A study of bauxite.

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Contents.

I. Introduction.

BAUXITE is of twofold interest due firstly to its economic importance, and secondly to the scope it affords for scientific investigation. When these two reasons are taken into consideration, one can easily account for the enormous and rapid accumulation of literature concerning this subject. Any attempt to give a detailed account of the literature will only mean unnecessary repetition of what has been already dealt with at great length by several writers, of whom Anderson[1] and Fox[2] may be specially mentioned. The relation between bauxite and laterite is so intimate that a detailed study of the one is impossible without any reference to the other, and as such the description of and frequent reference to the latter should not be considered as any digression from the subject.

II. Nomenclature.

Perusal of the literature on the subject makes one realize that the terms 'laterite' and 'bauxite' are used in a very loose sense. At one

[1] R. J. Anderson, Aluminium and its alloys. 1925.
[2] C. S. Fox, Bauxite. 1927. [Min. Abstr., vol. 3, p. 319.]

extreme iron [1] and manganese [2] ores are called laterites because they have been deposited as decomposition products of igneous rocks through a process somewhat similar to lateritization ; at the other extreme there are certain others [3] who consider free aluminium hydroxide as an essential constituent if the rock is to be called a laterite. There are still others [4] who make no distinction between laterite and bauxite and use the terms as synonymous. Under these circumstances it seems essential to state the sense in which the two terms are to be used.

The term laterite was originally applied by Buchanan [5] to the soft, decomposed gneisses found in southern India and used largely as a substitute for bricks. Since then it has been used for a variety of rock types, some of which do not possess even a remote resemblance to true laterites. No scientific definition of the term has ever been attempted, nor is there any general agreement as to its application.

Max Bauer [6] does not make any distinction between laterite and bauxite, nor does Holland [7] consider that the two terms mean different things. Between 1909 and 1911 correspondence on this point passed between Scrivenor, [8] Crook (loc. cit., and 1910, p. 234), and Evans. [9] Scrivenor laid stress on the suitability for building stones, Crook on the occurrence of free aluminium hydroxide, and Evans on the small amount of combined silica as the dominant feature of laterite. While Scrivenor's definition cannot be used for scientific purposes, that of Crook does not always make a distinction from clay. The most satisfactory definition is that of Evans, but it would have been much more precise if he had laid as much emphasis on the occurrence of free aluminium hydroxide as he does on the small amount of combined silica ; for there are specimens of altered igneous rocks with low percentage of silica, little or no alumina, and abundant iron oxides (cf. Simpson, loc. cit.). These are definitely not laterites, and if the low percentage of combined silica be the only criterion, iron ore, which they really are, would inevitably have to be included among them, and this would be undesirable.

[1] E. S. Simpson, Geol. Mag., 1912, dec. 5, vol. 9, p. 379.

[2] L. L. Fermor, Geol. Mag., 1911, dec. 5, vol. 8, p. 454.

[3] T. Crook, Geol. Mag., 1909, dec. 5, vol. 6, p. 524.

[4] F. W. Clarke, Data of geochemistry. 1920, p. 496.

[5] F. Buchanan, A journey from Madras through Mysore, Canara, and Malabar. London, 1807, vol. 2, pp. 436–437.

[6] Max Bauer, Neues Jahrb. Min., 1898, vol. 2, p. 163.

[7] Sir T. H. Holland, Rec. Geol. Survey India, 1905, vol. 82, p. 175.

[8] J. B. Scrivenor, Geol. Mag., 1909, dec. 5, vol. 6, pp. 431, 574 ; and 1910, dec. 5, vol. 7, pp. 139, 335, 382.

[9] J. W. Evans, Geol. Mag.. 1910, dec. 5, vol. 7, p. 189.

It would obviate confusion if the use of the term laterite were restricted to the residual and occasionally redeposited type of rock with a comparatively small amount of combined silica and sufficient free aluminium hydroxide to form the dominant constituent, the remaining constituents being accessory. The laterite may be called quartzose or ferruginous according to the dominant accessory. All the constituents present in laterites have been found in the course of this work to show a marked tendency to form definite minerals.

