# Laterite and bauxite profiles of West Africa as an index of rhythmical climatic variations in the Tropical Belt : with an appendix on the chief factors involved in the formation, and the preservation, of laterite and bauxite

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ECLOGAE GEOLOGICAE HELVETIAE

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# Laterite and Bauxite Profiles of West Africa as an Index of Rhythmical Climatic Variations in the Tropical Belt[1])

## With an appendix on the chief factors involved in the formation, and the preservation, of laterite and bauxite

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With 3 figures and 2 tables

## Summary

Studies of lateritic and bauxitic deposits made in Ghana and in western Senegal have revealed that the same sequence of events is responsible in each case for their formation. This sequence has three characteristic stages:

(a) Physical disintegration of the bed rock, leading to the formation of a stone layer.

(b) Chemical decomposition of the stone layer and the underlying bed rock, accompanied normally by accumulation of a sandy horizon above the stone layer.

(c) Eluviation and partial erosion of the sandy horizon, the stone layer, and the rotten portion of the bed rock, accompanied by cementation of the remainder by ferruginous or aluminous matter, leading to the formation of a crust.

Stage (a) represents a time of arid climatic conditions, stage (b) a time of warm humid conditions, and stage (c) a period of desiccation. The sequence therefore corresponds to a climatic cycle.

A number of these cycles have been found to follow one another rhythmically, two in the Eocene bauxites, and three others in the Quaternary lateritic profiles.

## Introduction

It is now generally accepted that the iron- and aluminium-rich formations known respectively as 'laterite' and 'bauxite' are two varieties of terrestrial residual deposit formed by weathering processes in the tropical belt. Various definitions have, however, been given to these formations by different workers. Some have stressed differences in composition or structure, others differences in the parent rock, and still others differences in details of their mode of formation. In this paper they are considered on the basis of composition, which is in keeping with the common usage of these terms in West Africa. Thus 'bauxite' is applied

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[1]) This paper is a revised and enlarged version of a communication delivered at the XXth International Geological Congress, Mexico City, September, 1956. Only the abstract of the original communication has been published in the proceedings of the congress.

to residual deposits rich in aluminium and with low silicon and low to moderate iron contents, and 'laterite' to markedly ferruginous and normally quartz-rich weathering products. The condition usually postulated for both bauxite and laterite, that the aluminium be present predominantly as hydrated oxide, is fulfilled only by some of the cases described here. The chemical and mineralogical characters of bauxites and laterites are, however, hardly dealt with in this paper where the main emphasis is on megascopic features.

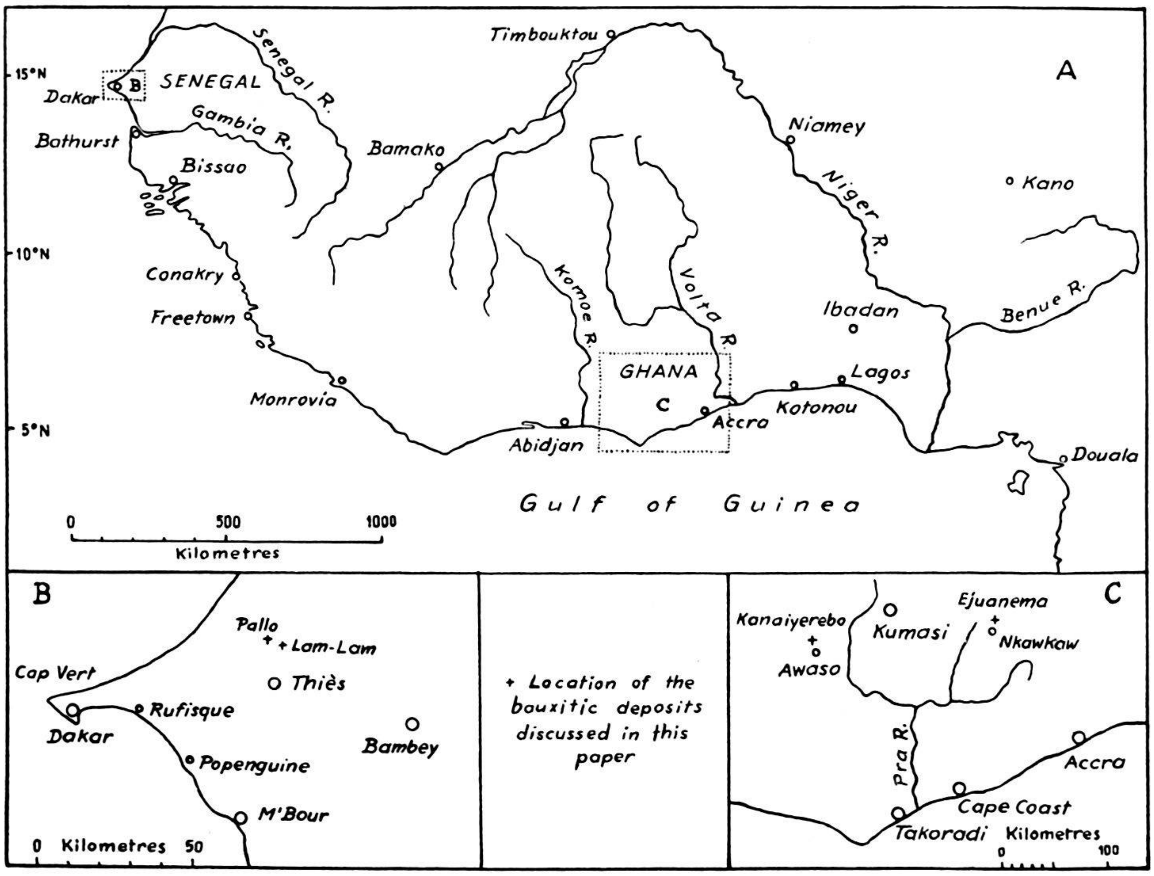

Fig. 1. Sketch maps of West Africa (A), of western Senegal (B), and southern Ghana (C).

The writer's studies of West African lateritic and bauxitic formations were principally made in Ghana, i. e. in the central portion of West Africa between 5° and 11° N latitude. In order to test the validity of his conclusions, the writer also visited western Senegal, i. e. the westernmost portion of West Africa at about 15° N latitude (see Fig. 1, map A). In the latter region he was accompanied, and led, by Dr. F. Tessier of the University of Dakar. In both these countries a lateritic and a bauxitic formation can be distinguished. The former consists of a nearly continuous superficial mantle and is comparatively young. The latter is preserved as remnants that underlie either the young lateritic blanket or locally pre-lateritic continental deposits; it is, therefore, comparatively old. The profile and genesis of these two formations will now be discussed, using as evidence only those compositional, structural, and textural features that were observed in the field and in hand specimens.

