transitional zone, extends to 20 in. and is underlain by the colour B horizon from 20 to 36 in. The transition into the mottled horizon begins at 36 in. and the latter occurs from 60 in. downwards.

Although the main morphological features are the same in both of these series, Buwekula Brown shows the following differentiating characteristics in addition to its brown colour. The first three layers have a much lower clay content associated with a considerable increase in quartz gravel which may account for partial eradication of structural features. The mottles found in the lower horizons lack the bright colours of Buwekula Red and there is a distinct predominance of yellow, brown, and dark grey indicating an advanced degree of hydration. In the lower horizons the concretions tend to be more numerous though by no means abundant. They are duller and less rounded than those of Buwekula Red.

Buwekula Yellow-Brown. This series occurs on slightly raised valley bottoms and valley slopes, and is described as follows:

0–3″	Grey (10 YR 5/1) humose loamy sand. Weakly crumbly and firm. Frequent roots.
3–8″	Light brownish-grey (10 YR 6/2) less humose loamy sand. Very weak crumb structure. Loose.
8–18″	Pale brown (10 YR 6/3) slightly stained with humus, coarse sand. Structureless and slightly compact.
18–36″	Light yellow-brown (10 YR 6/4) coarse sand, structureless and slightly compact. Sharp change to
36–60″	Very pale brown (10 YR 8/3) mottled rusty brown coarse sand. Structureless and compact.
60–72″	Light grey (10 YR 7/1) loamy sand with occasional rusty brown mottles. Structureless and compact.

The first two layers constitute the A_1 horizon. The underlying layer is transitional and merges into what may be an equivalent of a weakly developed colour B horizon which has been formed from the underlying material as a result of improved drainage conditions. This horizon extends to 36 in. approximately and its lower boundary marks the upper limit of a fluctuating water table in a normal rainy season. With an exceptionally high rainfall this horizon may become waterlogged but only for a very short time. The two bottom layers represent the grey C horizon similar to that occurring in the grey associate. The upper layer displays more frequent and larger rusty brown mottles which indicate longer periods of seasonal aeration due to the water table receding to greater depths in the dry season.

Buwekula Grey. This series occurs on the valley floor a few feet above the level of the stream and is often completely submerged in the rainy season. In larger flat-bottomed valleys such soils are permanently waterlogged and remain under swampy vegetation. The profile description is as follows:

0–3″	Grey (10 YR 5/1) humose loamy sand. Weakly crumbly and firm. Frequent roots.
3–8″	Grey (10 YR 6/1) stained with humus, coarse sand. Structureless and loose.
8–18″	Light grey (10 YR 7/1) slightly stained with humus, coarse sand with frequent rusty brown mottles. Structureless and loose.
18–36″	Light grey (10 YR 7/1) coarse sand with occasional faint rusty brown mottles. Structureless and loose.

The water table occurred at 36 in.

The profile consists of the sandy A_1 horizon about 8 in. in thickness, merging through the transitional 8–18-in. layer into the seasonally waterlogged C horizon. Rusty brown mottles in the grey soil material are evidence of alternate reducing and oxidizing conditions caused by seasonal fluctuations of the water table.

Analytical Results

Mechanical analysis. Stones and gravel were determined by 2-mm. sieving and direct weighing. Silt and clay were measured by the Bouyoucos hydrometer method and sand obtained by difference.

TABLE 1

Mechanical Analysis

Horizons (in.)	Coarse fraction gravel and stones (% whole soil)	Fine-earth fraction < 2 mm. Clay	Silt (% fine earth)	Sand
Buwekula Shallow				
0–3	44	18	6	76
–10	56	16	2	82
–18	72	7	1	92
–36	51	25	7	68
–60	60	45	8	47
–72	63	41	5	54
Buwekula Red				
0–3	7	29	5	66
–8	11	35	4	61
–18	15	34	2	64
–40	27	47	0	53
–60	11	51	4	45
–72	16	50	2	48
Buwekula Brown				
0–3	10	14	8	78
–8	51	24	2	74
–20	66	24	4	72
–36	44	42	8	50
–60	40	48	4	48
–72	35	54	6	40
Buwekula Yellow-Brown				
0–3	2	9	2	89
–8	13	12	4	84
–18	7	9	6	85
–36	4	7	8	85
–60	1	7	8	85
–72	0·5	11	6	83
Buwekula Grey				
0–3	1	9	8	83
–8	11	7	6	87
–18	3	5	4	91
–36	2	0	12	88

All the three upland soils show a relatively low clay content in the upper layers, increasing with depth. Gravel and stones are most frequent in Buwekula Shallow, particularly in the A_2 horizon of this profile. The gravel fraction in the first three layers of this series consists predominantly of angular quartz fragments. From 36 in. downwards, however, quartz gravel is mixed up with fragments of unweathered feldspar. Feldspar fragments do not occur in the other thoroughly weathered upland associates, in which the coarse fraction consists entirely of quartz.