Before proceeding farther the relation of bauxite to laterite has to be made clear. Clarke considers bauxite as no more than an aluminous variety of laterite, and in the nomenclature of Fermor (loc. cit., p. 514) it is only a type of laterite with sufficient free aluminium hydroxide to be of economic importance. Lacroix [1] defines it as 'une véritable roche' and classifies laterite as of bauxitic type if the aluminium hydroxide present in it is in a colloidal state, as distinct from the gibbsitic type in which the alumina is in a crystalline form. Any laterite containing more than 50 % of alumina, free or otherwise, would be bauxite according to Fox (loc. cit., p. 5). Evans is the only one to state unequivocally that laterite is a rock largely composed of the mineral bauxite with a chemical composition intermediate between that of gibbsite and diaspore, and the work carried out for this paper has gone far to confirm this view.

The next point in this section will be to state the distinction between bauxite and the other two known hydroxide minerals of aluminium. Berthier [2] was the first to identify bauxite as a distinct mineral having a composition corresponding to the formula $Al_2O_3 . 2H_2O$, and both Dana [3] and Miers [4] entertain the same view. Iddings,[5] however, differs from Berthier and does not include it among his rock-forming minerals. Holland (loc. cit., p. 176) attributes the composition of bauxite approaching a dihydrate to an intimate mixture of gibbsite and diaspore, thereby denying its occurrence as an independent mineral. Much emphasis should not be laid on the empirical calculation made by Warth [6] of the proportion of gibbsite and diaspore out of the total amount of alumina and water present in the specimens of laterites analysed by him

[1] A. Lacroix, Les latérites de la Guinée. Nouv. Arch. Mus. Paris, 1913, ser. 5, vol. 5, p. 255.

[2] P. Berthier, Annales des Mines, Paris, 1821, vol. 6, pp. 531-534.

[3] J. D. Dana, System of mineralogy, 5th edit., 1868, pp. 174-175.

[4] H. A. Miers, Mineralogy, 2nd edit., 1902.

[5] J. P. Iddings, Rock minerals, 2nd edit., 1911.

[6] H. Warth, Geol. Mag., 1903, dec. 4, vol. 10, pp. 154 and 172.

as they are not supported by microscopic evidence. It will be shown in the sequel that bauxite is an independent mineral forming the dominant constituent of laterites.

III. *Lateritization.*

Although the two end-products are known, the process of alteration of the original rock into laterites has so far been an open question. But several views suggesting the probable mode of formation have been expressed, and some of them may be briefly stated here.

As early as 1890 Walther[1] suggested that the frequently occurring thunderstorms of the tropics, together with the ozone present in the air, formed strong oxidizing agents, such as nitric acid. These agents in combination with the salts dissolved in rain-water were in his opinion sufficient to cause lateritization of rocks. Hayes[2] in 1894 suggested a different reason for the formation of the laterite deposits of the United States. Surface water with its dissolved oxygen while percolating through beds of shales reacted on the pyrites present in them, forming sulphuric acid, which in turn formed aluminium sulphate out of the aluminium silicate of the shales. The solution of the aluminium sulphate formed during its passage towards the surface came in contact with beds of limestone, forming unstable hydrated aluminium carbonate, which decomposed, giving off carbon dioxide and leaving behind hydrated aluminium oxide in the form of bauxite. In 1903 an ingenious suggestion was made by Holland[3] as the most probable cause of lateritization in India, and this view found favour among many other geologists. According to him some special form of bacteria removed the silica necessary for their development from the rocks, leaving behind aluminium hydroxide. Fermor[4] states that Holland later modified this view by including all vegetable organisms, of which bacteria, the lowest forms, were the most potent, being the most prolific, as the agents responsible for lateritization of rocks. Maclaren,[5] Cole,[6] and Campbell[7] are some of the many others to offer suggestions on this point. All these views only go to illustrate the difference of opinion among geologists regarding this form of alteration of rocks.

[1] J. W. Walther, Rec. Geol. Survey India, 1890, vol. 23, pp. 111–112.
[2] C. W. Hayes, Trans. Amer. Inst. Min. Eng., 1894, vol. 24, p. 253.
[3] Sir T. H. Holland, Geol. Mag., 1903, dec. 4, vol. 10, pp. 59–69.
[4] L. L. Fermor, Geol. Mag., 1915, dec. 6, vol. 2, p. 127.
[5] J. M. Maclaren, Geol. Mag., 1906, dec. 5, vol. 3, p. 539.
[6] G. A. J. Cole, Trans. Roy. Dublin Soc., 1896, ser. 2, vol. 6, p. 105.
[7] J. M. Campbell, Trans. Inst. Min. Met., 1910, vol. 19, pp. 432–457.