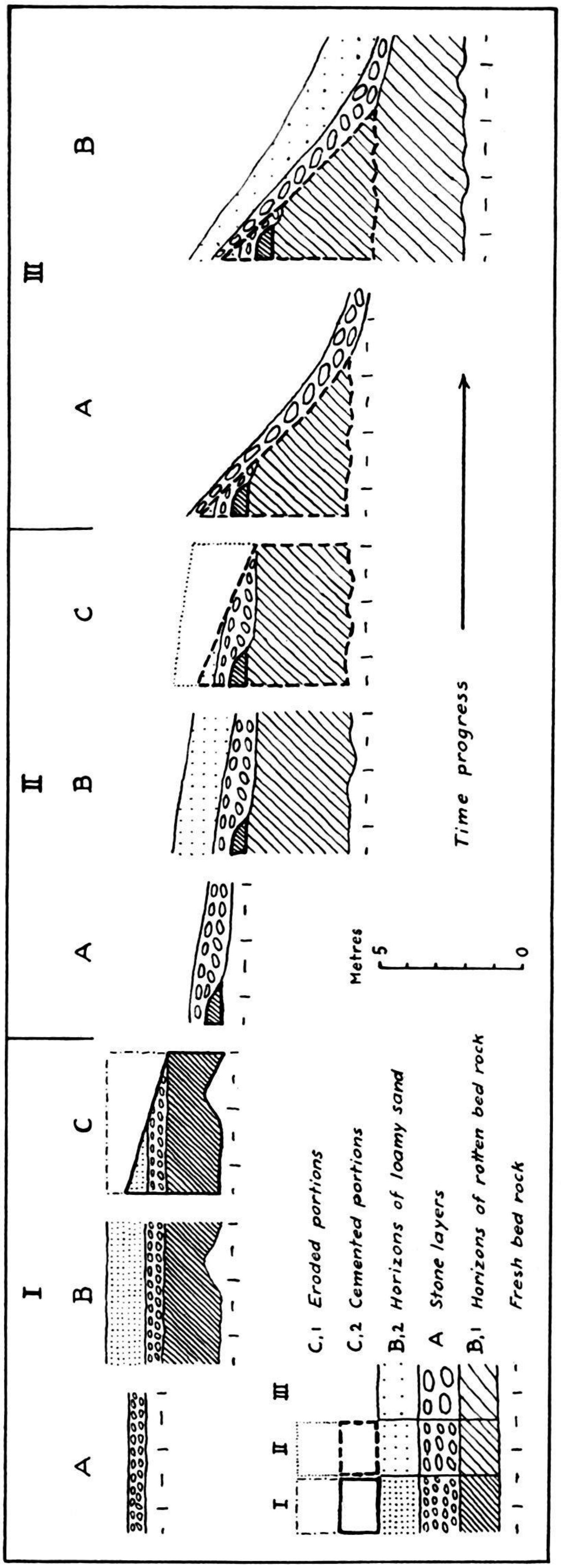

Fig. 2. Development of the young lateritic mantle in Ghana. I, II, III = Cycles of lateritization, A; B, 1; B, 2; C, 1; C, 2 = Stages of development in the cycles (see text). The thicknesses shown are roughly estimated average values.

## The young lateritic mantle

In an earlier paper (W. Brückner, 1955), the writer dealt with the profile of the young lateritic mantle in Ghana and its cyclic development under changing climatic conditions. Subsequent studies of the lateritic mantle profile in western Senegal have shown that no fundamental differences from the Ghana profile exist in that country. It suffices here, therefore, to give a synopsis of the results obtained in Ghana, as they seem to be generally applicable in West Africa. Readers interested in the details are referred to the earlier paper.

Figure 2, which is a schematized reconstruction based on the study of a large number of profiles, shows the essential steps in the development of the young lateritic mantle up to its present-day state (see also Table 1). This story comprises three 'cycles of lateritization', two completed and one still in progress. The sequence of events in any of these cycles can be subdivided into three fundamentally different stages, as follows:

Stage A: Physical disintegration of any formation outcropping at the land surface, accompanied by removal of the fine-grained particles and concentration of the coarser ones, results in the formation of a stone layer.

Stage B: Two processes take place simultaneously:

1. Intensive chemical decomposition affects the stone layer and the formations underlying it, so that a layer of rotten material is formed that grows downwards, while
2. a sandy to loamy layer is built-up mechanically above the stone layer. Initially this is probably due to wind transport, but subsequently the activity of soil animals is responsible. The termites in particular carry sand and clay particles from the rotting layer below to the surface where they later become spread out by rainwash.

Stage C: Here again, two processes occur at the same time:

1. Portions of the layers formed during the stages A and B are removed mechanically by eluviation and erosion, while
2. the remainder becomes cemented chemically, chiefly by the iron oxides present²). Initially, concretions (and locally hardpans) form under the surface, then a partial to complete impregnation takes place, the top portion of the profile becoming a hard ferruginous crust, which may include pisolites formed at the very surface. With increasing cementation (C, 2) the eluviation and erosion (C, 1) become less and less effective.

Since the processes responsible for each of these stages give way gradually to those of the following stage, no sharp limits exist between the stages.

The various layers and other significant features of the young lateritic mantle that provide evidence for its cyclic development are listed in Table 1, quoting the names and numbers introduced in the writer's earlier paper³) (W. BRÜCKNER, 1955, pp. 308–316).

It is evident that climatic changes must be invoked in order to explain the successive formation of such different layers and features during any one cycle of lateritization. The following climatic interpretation was given:

Stage A: The stone layers are desert pavements that formed during arid periods. This conclusion is supported by the discovery of wind-polish on many of the stone layer constituents.

Stage B: The layers of rotten rock (B, 1) indicate periods of warm humid climate (the only type of climate that allows such intensive chemical weathering).

Humidity sufficient to support a closed forest (or thicket) cover is also required for the growth of the sandy to loamy layers (B, 2) as it can be seen today that the youngest loamy sand is undergoing removal wherever the forest (or thicket) cover has recently disappeared.