Buwekula Brown is distinctly lighter in texture than its red associate and contains higher proportions of quartz gravel, indicating a more intensive eluviation. The clay content increases with depth as in Buwekula Red.

Both the upland and the alluvial profiles show a very low silt content—a characteristic shared by many tropical soils, in which rapid and intense weathering seems to result in a more or less direct transformation of feldspars into clay with insignificant proportions of silt being formed. Furthermore, a large proportion of the estimated silt fraction does not consist of true silt particles but of re-aggregated clay particles.

The dominant fraction of the alluvial associates is coarse and fine quartzose sand with very small proportions of other constituents. The low proportion of gravel in the alluvial soils indicates fragmentation during transport.

Chemical analysis. pH values were determined by glass electrode (Cambridge pH meter) on soil samples saturated to a wet paste; the content of available phosphorus (P_2O_5) by the Truog method; organic carbon by the Walkley–Black method; and exchangeable cations by the Lundegårdh flame method on a medium quartz spectrograph using neutral normal ammonium-acetate extracts. The figure for exchangeable hydrogen, estimated by the Schofield para-nitrophenol method, was used in calculating the total exchange capacity and the percentage base saturation.

The pH values reveal that all the members of this catena are acid and characterized by an advanced degree of leaching. The highest pH values are encountered in the A_1 horizon of Buwekula Shallow: pH values of just over 6 were recorded from samples of this layer elsewhere. The acidity increases with depth in all the profiles except in Buwekula Red where there is a slight rise in pH in the lower layers. With low percentages of base saturation both Buwekula Red and Buwekula Brown may be regarded as through-leached soils. The main factor responsible for their present pH trend appears to be rainfall.

X-ray analysis of the clay was not carried out, but the total exchange capacities of these soils seem to be typical of a clay complex consisting of kaolinite. The exchangeable bases show a remarkably high proportion of magnesium to calcium—a phenomenon also observed in Tanganyika (Muir *et al.*, 1957) and there attributed to a hornblendic parent rock. There is no hornblende in the parent rock of Buwekula soils which are derived from quartzose granites, and the high content of exchangeable magnesium may perhaps be due to differential leaching with calcium and potassium being lost at a more rapid rate than magnesium (de Endredy and Montgomery, 1956).

TABLE 2

Chemical Analysis

Horizons (in.)	*pH*	P_2O_5 *(p.p.m.)*	*C* (%)	*Exchangeable cations (m.e./100 g.)*				*Total exchange capacity (m.e./100 g.)*	*Base saturation* (%)
				Ca	*Mg*	*K*	*Mn*		
Buwekula Shallow									
0–3	5·8	12	2·13	3·0	1·8	0·31	<0·02	10·9	46·9
–10	5·7	13	2·12	2·3	1·4	0	0	8·6	43·0
–18	5·7	8	0·50	<0·8	<0·6	0	0	3·3	42·4
–36	4·9	9	0·36	<0·8	<0·6	0	0	5·2	26·9
–60	5·0	5	0·14	1·6	1·4	0	0	6·7	44·8
–72	4·9	5	0·08	1·1	1·5	0·25	0	6·8	41·6
Buwekula Red									
0–3	5·6	14	2·01	2·3	1·9	0·66	0·02	10·5	46·6
–8	5·1	10	1·23	2·2	1·1	0·46	0·02	9·8	37·9
–18	4·9	9	0·72	1·4	0·6	0·36	Trace	8·4	28·2
–40	5·2	8	0·39	1·2	1·8	Trace	0	8·0	37·5
–60	5·4	5	0·38	1·2	1·8	Trace	Trace	7·4	40·5
–72	5·9	6	0·15	1·1	1·5	0	0	7·0	37·1
Buwekula Brown									
0–3	5·6	15	1·89	2·0	1·3	0·33	0·04	8·8	41·8
–8	4·9	11	1·29	<0·8	<0·6	0·36	0·03	8·6	20·8
–20	4·9	9	0·78	0	0	0	0	6·8	..
–36	5·0	12	0·33	Trace	0	0	0	6·8	..
–60	4·9	9	0·24	1·0	0	0	0	7·0	14·3
–72	4·9	9	0·29	1·4	<0·6	0	0	8·6	23·2
Buwekula Yellow-Brown									
0–3	5·4	15	1·46	1·6	1·1	0·30	0·04	6·4	47·2
–8	5·0	7	0·75	0·8	Trace	0	0·03	5·1	16·2
–18	4·8	10	0·45	Trace	0	0	<0·02	..	..
–36	4·7	3	0·26	0	0	0	<0·02	4·2	50·3
–60	4·8	5	0·08	<0·8	0	0	0	2·6	30·8
–72	4·8	8	0·12	0·8	<0·6	0	0	3·0	46·7
Buwekula Grey									
0–3	5·3	19	1·52	0·8	0·6	0·16	0·04	6·7	21·2
–8	5·0	4	0·71	0	0	0	0	3·2	..
–18	5·0	4	0·08	0	0	0	0	1·6	..
–36	5·0	3	0·03	0	0	0	0	1·2	..