IV. *Experiments on Lateritization.*

With a view to studying the exact process of formation of laterites in nature the following experiments were carried out. Figs. 1 and 2 show the chief piece of apparatus set up for this purpose. The circular copper cylinder *B* with its lid formed a jacket round four hard-glass tubes each about a foot long and half an inch in diameter. These tubes were filled nearly to the top with granulated fragments of the rock intended for treatment. The granules were just large enough to pass through a sieve of ten meshes to the inch. The stone jar *C* contained a 3 % solution of sulphuric acid, which was allowed to drop, by means of a syphon tube, on the granulated rock in one of the hard-glass tubes at the rate of three drops a minute. A 5 % solution of carbonates of potassium and sodium, in the proportion of one part of potassium carbonate to four parts of sodium carbonate, contained in the stone jar *D* was allowed to drop on the contents of the second hard-glass tube at the same rate. Three to four drops from the jar *E*, which contained only distilled water, were allowed to trickle through the granules of the rock held in the remaining two glass tubes. Besides the distilled water, from four to eight bubbles per minute of carbon dioxide from the cylinder *F* were led into one of the last two glass tubes. Thus solutions of (i) sulphuric acid, (ii) alkali carbonates, (iii) carbonic acid, and (iv) distilled water alone, were allowed to percolate through the granules of the rock packed in the four glass tubes. After percolating, these reagents dropped through the narrow drawn lower ends of the hard-glass tubes into small funnels supported below the copper cylinder and were led by means of rubber tubings to the sink. An unfailing supply of the above reagents was maintained throughout the period of the experiment.

Water from the tap, after flowing through a long coil of composition tubing (lead alloy), entered the copper cylinder *B* through a side tube near its lower end, flowed out into the sink through an opening on the side near its top, and in this manner a constant current of water was allowed to circulate in the cylinder. The coil of composition tubing, about 12 feet long, was kept immersed in a bath of water *A*, whose temperature was so adjusted by means of a thermostat as to maintain the water circulating in the cylinder *B* within a constant range. The bath *A*, the cylinder *B*, and the exposed ends of the composition tubing were all wrapped in folds of asbestos cloth to prevent radiation of heat.

The specimen of rock used for the treatment described above was a portion of the fresh basalt of the Upper Volcanic Series from the Giant's

Causeway. The experiment was run continuously for a period of nine
months, and the temperature of the water in the copper cylinder was
maintained throughout the period between 32° and 52° C., that is,
slightly above tropical temperature. But at the end of six months the
supply of sulphuric acid was cut out and alkali carbonate solution intro-
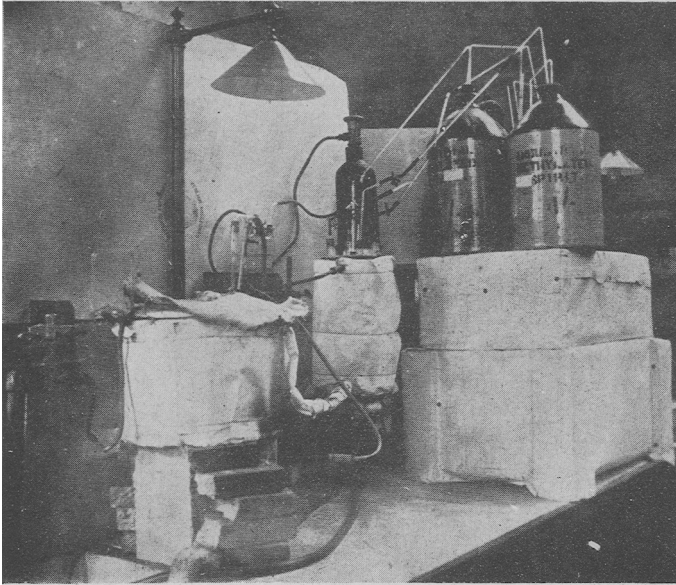duced instead into the first hard-glass tube. Before this operation a

Fig. 1.   Photograph of apparatus.

portion of the rock from this glass tube was removed for the purpose of
studying the action of the acid.

Throughout the experiment, iron in a ferric state was proved to be
removed in varying amounts from all the tubes. One or more of the
other constituents of the rock were also leached out in varying amounts
from some of the tubes, but it was not possible to examine them in
detail.