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²) Siliceous and aluminous matter can also take part in this cementation; the migration of these latter substances in the lateritic profiles has, however, not yet been studied in detail.

³) Since this earlier paper was written, some additional information has been gained, particularly on the first-cycle laterite whose relics can now be interpreted with more certainty than two years ago. The only, and possibly arbitrary, change of interpretation introduced here concerns the ferruginous concretions of the second and third cycles, which are now placed in stage C instead of stage B.

Stage C: The fact just mentioned is evidence that the eluviation and erosion (C, 1) were a consequence of the desiccation that caused the forests (or thickets) to dwindle. The same desiccation seems to have brought about the ferruginous cementation (C, 2) by alternating small-scale solution and precipitation[4]).

Table 1: Main features of the young lateritic mantle of Ghana, in chronological order of development (oldest features at bottom; features 1 and 2 of stages B and C respectively have developed more or less simultaneously)

| Cycle | Stage | | Features |
|---|---|---|---|
| III | C*) | 2 | 'Soft limonitic concretions' and occasional ferruginous encrustations |
| | | 1 | 'Top layer (9), sandy type' (= eluviated 'Upper loamy sand (8)') |
| | B | 2 | 'Upper loamy sand (8)' |
| | | 1 | 'Lower layer of rotten rock (2a)' |
| | A | | 'Upper stone layer (7)' |
| II | C | 2 | 'Limonitic crust (6)' with 'rootlike extensions' and 'limonitic pisolites';<br>'Hard limonitic concretions' |
| | | 1 | 'Lower stone layer (5)' (= eluviated horizons (4), (3), and (2b)) |
| | B | 2 | 'Lower loamy sand (4)' |
| | | 1 | 'Upper layer of rotten rock (2b)' |
| | A | | 'Breccia (3)' |
| I | C | 2 | Thorough ferruginization of the material representing stages B and A of this cycle; 'Compact limonite free of inclusions' in 'stringers' in situ and in loose pieces**) |
| | | 1 | No evidence preserved |
| | B | 2 | 'Evenly distributed grains of quartz sand' included in pieces of 'Compact limonite' |
| | | 1 | Rotten bed rock material included in 'stringers of compact limonite' and in pieces derived therefrom |
| | A | | 'Rock and vein quartz fragments' included in pieces of 'Compact limonite' |

*) Initial phase only.

**) The inclusion-free material seems to have been the very 'epidermis' of the first-cycle laterite crust. In Ghana it has been found only in the southern part of the country, but it has furthermore been observed in the southern Ivory Coast and on the Conakry Peninsula in French Guinea.

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[4]) This latter process, although greatly favoured by semi-arid conditions, is not entirely restricted to them. It can likewise occur under humid and under arid climates, provided that the concentration of iron oxides in the uppermost mantle layers has already been high previously, and that the latter are temporarily drying out, or getting wetted, respectively.

Lateritization as observed in the young mantle rock of West Africa is, therefore, not a process that takes place under one and the same tropical or equatorial climate. It requires a specific sequence of climatic changes comprising (A) an arid stage, (B) a warm humid stage, and (C) a predominantly semi-arid stage of desiccation. Of these three stages, the latter two are essential for the formation of laterite (deep chemical rotting followed by ferruginous cementation[5]); the first stage has a purely preparatory significance (planation and freshening-up of the land surface).

The succession of three major cycles of lateritization in the young mantle rock of West Africa is thus evidence for three major climatic cycles[6] in this part of the world. These climatic changes most likely correspond to the alternations of major pluvials and interpluvials known from Central and Eastern Africa which have, in turn, been correlated with the major glacial and interglacial periods of the northern hemisphere. This seems justification for placing the whole of the young lateritic mantle of West Africa in the Quaternary period (see also W. BRÜCKNER, 1955, pp. 324–326).

## The bauxite remnants

### Ghana

The bauxite remnants of Ghana[7] (see W. G. G. COOPER, 1936) occur on the summits of flat-topped, more or less isolated hills, several hundred metres higher than the general level of the land surface. All occurrences are situated in the forest-covered south-western part of the country, and they are, therefore, poorly exposed and hardly accessible. At two places, however, where the ore has been quarried, the bauxite profile can be studied easily (see Fig. 1, map C). The first of these is on 'Kanaiyerebo Hill', a summit of the 'Affoh' or 'Sefwi Bekwai' group of hills (about 550 metres above sea level). It lies north of the town of Awaso, about 165 kilometres NNW of Takoradi, and about 90 kilometres SW of Kumasi. The second quarry is on 'Mount Ejuanema', a remarkable summit on the southern edge of the 'Kwahu' plateau (about 850 metres above sea level). This hill lies north of the town of Nkawkaw, about 130 kilometres NW of Accra, and about 100 kilometres E of Kumasi.

On Kanaiyerebo Hill (see Fig. 3) the bauxite deposit overlies steeply dipping phyllites and slates, including manganiferous layers, belonging to the Birrimian

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[5] Although a sufficient amount of conclusive data is not yet available, the writer believes that the removal of free silica as well as the break-down of hydrated aluminium silicates to hydrated oxides plus colloidal silica, a process representing for most writers a very essential step of lateritization, does not normally take place during the humid stage, but only, or at least predominantly, during the subsequent stage of desiccation. If this is true, the duration of stage C determines the degree of desilicification.

[6] Subordinate climatic variations have certainly also occurred; investigations into this problem are being carried out at present, and they already reveal that the youngest laterite cycle as defined in this and the writer's earlier paper comprises two or three sub-cycles, and that the horizons (7) to (9) attributed in Table 1 to the whole cycle represent in many places only a sub-cycle.

[7] Unlike the 'special' bauxites of Senegal, which are discussed below, the Ghana bauxites are of the 'ordinary' kind, their aluminium being present as hydrated oxide.

series (Pre-Cambrian), and in the quarry studied it has an average thickness of 15–20 metres. The greater part of the deposit consists of a moderately hard and porous, yellow to red-coloured mass of bauxite in which the structure of the parent rock has been preserved with many of its details. Below it is a zone of soft whitish highly weathered rock, so-called 'lithomarge', which according to W. G. G. COOPER (1936, p. 14) has a "composition... similar to that of kaolin". Locally large ,pinnacles' of this lithomarge extend upwards into the bauxitized mass, and portions of it have a nearly lenticular character. The fresh bed rock is not exposed.