As may be expected, the organic carbon is highest in the surface layers and drops sharply with depth. The exchangeable cations and to a large extent the acid-soluble phosphorus are generally highest in the surface layers, demonstrating once again the repeatedly proved fact that most of the easily available plant nutrients in tropical soils are held by the organic colloids in the humose topsoil.

Mineral analysis

The fine-sand fractions (0·2–0·02 mm.) were retained after mechanical analysis of the soils, and semi-quantitative mineralogical examinations carried out. Mineral separations were done with bromoform and a magnet. It was not necessary to treat the sands to remove iron oxide stains. Feldspar percentages were obtained by counts, but the other figures given in Table 3 are estimates.

Quartz is the dominant mineral in most horizons but feldspar is more abundant in some horizons of Buwekula Shallow. The feldspar is extremely weathered and cloudy with alteration products. The heavy minerals are described as follows:

Opaque minerals. Magnetite varied from rounded to euhedral grains. Ilmenite was fairly common as black, non-magnetic grains. Opaque grains which are red or yellow in reflected light are probably goethite or limonite. These are always rounded and may be secondary grains or concretions.

Zircon occurs in a wide variety of forms from perfect euhedra to well-rounded grains and may be of various colours or colourless. Most are slightly worn grains of a pink/brown colour.

Tourmaline is found as platy grains with pleochroism from pale pink to dark green or opaque.

Epidote is usually found as irregular grains with hackly surface, usually showing signs of alteration. Grains are generally dirty green in colour but are often bleached in patches, and dirty with opaque alteration products. A few less weathered grains retain some crystal form and show typical epidote optical properties.

Muscovite and *Biotite* are present as basal flakes with typical colour and interference figures.

Andalusite occurs as slightly corroded grains with typical red to colourless pleochroism.

Rutile of both red and yellow varieties is found as rounded grains.

Apatite is in the form of corroded rounded laths with pitted surface.

Sphene is present as small, yellow/brown diamond-shaped grains with incomplete extinction.

Fig. 5 shows the appearance of some typical heavy minerals.

The relative proportions of minerals are shown in Table 3, and from them certain deductions can be drawn regarding the pedogenesis of both the individual profiles and the catena as a whole.

The most striking feature of this is that Buwekula Shallow is richer than the other profiles in abundance of mineral species, with high proportions of feldspar and magnetite, and having epidote, muscovite, and biotite as main heavy minerals.

These mineralogical features would suggest that Buwekula Shallow had a different parent material than the other upland soils of the catena, the former having a varied mineral assemblage and the latter a poor one. But the geological evidence indicates that both are derived from granite. The solution to this problem lies in the fact that the soils are not derived directly from granite but from weathered granite residue left after a former cycle of weathering. Buwekula Shallow is formed on fresh or only slightly pre-weathered granite, whereas Buwekula Brown and Red are formed on the residue left after prolonged earlier weathering. The mineralogical evidence for a former cycle of weathering is thus in agreement with the postulated geomorphic history of the area.