Another part of the experimental work consisted in studying the action
of organic acids on rocks. A humic acid solution extracted from peat
was allowed to flow through a glass tube filled with the same specimen
of granulated basalt as before. For a short time the temperature of the

glass tube with its contents was maintained between 30° and 50° C. This part of the work was also carried out for nine months. The jelly-like humic acid had to be deflocculated with a few drops of ammonia before it could be made fit for use.

A study of the effect of pressure on rocks formed the third part of the experimental work; but in this case a specimen of dolerite was used. Broken bits of this rock were packed inside a small copper wire gauze bag
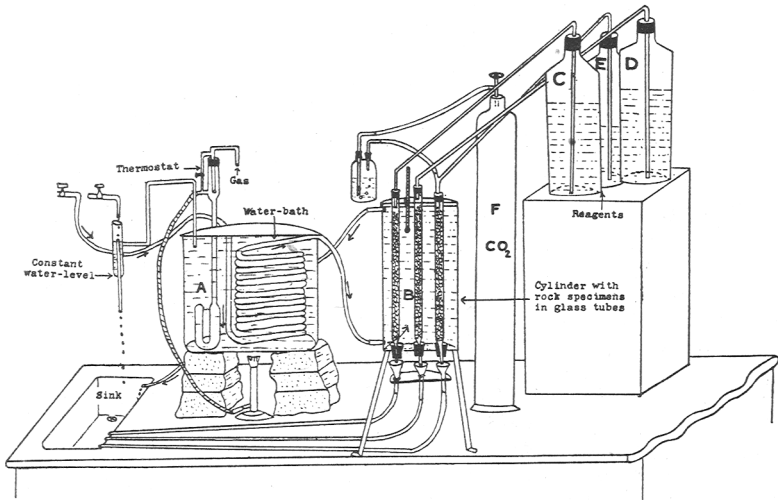

Fig. 2. Diagrammatic sketch of apparatus.

suspended in an autoclave, and were subjected to steam pressure varying from 800 to 1,600 lb. to the square inch at a temperature ranging from 250° to 830° C. The treatment extended over a period of six months at the rate of six hours per day. A small amount of carbon dioxide was also introduced into the autoclave every morning before it was started.

Description of resulting specimens.—After the various treatments the specimens were removed from the several glass tubes, washed till they were free from the reagents and dried at 110° C. for four hours, and were then used for chemical analysis and microscopic examination. The chemical composition of the original and resulting specimens is given in the following table, which was obtained by taking the mean in each case of two independent analyses with concordant results.

Chemical composition of the rock before and after the various treatments.

[Analyses by T. V. M. Rao.]

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
SiO_2	51·20	71·32	63·42	48·84	50·30	50·63	50·98	44·19	41·55
Al_2O_3	14·60	3·96	3·40	18·25	17·93	15·68	15·34	13·56	15·26
Fe_2O_3	4·56	4·79	9·18	10·61	11·85	11·01	12·06	11·30	15·29
FeO	8·13	0·26	0·85	0·76	0·75	0·79	0·79	0·94	0·68
MgO	4·40	0·22	6·20	5·42	2·21	4·76	4·75	16·56	11·47
CaO	10·85	8·06	11·48	9·32	9·85	9·66	9·44	8·46	8·70
Na_2O	3·23	1·09	2·01	2·48	2·03	2·60	3·06	2·06	1·35
K_2O	0·82	0·85	1·76	1·19	0·93	0·74	0·42	0·36	0·17
$H_2O +$	2·11	9·42	1·01	2·07	2·51	2·39	2·40	1·68	3·20
TiO_2	0·96	0·42	0·81	1·16	1·50	1·17	0·94	0·83	1·49
CO_2	0·04	0·01	0·03	0·24	0·16	0·08	nil	0·29	0·40
Total	100·40	100·40	100·15	100·34	100·02	99·51	100·18	100·23	99·56

I. **Fresh basalt from Giant's Causeway, Co. Antrim.**—The basalt used for the experimental work is black in colour and very fine-grained. In thin sections labradorite felspar and augite are found to be present both in the groundmass and as porphyritic crystals. Some interstitial glassy material and accessory crystals of ilmenite and magnetite make up the rest of the rock. No trace of alteration can be detected either in hand-specimens or in thin sections of the rock.