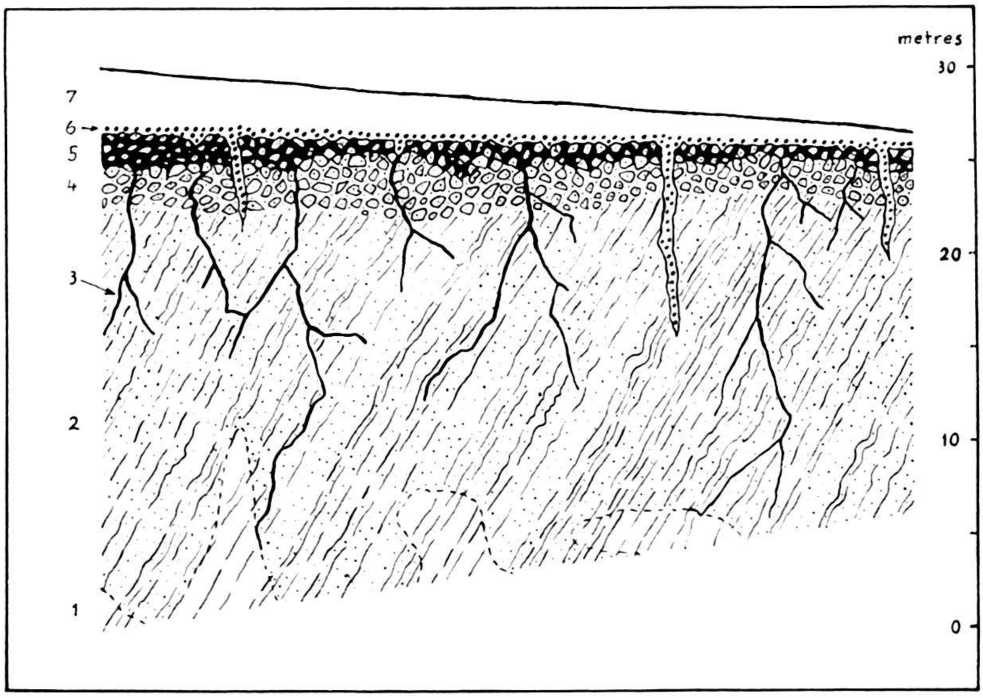

Fig. 3. Schematized profile of the bauxite quarry on Kanaiyerebo Hill.

1: Altered bed rock, kaolinitic ('lithomarge'); 2: Altered bed rock, bauxitic; 3: Ferruginized bands in 2 and 4; 4: Breccious crust, lower part with bauxitic cement; 5: Breccious crust, upper part with ferruginous cement; 6: Rubble layer; 7: Red sandy loam.

Cyclic interpretation: Eocene: Bulk of fragments in 4 = older bauxite cycle, 2 and cement of 4 = younger bauxite cycle; Quaternary: 3 = relics of first (oldest) laterite cycle, 5 = second laterite cycle, 1, 6, and 7 = third (youngest) laterite cycle.

Above the main bauxite mass is a layer about 4 metres thick which can be distinguished from it by its more massive, and breccious, crusty character. The lower part of this layer, which is the thicker portion, is composed of bauxitic and rare ferruginous fragments embedded in a bauxite matrix; the composition of this part will be discussed in more detail below.

The upper part of the crusty layer is firmly but irregularly joined to the lower bauxite part and consists predominantly of limonite-overcoated fragments derived from it; fragments of vein quartz and quartz sand from a non-bauxitized source are also present, and all constituents are cemented together by hard limonitic matter in which irregular-shaped cavities are frequent. This ferruginous top crust is overlain by loose rubble some decimetres thick that has been formed by partial break-down of the top crust. Similar material also fills some deep crevices in the bauxite, the walls of which are limonite-coated. Finally, above the rubble, there is a red sandy loam with a thickness of up to 3 metres.

Irregular black bands, which may be a few decimetres thick, occur predominantly in the upper part of the profile, although not above the lower, bauxitic part of the breccious crust; they represent fully ferruginized portions of the bauxite.

The formations mentioned in the last two paragraphs can be identified as parts of the Quaternary lateritic mantle (see Table 1): The red sandy loam is the 'Upper loamy sand (8)', and the rubbly material above the bauxite and in its crevices is the 'Upper stone layer (7)' of the youngest laterite cycle. The limonite-cemented top portion of the crusty layer below the rubble represents the second-cycle laterite crust (6), and the ferruginized bands in the bauxite are 'stringers of compact limonite' formed during the first cycle. The bauxite deposit on Kanaiyerebo Hill is, therefore, older than the lateritic mantle.

The bauxite on Mount Ejuanema (see also A. E. Kitson, 1925) overlies dark grey, nearly horizontally-bedded shales which belong to the upper part of the Voltaian series (Ordovician ?). The deposit varies in thickness between about 6 and 9 metres. At the site of the quarry the higher figure applies as some 6 metres of bauxite are exposed in the quarry face and the remainder in a shaft sunk into its floor.

The whole deposit is more or less strongly disintegrated into bauxite fragments ranging from large massive blocks to fine rubble. The former predominate in the upper and the latter in the lower part of the profile. The fragments are generally hard, angular to somewhat rounded, and have irregular surfaces, that are covered in the upper part of the profile by hard, layered, ferruginous coatings. The interstices between the fragments are filled with unconsolidated red sandy loam, of similar character to the material composing a 'soil' layer which overlies the bauxite to a thickness at the quarry site of about 60 centimetres. The deposit in its present state can be correlated with the young lateritic mantle as follows: The red 'soil' layer represents the 'Upper loamy sand (8)', and the disintegrated bauxite mass below it the 'Upper stone layer (7)'; its extraordinary thickness at this place has resulted from the increased exposure to disintegration of the narrow summit. The ferruginous coatings on the bauxitic fragments are comparable with those observed in the limonite-cemented top-crust of the Kanaiyerebo Hill profile and can, therefore, be interpreted as remnants of the 'Limonitic crust (6)' of the second laterite cycle. The bauxite of all the fragments mentioned above was in existence before it became disintegrated and incorporated in the lateritic horizons mentioned, and it therefore seems reasonable to assume that the original age of this bauxite deposit is pre-lateritic and the same as that of the bauxite of Kanaiyerebo Hill, although no definite traces of the first laterite cycle have so far been discovered here (see also p. 250).