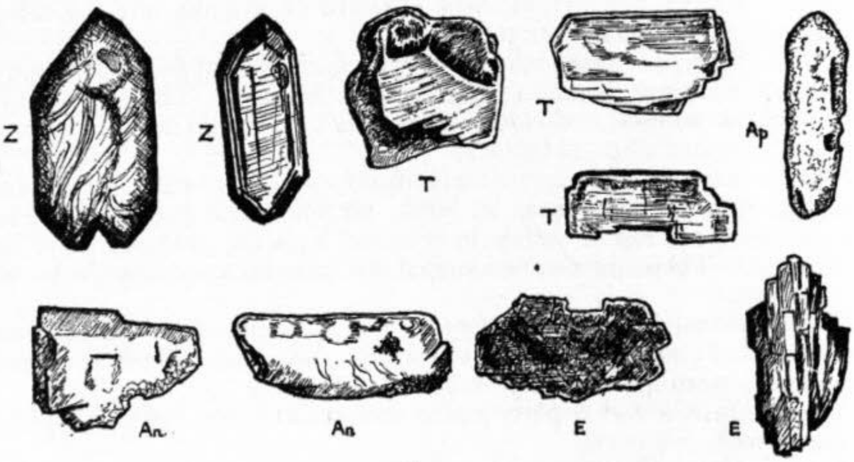

FIG. 5.

The minerals present in the alluvial associates show that the alluvium was derived locally, and the scarcity of weatherable heavy minerals indicates that the pre-weathered rock, rather than fresh rock, made the largest contribution. The abundance of opaque heavy minerals other than magnetite is due to alluvial concentration of ilmenite, and has no pedological significance.

Magnetite shows rather surprising weatherability, being present in quite large amounts in Buwekula Shallow, but in small quantities in the other associates.

Zircon and tourmaline, two extremely resistant minerals, persist throughout the catena in all series and all horizons.

To summarize, the mineralogical evidence indicates that there were three parent materials concerned in the formation of the Buwekula catena. Buwekula Shallow is derived from fresh or slightly pre-weathered granite, Buwekula Red and Brown are derived from intensely pre-weathered granite, and Buwekula Yellow-Brown and Grey are formed on alluvium derived from pre-weathered granite.

When each soil series is considered in turn, there is some mineralogical evidence for weathering within the profile, that is pedological weathering in the present cycle.

In all profiles except Buwekula Grey there is depletion of feldspar towards the top of the profile. This is well marked in Buwekula Shallow; Buwekula Red, having very little feldspar anyway, does not show this so well. The deep subsoil of Buwekula Red and Brown also show depletion, but the significance of this is not known. Buwekula Grey provides no

TABLE 3

Mineral Analysis

Depth (in.)	Relative amount of heavy minerals	% magnetite in heavy fraction	% other opaque minerals after removal of magnetite	% feld-spar in light fraction	Main non-opaque heavy minerals	Accessory non-opaque heavy minerals
Buwekula Shallow						
0–3	2	50	50	56	Z, T, E	M
–10	2	50	40	45	Z, T, E, M	..
–18	5	20	50	75	Z, T, E, M	..
–36	3	50	70	72	Z, T, E, M, B	R
–60	5	40	70	70	Z, T, E, M, B	R
–72	5	60	60	75	Z, T, E, M, B	
Buwekula Red						
0–3	10	5	50	0	Z, T	M, E, R
–8	5	5	50	0	Z, T	M
–18	5	10	50	1	Z, T	A, E
–40	5	10	50	1	Z, T	E
–60	3	20	50	1	Z, T	M
–72	6	10	90	0	Z, T	M
Buwekula Brown						
0–3	50	5	30	0	Z, T	M, At, S
–8	50	5	30	0	Z, T	M, At, S
–20	5	5	30	6	Z, T	A, E
–36	3	5	80	10	Z, T	R, A
–60	2	5	70	6	Z, T	A
–72	6	3	60	1	Z, T	M
Buwekula Yellow-Brown						
0–3	3	5	60	5	Z, T	R
–8	4	10	80	4	Z, T	A, M
–18	3	3	80	5	Z, T	A, E
–36	2	3	80	12	Z, T	M
–60	1	3	80	10	Z, T	A, M
–72	4	20	70	14	Z, T	A, R
Buwekula Grey						
0–3	2	1	80	10	Z, T	R
–8	1	0	90	12	Z, T	..
–18	1	0	80	6	Z, T	..