II. **Basalt after six months' treatment with sulphuric acid.**—The granules are grey in colour and are very light. The chemical analysis proves a tremendous increase in the amount of silica and water and a slight increase of ferric iron. The other constituents, especially alumina and ferrous iron, have diminished. Examination of crushed grains shows abundant quartz, augite in different stages of alteration and often presenting a spongy appearance, and a complete absence of felspar. Augite partly altered to quartz is occasionally seen, but the latter is too abundant to be derived entirely from this source and should have been derived from felspar[1] also.

III. **No. II after further treatment for three months with alkali carbonates.**— The specimen was reduced to a grey powder. An appreciable amount of silica has been removed by the action of the alkali carbonates.

IV. **Basalt after nine months' treatment with alkali carbonates.**—The chemical analysis proves an increase in the amount of alumina and a decrease in that of silica. On examination of the crushed grains it is found that some of the felspar crystals have partly or completely altered to an opaque mass very much resembling the milky-white grains of bauxite to be described in the next section (cf. Leonard, loc. cit., p. 32).

V. **Basalt after nine months' treatment with water and carbon dioxide.**—The action of carbon dioxide seems to be similar to that of alkali carbonates, though the difference is not so appreciable.

[1] Cf. R. J. Leonard, Econ. Geol., 1927, vol. 22, p. 25.

VI. Basalt after nine months' treatment with distilled water.—The only difference is in the silica content, showing that water by itself is capable of removing silica in small amounts.

VII. Basalt after nine months' treatment with humic acid.—Humic acid seems to have had no action.

VIII. Dolerite (locality unknown).—The specimen used for treatment under pressure is an olivine-dolerite having a groundmass largely made up of fresh crystals of felspar and augite. Porphyritic crystals of olivine, partly altered to serpentine, are abundant. The vesicles present in the rock are filled with calcite; ilmenite and magnetite occur as accessories.

IX. Dolerite after six months' treatment with steam and carbon dioxide under pressure.—The difference after this treatment is only in silica and magnesia, the former due to the effect of steam and the latter probably to carbon dioxide. The crushed grains of the specimen are largely composed of felspar and augite, both of which are fresh; but there is no trace of serpentine, which should have been decomposed by steam and carbon dioxide.

Review of experimental work.—From the foregoing description of the resulting specimens it will be noticed that the action of acid results only in an increase of silica. Water by itself has little action in the process of lateritization, and that of humic acid is not worth mentioning. The effect of steam and pressure is analogous to that of water except that it is more intense. It is only alkali carbonates, and to a small extent carbon dioxide, that effect a reduction of silica and an increase of alumina. No doubt a certain amount of alumina is also removed, but that is negligible when compared to the amount of silica leached out.

From the results of the experimental work it is safe to conclude that the whole key to the process of lateritization rests with the alkali carbonates. Further, the fact that the alkali radicals present in igneous rocks and shales do not by themselves bring about this form of alteration is sufficient proof for considering that they should be present as carbonates. Hence the role played by carbon dioxide during lateritization is significant.

The process of lateritization may now be summarized as follows. The carbon dioxide present in rain-water combines with the alkalis present in rocks and soils forming alkali carbonates. Aqueous solutions of these carbonates react on the felspars and other aluminium silicate minerals present in rocks, giving rise to alkali silicates and hydrated aluminium carbonates; the former are removed in solution and the latter, being unstable, are decomposed into carbon dioxide and hydrated aluminium oxide, which is deposited in the form of bauxite. Those constituents of the original rock that are not or only partly decomposed are left behind as accessories, and these with the bauxite form deposits of primary

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laterite. The chemical reaction involved in the alteration to laterite
may be expressed as follows :

Aluminium silicates + alkali carbonates + water → alkali silicates + hydrated
    aluminium carbonate.
Hydrated aluminium carbonate → hydrated aluminium oxide (bauxite) + carbon
    dioxide.

Some of the liberated carbon dioxide may help in the removal of
magnesia as bicarbonate. The fact that lateritization takes place only
in tropical countries, although the necessary constituents are always
everywhere present, suggests the need for tropical temperature for this
type of alteration.