The examination of numerous bauxite specimens from Mount Ejuanema has revealed that the young disintegration has caused only moderate disorder and that the upper portion of the original bauxite profile can still be reconstructed satisfactorily. All specimens must have belonged to a breccious mass composed of bauxitic (and some ferruginous) fragments or bodies in a bauxitic matrix. This breccia can be correlated with the crusty bauxitic breccia forming the upper part of the Kanaiyerebo profile. A zone of bauxitized bed rock in situ has not been found on Mount Ejuanema. In the bottom part of the test shaft mentioned above, fresh, or nearly fresh, shale is overlain along a clear boundary by some fractured and more or less transported highly rotten shale which latter material grades upwards directly into the disintegrated breccious bauxite. It is, however, probable that originally a zone of bauxitized shale in situ was present and that its absence in the quarry profile is a secondary feature due to the material from the upper breccious part of the bauxite having spread downslope faster than that of the lower part – thus overlapping it – when the bauxite mass became disintegrated in young lateritic times.

The similarity between the bauxite profile of Kanaiyerebo Hill and that of Mount Ejuanema becomes still more obvious when the composition of the bauxitic breccia is studied in detail.

The matrix of this horizon is partly hard and compact, but in part also of spongy to cellular texture, particularly on Kanaiyerebo Hill where its porosity is strongly reminiscent of that in the bauxitized bed rock below. When fresh, the matrix has a medium brown-red colour, but it becomes grey to whitish or yellow towards the larger pores as a result of secondary weathering. Towards the top of the profile the matrix becomes dark brown due to an increasing iron content.

The constituents included in this matrix have diameters ranging from fractions of a millimetre to several centimetres, and they possess angular to round shapes. Several kinds of constituent can be distinguished. There are fragments composed of very fine-grained compact and hard matter with and without 'inclusions' (see below). They are accompanied by fragments of fully altered bed rock which are also hard and compact (various types of phyllite on Kanaiyerebo Hill, shale on Mount Ejuanema). Both these types of fragment normally are of bauxitic, i. e. predominantly aluminous, composition and characterized by a moderately dark, red or brown-red colour, although many of them (particularly on Mount Ejuanema) have whitish outer zones that are evidently bleached and which are better developed around fragments in the upper part of the profile than in the lower; many of the smaller fragments in the upper part have therefore lost their red cores entirely. The decolourization of these fragments is independent of the bleaching observed in the enclosing matrix. Towards the top of the profile there are in addition black-coloured ferruginous fragments which texturally are of the same type as the two kinds of bauxitic fragments just described. In a few of the specimens examined they are accompanied by well-layered ferruginous pisolites with diameters of up to several millimetres. Some of the latter have bauxitic cores while others have pale outermost shells. A few of the ferruginous and bauxitic fragments are covered by secondary coatings of bauxitic matter.

In addition to all these compact constituents with clearly defined boundaries rather porous fragments of bauxitized bed rock are frequent on Kanaiyerebo Hill, particularly in the lower part of the breccia. These fragments look like the bauxitized rock in situ below the breccia; they have less clear outlines than the compact constituents and seem to merge with the surrounding matrix and to be partly penetrated by it. This suggests that they were bauxitized at the same time as the matrix was formed, whereas the bauxitization of the compact constituents must have occurred previously.

The arrangement of the constituents within the matrix is variable. The predominant texture is that of a fine- to medium-grained breccia or breccious conglomerate, but portions where the texture is sandy to loamy or in which the matrix predominates are intercalated irregularly, particularly in the upper part of the profile.

It has already been stated that many of the bauxitic and ferruginous fragments of compact texture contain 'inclusions' in their fine-grained matrix. This is particularly a feature of the Mount Ejuanema material where the larger inclusions have been identified as fragments of altered shale[8]). Most of the smaller bits probably consist of the same material, although their smallness has not allowed an exact determination. Some of these 'included' fragments have secondary bauxitic coatings. Small bauxitic pisolites composed of several concentric layers, and fragments of such bodies also occur. These pisolites were observed more frequently in the upper part of the (Ejuanema) profile than in the lower. In some of the compact pieces with inclusions the texture is breccious, in others sandy to loamy. The compact pieces without visible inclusions seem to consist of matrix alone or of matrix cementing very fine-grained material. It appears therefore that the compact constituents of the bauxitic breccia are the fragments of an older crust of breccious to pisolitic texture.

## Senegal

In the region of Thiès, a town some 60 kilometres E of Dakar (see Fig. 1, map B), there are bauxitic deposits of unusual composition. In his thesis, F. TESSIER (1952, vol. 1) gave a detailed account of these deposits, and up-to-date summaries have also been published in the explanatory notes to the geological maps of the region (F. TESSIER, 1954 a, b).

The bauxitic deposits of Thiès have developed at the expense of a gently dipping sedimentary series of Lower Lutetian age that is composed of marls, argillaceous limestones, and particularly of calcium phosphates. This latter material is present in several forms, the most conspicuous of which are poorly consolidated white chalk-like masses and fairly hard nodules (coprolites?). The presence of this phosphate material has resulted in the bauxite deposits consisting of hydrated phosphates of aluminium[9]) instead of the oxides that characterize 'ordinary' bauxites.

F. TESSIER discovered that these aluminium phosphates actually constitute two different formations, both of which are known under the name of 'latéritoide phosphaté'. The first of them is restricted in its occurrence to the region directly underlain by the phosphate-rich facies of the Lower Lutetian series, as it has developed approximately in situ. The second formation consists of an unconsolidated breccious blanket that has formed from the first by partial disintegration and by gradual spreading of the fragments. It therefore covers a far wider area

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[8]) On Kanaiyerebo Hill several kinds of altered phyllite could be identified among these 'inclusions'.

[9]) According to L. CAPDECOMME (1953), the predominant minerals are augelite, crandallite, and an unidentified 'phosphate X'; wavellite and turquois occur as accessories.

than the first. The profile of the bauxite formation 'in situ' is thus now incomplete, and its top portion can only be reconstructed by means of a study of its fragments in the 'derived' formation. F. TESSIER has shown that both these formations are older than the young lateritic mantle[10]).

The 'latéritoide phosphaté' in situ is well exposed in some quarries at Pallo, about 14 kilometres N of Thiès (Fig. 1, map B), and additional information on it has become available from numerous test shafts that were dug throughout the region. Of these exposures, the writer has seen the Pallo quarries Nos. 1 and 4, and material brought up from two of the test shafts.

The fresh bed rock is usually separated from the overlying aluminium phosphates by a band of 'argiles grasses', an argillaceous layer of more or less disturbed structure that has been formed from the bed rock by decalcification.