Z, Zircon; T, Tourmaline; E, Epidote; M, Muscovite; B, Biotite; R, Rutile; A, Andalusite; S, Sphene; At, Anatase.

mineralogical evidence for weathering *in situ*, presumably because there has been insufficient time for appreciable weathering since deposition.

Magnetite provides similar evidence of weathering within the profile in some cases. Removal of feldspar by weathering should cause a corresponding increase in the relative amount of heavy minerals if the latter are not weathered. This increase is very marked in Buwekula Red and Brown. Buwekula Shallow does not show this trend because some of the heavy minerals are weathered out at the same time.

Buwekula Shallow demonstrates a very nice sequence of weathering in the non-opaque heavy minerals. Biotite is the first mineral to go, and then muscovite. Epidote persists to the surface but would be the next mineral to go, and is absent in the more weathered associates.

The mineralogical evidence shows plainly that the soils are sedentary and not transported. Drift from the fresh rock on to Buwekula Shallow would increase the proportion of weatherable minerals in the upper layers. In fact there is a decrease in weatherable minerals in the topsoil. Drift from Buwekula Shallow on to Buwekula Red or Brown would contain a high proportion of feldspar. In fact there is no feldspar in the topsoils of Buwekula Red and Brown.

Minor heavy minerals show little of importance except that muscovite and epidote, common in Buwekula Shallow, occur as occasional grains in many of the other soils.

Pedology

From the field and laboratory data presented it is possible to come to several conclusions regarding the origin of the soils and the processes which gave rise to them. Each component of the Buwekula catena will now be discussed in turn.

Buwekula Shallow. The most important factor in the pedogenesis of this profile is the nature of the parent material. In the light of its geomorphic setting it seems probable that the parent material was only slightly weathered rock situated in the zone just above the basal surface of weathering in a previous cycle. This has subsequently been exposed by erosion to the present land surface and the present cycle of weathering has caused further changes. This second weathering is reflected in the mineralogical analyses.

Due to its closeness to the basal surface of weathering Buwekula Shallow usually occurs in the vicinity of rock outcrops often on hill-tops and upper slopes. The bare rocks contain many cracks and fissures and act as water-collecting surfaces. Rainwater penetrates the rocks and often emerges at their bases in the form of springs. The soils immediately below are thus subjected to rapid lateral drainage and consequent eluviation. This accounts for a high content of residual quartz gravel in the upper horizons of Buwekula Shallow.

Buwekula Red. This soil differs from Buwekula Shallow in the degree of weathering, which can be explained by a considerable difference in the type of parent material. The parent rock is no longer a limiting factor in the formation of Buwekula Red, where an almost complete decomposition of primary minerals, mobilization of iron, and the formation of the mottled and semi-indurated horizon indicate prolonged and thorough weathering. The iron concretions in the 40–60-in. layer are irregular in shape and of dull brown colour, closely resembling cemented clay fragments. In the 18–40-in. horizon they become darker brown, somewhat polished, and semi-rounded. This progressive change in shape and appearance of the concretions has been observed in other parts of the tropics, particularly West Africa (Vine, 1949; Nye, 1955). Nye recognizes a range of maturity in such concretions and suggests that their formation and subsequent destruction is a contemporary process. This is quite evident in Buwekula Red though the intensity of this process is much lower than in some other soils, most likely due to a low content of ferromagnesian minerals in the parent granite and the consequent limited supply of iron.

With the present arrangement and appearance of the soil horizons in Buwekula Red its genesis may now be postulated. A thorough decomposition to a considerable depth appears to have taken place in a previous cycle of weathering. After a period of erosion formed the present valleys, pre-weathered rock remained on the mid-slopes. In the present cycle there are further changes which are truly pedological.

Intense leaching is reflected in low pH values throughout the solum.* The loss of clay by eluviation from the upper part of the profile induces a condition of relatively rapid internal drainage there whilst the underlying clayey layers are only slowly permeable. Due to the steepness of slopes downslope movement of water is just as important as down-profile movement. This prevents the formation of a true perched water table above the slowly permeable horizon although the latter becomes completely saturated in the wet season. Therefore, the precipitation of iron in the lower part of the profile and the consequent formation of the mottled and semi-indurated horizon takes place seasonally under alternate wetting and drying conditions.