Geological significance.—The results of the experimental work are all
the more convincing as they bear certain points of resemblance to
evidence obtained in the field. Kitson [1] refers to the presence of carbon
dioxide in the shafts and borings put down in the laterite deposits of the
Gold Coast, and this should be due to the breaking down of the hydrated
aluminium carbonate as deduced from the experimental work. Hayes
suggests the formation of hydrated aluminium carbonate as an inter-
mediate product during the formation of the American laterite deposits.
Again, the occurrence in nature of the mineral dawsonite suggests the
formation of hydrated aluminium carbonate as quite feasible.

In conclusion it may be observed that when it is possible for lateritiza-
tion to take place by the action of the constituents mostly present in the
rock itself, there seems no necessity to invoke the aid of extraneous
agents such as vegetable organisms.

V. *Description of Laterites.*

(a) *India.*—The chief deposits of laterites in India are derived from
the Deccan traps, although those formed from metamorphic and sedi-
mentary rocks are not uncommon. In hand-specimens these laterites are
massive, spherulitic, vermicular, or conglomeratic, the last type being
not so common as the others. The massive type resembles a piece of
burnt clay except as regards its colour. The spherulitic type may be
full of spherules of varying size, the matrix forming merely a cement, or
there may only be a few. In some cases the spherules are easily detach-
able intact. When split open these spherules are found to have either
a concentrically banded structure or to be hollow and partly filled with a
white powder. The structure, composition, and relation of these spherules

[1] Sir A. E. Kitson, Outlines of the mineral and water resources of the Gold
Coast, 1924, p. 22.

to the matrix will be fully discussed at the end of this paper. The matrix, whether forming merely a cementing material or the bulk of the specimen, may be either more or less stained with iron than the spherules, and is specifically lighter than them. The pores in the vermicular type lead to zigzag holes which may be empty or lined or filled with haematite, limonite, or some indistinguishable powder having a red, yellow, or brown colour. One or all of the structures described above may be found in the same deposit and even in the same specimen.

The colour varies through a wide range, but is usually in some shade of pink, red, or brown. It may or may not be evenly distributed, and when uneven the intensity may vary in different patches. The colour with its different shades is entirely due to oxides and hydroxides of iron. Those poor in iron are grey in colour. But in all of them intensity of colour is not always a true indication of the amount of iron content.

The thin sections of the rock are opaque, as they always are, and afford little scope for detailed

FIG. 3. Photomicrograph showing bauxite (B) altering into gibbsite (G), Central Provinces, India. × 35.

examination, especially with polarized light, any possible microscopic work being carried out by using reflected light. Even the few identifiable minerals present are often masked by the iron stain, which, due to its unevenness, imparts a chequered appearance to the whole section. In many cases the sections are full of holes and zigzag cracks, often filled or lined with crystals of gibbsite (fig. 3). The peculiar arrangement of these crystals in the holes and cracks leaves little doubt regarding their secondary formation after the lateritization of the rock. The structures, especially the spherulitic and the conglomeratic, of the specimens are better displayed in thin sections than in the large masses. Some of the spherules have a core of an oxide or hydroxide of iron, very often of limonite. Occasional groups of weathered and iron-stained
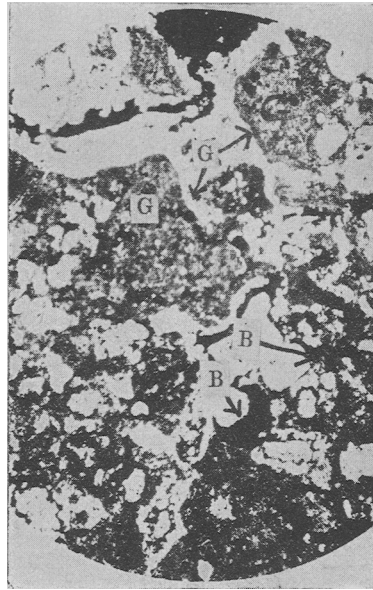
crystals of felspars, probably plagioclase, platy grains of ilmenite, and four-sided grains of magnetite are the only identifiable minerals in thin sections. But an examination of the crushed grains of the rock reveals the presence of muscovite, weathered biotite, zircon, amphibole, pyrites, tourmaline, sphene, and rutile. The composition and properties of the opaque grains having a milky-white appearance when not stained with iron and forming the bulk of the crushed rock will be discussed in full in a subsequent section.