The main mass of the primary 'latéritoide phosphaté' is white to light grey, poorly consolidated and of more or less disturbed texture. Large parts of it are reminiscent of chalky calcium phosphate beds with nodules and these parts seem to be only moderately disturbed. Other parts are breccious, with fragments that must have belonged to beds of marl or argillaceous limestone intermingled with whole or broken nodular bodies in a chalky groundmass. The upper part of the profile in the back of Pallo quarry No. 1 has a loamy aspect, a few small still recognizable fragments lying in a matrix that has lost its original character very widely by the processes of alteration. More or less corroded quartz grains were observed throughout the profile; they are rare in the lower part and somewhat more frequent in the upper.

Locally this main mass is overlain along an irregularly indented boundary by a breccia cemented by a fairly hard grey matrix. The constituents embedded in it are fragments of the underlying formation.

This description shows that the mass of primary 'latéritoide phosphaté' does not, in reality, contain any portion that represents, sensu stricto, altered bed rock in situ. It has suffered collapse and disintegration to a variable degree before attaining its present form. The expression 'in situ' must therefore be interpreted here liberally in the sense of 'comparatively little disturbed or reworked'.

The secondary 'latéritoide phosphaté', i. e. the breccious blanket that overlies the mass 'in situ', was studied mainly in the large quarry of Lam-Lam, about 12 kilometres NNE of Thiès (see Fig. 1, map B); additional observations of it were made at Pallo as well as at one of the smaller occurrences NE of Popenguine. This formation chiefly consists of blocks and smaller fragments that must originally have been part of a breccious crust. Its matrix is yellowish to brown, becoming darker in the upper part of the profile due to an increased iron content. Although the matrix is, in general, compact it contains many irregular pores and holes some of which are reminiscent of the rootlike holes in the 'Limonitic crust (6)' of the young lateritic mantle. The fragments included in this groundmass are hard and compact (apart from some small cavities due to leaching). Most of them

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[10]) In the quarry of Lam-Lam (see p. 252), a layer 4 to 6 metres thick of whitish, but irregularly iron-impregnated, loamy sand is still intercalated between the secondary 'latéritoide' and the Quaternary laterite crust.

are 'aluminous' and of grey, yellow, or brown colour, but some nearly black ferruginous fragments also occur. Both the aluminous and ferruginous fragments may have secondary coatings of predominantly aluminous substance. A fair number of these fragments contain 'inclusions' and look like bits derived from the breccia that was observed locally at the top of the latéritoide mass 'in situ'. The fragments without 'inclusions' seem to consist of the matrix of this breccia alone. It can therefore be concluded that the breccia that composes the blocks of the blanket of secondary 'latéritoide' includes the fragments of an older breccious crust.

The boundary between the fresh Lower Lutetian rocks and the primary 'latéritoide phosphaté', which is marked by the band of 'argiles grasses', is highly irregular. F. TESSIER has pointed out that in some of the shafts there is an alternation of altered and fresh material and he therefore concluded that periods of continental weathering and marine sedimentation alternated in the area during the Lower Lutetian. To the writer, however, it seems more likely that the alternation of fresh and altered material is due to strong irregularity of one and the same 'front of weathering'. This irregularity can be compared with the pinnacle-and-lens phenomena observed at the bottom of the Kanaiyerebo Hill bauxite deposit in Ghana (see p. 245), and it may have been accentuated by the development of karst phenomena in the limestone-bearing strata[11]). The continental alteration would then have begun after the deposition of the marine series, i. e. not before the end of the Lower Lutetian. The profile of the bauxitic deposits must have been fully developed towards the end of the Upper Lutetian or at the beginning of the Upper Eocene, as sediments of these ages already include fragments derived from the iron-rich top crust of the bauxite (see F. TESSIER's discussion of the profile in the quarry of Lam-Lam, 1945b).

When the reconstructed or original bauxite profile of Thiès in Senegal and those of Ghana are compared with one another it becomes evident that in spite of some differences the same fundamental features have developed in both countries: The fresh bed rock is overlain by a zone of altered bed rock with moderately to hardly disturbed texture. The lower, argillaceous, portion of this weathered mass is sharply separated from its upper bauxitized portion. This latter is overlain by a bauxitic breccious crust that chiefly consists of the fragments of a reworked, older, breccious bauxite crust. Both these crusts contain some ferruginized material. In view of these similarities it seems reasonable to assume that the bauxites of both countries were formed under the same circumstances and during the same period. In Senegal this has been determined as Middle to Upper Eocene.

## Cyclic development of the bauxite profiles

When the three bauxite profiles that have been described are compared with the profile of the young lateritic mantle their similarity becomes obvious. Both the bauxite and the laterite are made up of portions of altered bed rock in situ, parts of stone layer aspect, portions of sandy to loamy character, and crustlike parts with pisolites and other overcoated constituents. An analysis of the mutual

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[11]) Collapse due to limestone solution is probably also widely responsible for the disturbed character of the primary 'latéritoide phosphaté'.

Table 2: Sequence of events in the development of the Ghana and Senegal bauxites
(Oldest events at bottom; events 1 and 2 of stages B and C respectively have happened more or less simultaneously)