Although there is no mineralogical evidence for hill creep, it is quite evident that on such steep slopes and under such a rainfall there must be some downslope eluviation of the finer soil fraction at least and the mechanical analyses support this. As indicated by a high content of quartz sand in the alluvial associates the upper eluviated horizons of Buwekula Red must be gradually removed by erosion enabling rain-water to penetrate more effectively into the lower horizons which are subjected to the same process of clay eluviation. However, the process of iron movement and its precipitation is taking place all the time and although the mottled subsoil seems to be gradually destroyed from above, it may develop downwards by encroaching on the underlying deeply weathered soil substratum. Under natural conditions the mottled subsoil is never exposed to the surface but always follows the slope gradient, at a certain depth.

The iron concretions formed at depth are never found in the surface layers of this soil and it is possible that with the lowering of the A_1 horizon they are redissolved, most likely under the influence of organic compounds derived from humus (Bremner *et al.*, 1946; Bloomfield, 1954).

It may, therefore, be suggested that the profile is in equilibrium with the present environment and that the development of all its horizons is keeping pace with all the processes responsible for their removal. In

* Other samples of Buwekula Red show even greater acidity, with pH of the top-soil often below 5.

other words the profile is lowered as a whole and its morphology is not affected.

Buwekula Brown. This series differs from Buwekula Red in texture and colour. A higher content of quartz gravel in its upper layers indicates a more intensive process of clay eluviation. The change of colour from red to brown and the associated dull coloured mottles in the indurated horizon are not caused by impedence of drainage such as occurs in waterlogged depressions. Ground water is moving laterally at much the same rate as that in Buwekula Red, but owing to the lower topographic site a lot more water supplied from higher hill sites passes through this profile. This process is repeated every rainy season and as a result of it the lower horizons of Buwekula Brown remain moist longer after the rains than those of the higher situated soils, though the upper light textured part of the profile is drained rather quickly. Partial hydration of the iron compounds is, therefore, a more lasting process in Buwekula Brown.

Buwekula Brown tends to develop more iron concretions than Buwekula Red. The difference in amount is not great but nevertheless significant, and it may be explained by lateral movement of iron solutions and their precipitation in the lower catenary sites (Greene, 1947).

Despite the differences in profile morphology described above, Buwekula Brown is very similar to Buwekula Red in the arrangement of its main horizons and parent material, suggesting a common genesis. This series originated in the same way as Buwekula Red but on a lower topographic site. Owing to its low position on the pediment Buwekula Brown is subject to excessive lateral run-off which originates on higher parts of the hill and causes considerable eluviation.

The alluvial associates. As shown in Fig. 3 colluvial or hillwash deposits found in other catenas are virtually absent here. This is due to a relatively steep relief under which the erosion products are washed out or moved by creep straight on to the valley bottom. Subsequently they are carried away by running water in the rainy season, during which the activities of streams and rivers rise out of proportion to their sluggish movement in the dry season. As a result of these erosional processes Buwekula Brown passes abruptly into the alluvial soils of valley slopes and bottoms.

The two valley series, though originally derived from weathering and erosion of similar granitic rocks, represent a separate genetic group of soils closely related to each other. Both these series have developed from alluvial deposits which are distinguished by their relative age as reflected by their present topographic position. Buwekula Yellow-Brown was originally formed in the valley bottom where the grey associate now occurs. Owing to subsequent downward cutting of the stream the upper layers of the grey associate emerged beyond the reach of the ground water. The resulting improved drainage conditions and aeration have caused the change of colour from grey to yellow-brown in the upper soil layers and the formation of what may be referred to as the colour B horizon between 18 and 36 in. Although this horizon shows no signs of clay illuviation—due to extremely low clay content in the profile—and no structure, it differs in colour from both the A_1 and the C horizons. Furthermore, it is derived from the C horizon by improved drainage and aeration.

The C horizon proper, which occurs from 18 in. downwards in Buwekula Grey and from 60 in. downwards in Buwekula Yellow-Brown, is identical in both series. By virtue of its grey colour, induced by intense reduction resulting from more or less permanently impeded drainage conditions, this horizon remains under the influence of the gleying process and may be termed the gleyed C horizon. The term 'gleying' is used here in a wider sense and refers to 'a specific set of soil-water characteristics' (Clarke, 1941, p. 61), rather than to the horizon definition. In the alluvial associates the gleying process affects the parent material represented by the C horizon, but with the subsequent evolution of the soil profile and its transformation from Buwekula Grey into Buwekula Yellow-Brown the intensity of gleying is gradually reduced until it becomes of little or no importance in the B horizon of Buwekula Yellow-Brown.