(*b*) *British Guiana.*—According to Harrison [1] these laterites are formed mostly from gabbros and diabases and to a small extent from porphyries, granites, and gneisses. Most of the specimens examined are massive and the others are nodular, stalactitic, or granular, the granules being loosely held together. They are mostly cream coloured, a few having a mottled appearance. In the stalactitic and nodular types iron in the form of haematite or limonite segregates in the centre forming a core. Thin sections reveal no new information beyond the fact that they are devoid of holes and cracks.

(*c*) *Gold Coast.*—There are several deposits with varying grades of ore, but the important ones are at Sefwi Bekwai and at Mt. Ejuanema. The specimens are mostly massive, rubbly, or granular, though spherulitic forms are not uncommon. Occasionally vermicular structure with the vermicules filled with a brown powder is also met with. Some of the specimens from Sefwi Bekwai are full of minute holes and white specks, of which the latter on microscopic examination are found to be made up of bunches of crystals of gibbsite. The spherules, which show concentric banding, are neither as numerous nor as easily detachable intact as in the Indian specimens.

The colour, which in the majority of cases is uniformly distributed, varies from orange, yellow, or brown to bright red. The iron stain, to which the colour is due, is, in the opinion of Kitson (loc. cit., p. 21), imparted subsequently to the lateritization of the rocks. If so, the fact that it has not stained the crystals of gibbsite is a further proof of their secondary nature formed after the lateritization of the rock. In hand-specimens, and in thin sections as well, it is possible to observe bedding-planes and parallel arrangement of lenticles reminiscent of the parent-rock.

The remarks made regarding the examination of thin sections of Indian laterites apply equally well to these specimens also. Among the crushed grains are found ilmenite, fresh or partly altered to leucoxene, brown

[1] Sir J. B. Harrison, Geology of the goldfields of British Guiana, 1908.

tourmaline, secondary sphene, occasional grains of amphibole, kyanite, and magnetite, the last mineral often altered to limonite.

(d) *Ireland.*—The writer had an opportunity for studying in the field the laterite deposits of Antrim during a visit paid there in 1925. These deposits, formed by the weathering of the basalts of the Lower Volcanic Series, are not as extensive as in India nor are they of any great economic importance. The basalts of the Upper Volcanic Series form a thick mantle over most of the deposits and there are only very few good exposures. The exposure along the cliff at the Giant's Causeway is probably the best and affords good facilities for a study of the process of lateritization. Along the path excavated on the cliff it is possible to trace the gradual passage of the fresh basalt at the western end into the soft red-coloured band of laterite at the eastern end. A close examination of this band leads one to conclude that the agent responsible for the alteration should have worked its way along the joints and crevices of the basalt and brought about the alteration.

The laterites in the south of Antrim are the results of alteration of acid igneous rocks such as rhyolites. Naturally these laterites are not so ferruginous as those derived from basalts and they were at one time exploited. In hand-specimens these laterites are massive or conglomeratic, the ferruginous varieties being bright red in colour. They are very friable and can be crushed between the fingers. In thin sections they are entirely opaque and quite compact. Secondary quartz is the only recognizable mineral. Besides the ubiquitous opaque milky-white grains, there are present in the crushed rock grains of anatase light blue and light green in colour, simple and geniculate twins of rutile, octahedral crystals of magnetite, bleached biotite, tourmaline, and zircon; occasionally transparent greenish-yellow crystals of rutile are also met with. Rutile and anatase are secondary as they are both absent in the original rock. But only a part of the magnetite is secondary and derived from the ilmenite of the basalt.

(e) *France.*—Specimens of laterites from France, the classical area for these rocks, were also examined with a view to making the study as comprehensive as possible. These laterites overlie rocks of Upper Cretaceous age forming a discontinuous stretch in the south and south-east of France. The specimens examined are either massive or spherulitic. Blocks of the massive type are quite white outside, resembling a piece of chalk with no trace of iron; but in the interior the material is red in colour, the iron having segregated towards the centre. The spherulitic variety is dark red in colour, the matrix being more intensely stained than the spherules.

The spherules show concentric banding and are closely cemented by the matrix.

The results of the chemical analyses of some of the typical specimens from the countries described above are given in the following table.

Analyses (by T. V. M. Rao) of Laterite.