<table>
<tr><th>Cycle</th><th colspan="2">Stage</th><th>GHANA</th><th>SENEGAL</th></tr>
<tr><td rowspan="5">II</td><td rowspan="2">C</td><td>2</td><td colspan="2">'Porous' cementation of the stone layer (II, A) and the remnants of the sandy to loamy material (II, B, 2) by aluminous and some ferruginous matter (= younger bauxitic crust)<br>Growth of aluminous coatings on some constituents of the stone layer (II, A)</td></tr>
<tr><td>1</td><td>Removal of most of the sandy to loamy material (II, B, 2).</td><td>No evidence discovered.</td></tr>
<tr><td rowspan="2">B</td><td>2</td><td>Surficial accumulation of sandy to loamy material (as preserved locally in the younger bauxitic crust).</td><td>No evidence discovered.</td></tr>
<tr><td>1*)</td><td>Chemical alteration of the fresh bed rock below, and its fragments in, the stone layer (II, A). Leaching of iron oxides from the outer seams and shells of the stone layer constituents derived from the older crust (I, C, 2).</td><td>Chemical alteration of the bed rock below the stone layer (II, A) with formation of the main mass of primary 'latéritoide phosphaté'.</td></tr>
<tr><td>A</td><td></td><td colspan="2">Physical disintegration of the older ferruginous and aluminous crust (I, C, 2) and, on Kanaiyerebo Hill, part of the fresh bed rock below, with formation of a stone layer (preserved as fragments in the younger bauxitic crust). Removal by erosion of most of the ferruginous material</td></tr>
<tr><td rowspan="6">I</td><td rowspan="3">C</td><td rowspan="2">2**)</td><td colspan="2">'Compact' cementation of the profile so far developed; top portion ferruginous, remainder aluminous (= older bauxite crust).</td></tr>
<tr><td>Growth of ferruginous and aluminous pisolites and of aluminous coatings on some of the 'inclusions'</td><td></td></tr>
<tr><td>1</td><td>Removal of most of the sandy to loamy material (I, B, 2).</td><td>Partial removal of the 'loamy' layer (I, B, 2) and the material altered during stage I, B.</td></tr>
<tr><td rowspan="2">B</td><td>2</td><td>Surficial accumulation of sandy to loamy material (represented by the fine-grained 'inclusions' in the 'compact' fragments of the older bauxitic crust).</td><td>Surficial accumulation of the upper, 'loamy', part of the primary 'latéritoide phosphaté'.</td></tr>
<tr><td>1*)</td><td>Chemical alteration of the stone layer (I, A) and a portion of the underlying bed rock.</td><td>Chemical alteration of the 'breccious portions' (I, A), possibly also of a part of the bed rock below them.</td></tr>
<tr><td>A</td><td></td><td>Physical disintegration of the bed rock with formation of a stone layer (represented by the larger 'inclusions' in the 'compact' fragments of the older bauxitic crust).</td><td>Physical disintegration of the bed rock with formation of the breccious portions in the primary 'latéritoide phosphaté'.</td></tr>
</table>

*) See remark No. 1 on p. 252. **) See remark No. 2 on p. 252.

relations between these features in the bauxite profiles reveals that their development can be explained by two cycles of events, or climatic changes respectively, of the same kind as those responsible for the formation of the young lateritic mantle (see pp. 241–244). This cyclic interpretation is shown in Table 2 where the same stage symbols as those given previously for laterite development are used. The table is self-explanatory, but a few additional remarks need to be made.

(1) In Ghana the zone of chemically altered rock that developed during the older bauxite cycle (I, B, 1) apparently became entirely broken up during the formation of the stone layer of the younger cycle (II, A). It is thus only represented by the compact bauxitized rock fragments of this horizon. The alteration responsible for the large porous mass of bauxitized bed rock in situ on Kanaiyerebo Hill, and for the porous bauxitized rock fragments in the stone layer (II, A) took place during stage B, 1 of the younger cycle. In the case of the Senegal bauxites, the writer's limited observations do not allow him to distinguish sharply between the stone layer I, A and the rock masses with collapse structure that weathered during stages I, B and II, B. The bulk of the preserved rotten zone was probably formed during the younger cycle, like that of Kanaiyerebo Hill in Ghana.

Neither the Ghana 'lithomarge' nor the 'argiles grasses' of Senegal, which do not contain hydrated aluminium oxides or phosphates but ordinary siliceous clay minerals, have been entered in Table 2, as they have in the writer's opinion resulted from a process of weathering younger than the bauxite development above them, most likely during the youngest Quaternary laterite cycle.

(2) Pisolites and crust fragments of ferruginous and of bauxitic composition occur side by side among the constituents of the second cycle stone layer (II, A). In Table 2 their formation is attributed to stage I, C, 2. As the pisolites have formed at the very surface, – their shells being devoid of foreign material – and as the encrustation has also been a process of surface or near-surface origin, it seems, however, improbable that the ferruginous crustal portions and pisolites have originated strictly at the same time as the bauxitic ones. It is more likely that three substages have to be assumed in the formation of the crust I, C, 2, substages that corresponded to a subordinate climatic oscillation between semi-arid and arid:

Substage (a): Growth of ferruginous pisolites followed by ferruginous cementation (semi-arid);

Substage (b): Disintegration of the ferruginous crust and removal by erosion of most of the ferruginized material (arid);

Substage (c): Growth of aluminous pisolites and coatings, followed by aluminous cementation (semi-arid).

(3) The breccious blanket of the secondary 'latéritoide phosphaté' in Senegal is evidence of a stage of disintegration post the formation of the younger bauxite crust (II, C, 2). It was followed by a stage of accumulation that is represented by the layer of argillaceous sand intercalated in the Lam-Lam quarry (see p. 249, footnote 10) between the secondary 'latéritoide phosphaté' and the Quaternary

laterite; no signs of either contemporary chemical rotting or of a crust formed after the stage of this accumulation have been observed by the writer. These 'intermediate' formations therefore do not represent a full laterite (or bauxite) cycle as only the stages A and B, 2 have developed. In Ghana no pre-lateritic layers are preserved above the bauxite remnants, unless the quartz fragments and sand embedded in the laterite are taken as such.

## Palaeoclimatological results and hypotheses

It has been shown in the preceding sections of this paper that the development of the West African lateritic and bauxitic formations was governed by a specific sequence of events which can be interpreted as the result of a series of climatic cycles each comprising an arid, a warm humid, and a semi-arid stage. Five cycles of this kind have been distinguished; two successive ones determined the formation of the Eocene bauxites, and three successive ones the development of the Quaternary lateritic mantle. Between these two groups of cycles a sixth, but incomplete, cycle is preserved in Senegal.

In addition to the similarities exhibited by these cycles certain differences must also be emphasized. There exist, on the one hand, moderate regional differences within one and the same cycle, features related to aridity being somewhat more conspicuous in the north, and properties related to humid conditions in the south. There exist, on the other hand, marked differences between the individual cycles, demonstrated e. g. by a different degree of chemical rotting or of desilicification, by a different composition of the cementing matter, or by a different degree of cementation. These latter differences can be explained as due to one or other of the following causes, or their combined effect: (1) different duration of the cycles, (2) different relative duration of the three stages within different cycles, and (3) different amplitude of the climatic changes within different cycles.

To conclude, three working hypotheses for future research are given:

(1) It seems reasonable to assume that climatic cycles like those discussed above have governed the formation of the laterites and bauxites of any region and of any age.