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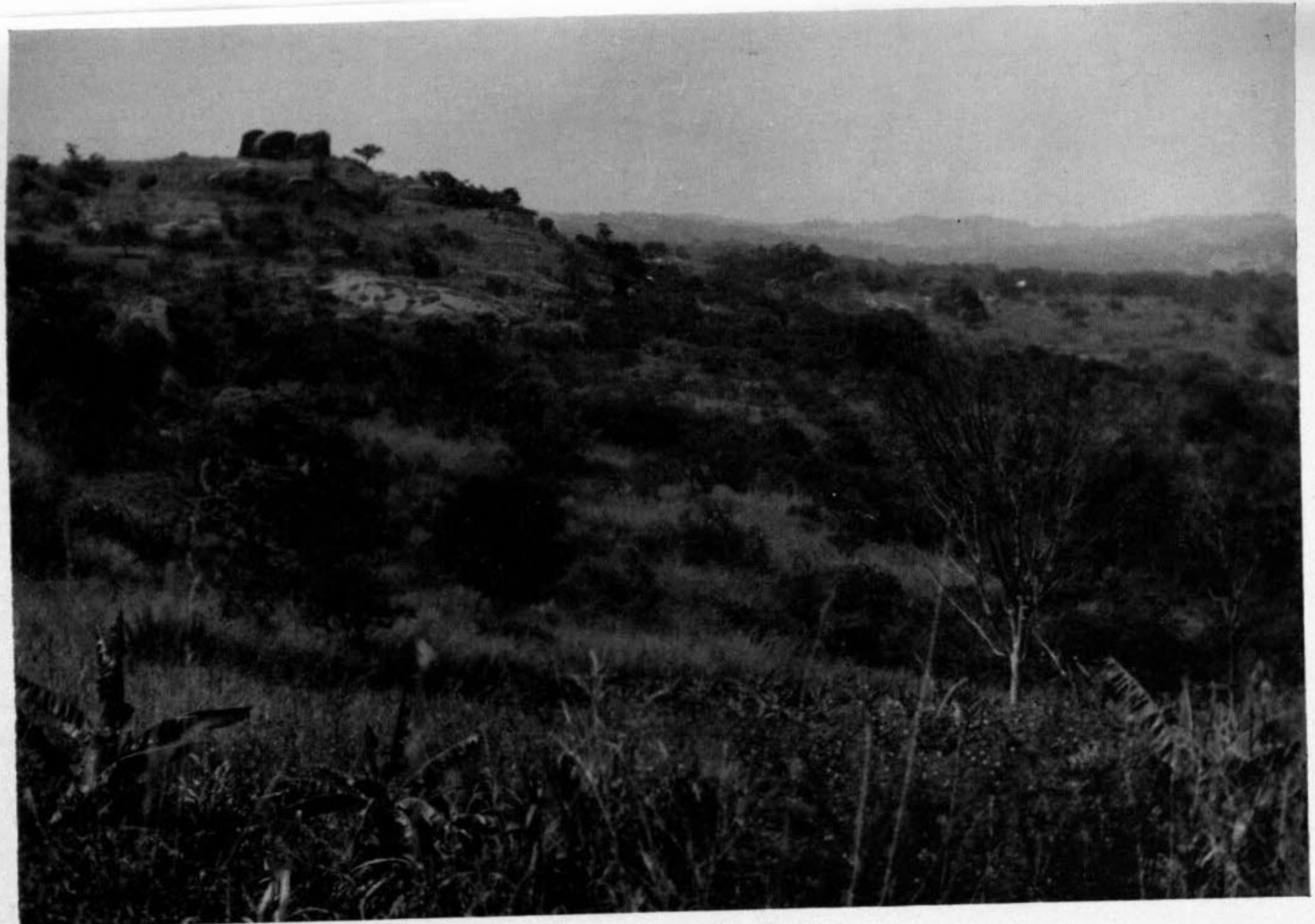

General appearance of the country.

S. A. RADWANSKI *and* C. D. OLLIER—PLATE I

A sharp junction between fresh and weathered rock 'Basal surface of weathering'.

S. A. RADWANSKI *and* C. D. OLLIER—PLATE II

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