(2) It seems likely that in the tropical belt climatic oscillations of the order discussed above have taken place generally; in the times during which neither laterite nor bauxite were formed the oscillations may have been represented by modifications of so dry a climate that physical disintegration and mechanical transport governed in the terrestrial environment without interruption.

(3) A continuous succession of somewhat irregular climatic cycles (with subordinate oscillations) is not only being invoked here in order to explain the genesis of the terrestrial laterites and bauxites, but it has also been held responsible for the cycles (and subordinate rhythms) that characterize the epicontinental marine marl-limestone series of the earth (W. BRÜCKNER, 1951, 1953). It might therefore be possible to correlate terrestrial and marine deposits of these kinds assuming that the climatic variations which caused their cycles were contemporaneous at least within the tropical belt.

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## References

Within the limited space available it is not possible to give a complete record, or even a fair selection, of all the papers dealing with the laterites and bauxites of West Africa, or with the genesis of such formations in general. The following list of references contains only the few works mentioned in the text. The writer feels, however, indebted to a large number of authors whose papers have helped him, either with detailed data, or with general considerations, to develop his own interpretation.

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## Appendix

### The chief factors involved in the formation, and the preservation, of laterite and bauxite

After the writer's paper had been read at the XXth International Geological Congress in Mexico, several significant questions were asked[12] which may be summarized as follows:

1) Is laterite or bauxite formation dependent on the nature of the parent rock?

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[12] By Y. Bentor, M. A. Besson, A. J. Terrones, and V. A. Zans.

2) Can different bauxite and laterite horizons be recognized from their topographical elevation?

These questions can best be answered by a consideration, based on the writer's findings, of the factors involved in (a) the formation, and (b) the preservation of laterite or bauxite.

(a) Factors controlling the formation of laterite or bauxite.

These factors are in order of importance: climate, time, nature of bed rock, and relief. The first two may be regarded as regional factors and the last two as local factors.

I. Regional factors:

1) Climate: A climatic cycle involving three stages – arid, humid, semi-arid – of which the last two are essential, is the prime factor in laterite and bauxite formation. These residual deposits therefore develop as surficial blankets throughout the region or belt concerned and consequently on any kind of bed rock.

2) Time: The relative duration of each of the stages within any such climatic cycle, and particularly of the semi-arid stage, determines the individual character of the lateritic or bauxitic blanket developed. Thus a prolonged humid stage favours deep chemical rotting, while it appears that a comparatively short semi-arid stage results in the formation of (silica-rich) ferruginous laterite, and an extended very gradual desiccation the formation of (silica-free) bauxite (see p. 244, footnote 5).

II. Local factors:

1) Nature of bed rock: Local differences in the bed rock are responsible for variations in the composition and thickness of lateritic or bauxitic blankets. Thus an iron-rich bed rock (e. g. a basic igneous or metamorphic formation) will favour thick development of iron-rich laterite, and an aluminium-rich bed rock (e. g. shale, phyllite, syenite, or terra rossa) the formation of thick high-grade bauxite, provided that the regional climatic conditions are favourable for the development of either laterite or bauxite. Where the bed rock contains little iron or aluminium, only a thin lateritic, or bauxitic, crust can normally form.

2) Relief: This is a factor of minor importance in the formation of laterite or bauxite. Observations made on the distribution of the Quaternary lateritic mantle have clearly shown that they develop not only on surfaces of low gradient, but also on slopes of considerable steepness. At such places the zone of young rotten rock (2a), the Upper stone layer (7), and the Upper loamy sand (8), i. e. all the layers of the youngest laterite cycle, are nearly always present, although their thickness is usually less than when they are developed on flat surfaces. Remnants of the second-cycle limonitic crust (6) have also been observed locally (e. g. at Saltpond in Ghana) on slopes of up to 40° of gradient and their presence is evidence that ferruginous encrustation on steep slopes is also possible. The fact that laterite or bauxite crusts are usually missing on steeper slopes and in valleys is therefore to be explained by erosion subsequent to their formation; these relief portions are obviously far more vulnerable to the effects of rejuvenation than high flat ground.

(b) Factors controlling the preservation of laterite or bauxite.

The preservation of laterite or bauxite blankets is the result of events occurring after their formation. The chief factors to be considered here are sedimentation and denudation, and in the latter case the intensity of dissection and of weathering, and variation in the resistance of the bed rock to weathering are of importance.

I. Sedimentation:

Laterite or bauxite blankets are best protected from destruction when covered by younger deposits, which may be terrestrial or marine (occasionally also volcanic). Their preservation is, nevertheless, rarely complete, denudation usually intervening before a younger cover can provide full protection. In West Africa only terrestrial covers have been observed, usually consisting of partly or wholly developed bauxitic or lateritic blankets of younger cycles.

II. Denudation:

1) Intensity of dissection: Relief renewal due to rejuvenation is the most powerful enemy of surficial deposits such as bauxite and laterite. As there have been several major stages of rejuvenation in West Africa since Eocene times, it is not surprising that only a few bauxite-capped residuals of the Eocene land surface still exist. Remnants of the Quaternary first cycle laterite are more frequent, as the older Quaternary land surface is more extensively preserved than the Eocene surface. The remnants of the second cycle laterite crust occupy still larger areas, and the young third-cycle deposits which are developed on the actual land surface are present nearly everywhere.

The land surface of any of these periods included, of course, all the residuals of older surfaces that had not yet succumbed to denudation. This explains the superposition of two or more bauxitic and lateritic blankets on the older residual surfaces and the fact that the older bauxite or laterite blankets are generally missing on the surfaces rejuvenated after their deposition.

2) Intensity of weathering: This factor is, of course, the indispensable precursor of the dissection discussed above. On flat or gently sloping surfaces not yet attacked by dissection it becomes the chief factor determining preservation or destruction of laterite or bauxite. Under a humid or semi-arid climate fossil blankets of these formations are fairly stable; under arid conditions, however, physical destruction will break them down fairly rapidly to loose ferruginous or aluminous rubble.

3) Differential resistance of the bed rock to weathering: this factor locally modifies the intensity of the disintegration of overlying bauxite or laterite blankets. It is obvious that these blankets will crumble more readily on rocks that offer little resistance to chemical and physical sub-surficial break-down than on rocks resistant to it. Thus in the North of Ghana (under one and the same regime of climate and dissection) only a few residuals of the second-cycle Quaternary laterite crust occur in the areas occupied by granite, which is easily attacked in that area by chemical and physical weathering, whereas such remnants are very common on the more resistant Voltaian sandstones and shales.