No.[1]		5.	12.	15.	54.	7A.	7.	17.
SiO_2	...	1·52	1·90	2·04	25·26	1·18	44·54	1·18
Al_2O_3	...	55·56	58·83	55·20	14·49	60·62	34·78	58·47
Fe_2O_3	...	4·18	2·89	3·97	34·85	2·26	1·22	6·27
MnO	...	n.d.	n.d.	n.d.	9·02	n.d.	n.d.	n.d.
MgO	...	0·11	0·11	0·11	0·18	0·21	nil	0·09
CaO	...	0·41	0·74	0·71	0·30	0·66	0·44	0·40
Na_2O	...	0·30	2·75	0·72	0·17	0·27	0·27	0·84
K_2O	...	0·44	0·70	0·46	0·21	0·37	0·35	0·08
$H_2O +$	...	28·85	27·06	24·65	14·22	32·73	17·92	32·26
TiO_2	...	8·76	5·83	11·69	1·13	1·58	0·26	1·27
Total	...	100·13	100·31	99·55	99·83	99·83	99·78	100·36

No. 5.—West scarp, Samnapur, Central Provinces, India.
12.—Ridge of Nauga, Belgaum, Bombay, India. (806.)
15.—NW. of Samnapur, Central Provinces, India. (1128.)
54.—Varkala, Travancore, India.
7A.—Demerara, British Guiana.
7.—British Guiana (unlocalized).
17.—Bepo Khini, Sefwi Bekwai, Gold Coast. (9434.)

No.[1]		22B.	29.	32.	37.	33.	60.	61.
SiO_2	...	0·61	0·61	0·69	21·29	7·03	3·09	1·90
Al_2O_3	...	64·99	59·69	56·31	46·64	49·87	67·10	76·05
Fe_2O_3	...	2·89	10·61	10·72	2·58	5·78	7·79	1·87
MnO	...	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0·03
MgO	...	0·14	0·33	0·33	0·09	0·20	0·14	0·15
CaO	...	0·63	0·44	0·46	0·71	1·07	1·27	0·56
Na_2O	...	0·84	n.d.	n.d.	0·26	trace	0·45	0·88
K_2O	...	0·06	n.d.	n.d.	0·26	trace	0·14	0·83
$H_2O +$	...	27·87	23·97	29·78	{ + 23·80 { − 2·12	30·43	17·73	15·30
TiO_2	...	2·40	4·05	0·85	4·08	6·22	2·52	3·34
Total	...	100·43	99·70	99·14	99·71	100·10	100·23	99·91

No. 22B.—Ejuanema, Gold Coast, West Africa. (2.)
29.—Top of Mt. Ejuanema, Gold Coast. (14911.)
32.—Top of Mt. Ejuanema, Gold Coast. (14911.)
37.—Ballintoy, Co. Antrim, Ireland.
33.—Straid, Ballynure, Co. Antrim.
60.—Le Valare, Foix, Ariège, France.
61.—Brignoles, Var, France.

[1] These numbers are those of specimens in the writer's collection. The numbers given after some of the localities are those of the Indian and Gold Coast Surveys.

With the high alumina content in most of them they should prove to be of economic importance. The high percentage of titanium content is a noteworthy feature of Indian specimens. Evidence of the occurrence of carbon was obtained in the course of the analysis in some of the Irish specimens, and this might account for the abnormally high percentage of hygroscopic moisture in some of them. Reference will be made presently regarding the low percentage of water in the two French specimens analysed.

VI. *Relation of Laterites to the original rock and to each other.*

Comparison of the composition of laterites (II) and of the rocks (I) from which they were derived.

INDIA.[1]

	Set No. 1.			Set No. 2.			Set No. 3.		
	I.	II. (No. 5).	$\frac{(I-II)}{I}$.	I.	II. (No. 12).	$\frac{(I-II)}{I}$.	I.	II. (No. 15).	$\frac{(I-II)}{I}$.
SiO_2	48·84	1·52	− 0·96	48·62	1·90	− 0·95	49·98	2·04	− 0·95
Al_2O_3	14·37	55·65	+ 2·82	14·12	58·83	+ 3·40	12·51	55·20	+ 3·45
Fe_2O_3	13·70	4·18	− 0·69	15·06	2·89	− 0·64	15·94	3·97	− 0·75
MgO	5·33	0·11	− 0·98	5·29	0·11	− 0·97	5·42	0·11	− 0·97
CaO	9·82	0·41	− 0·96	9·49	0·74	− 0·92	10·00	0·71	− 0·92
Na_2O	2·26	0·30	− 0·88	2·95	2·75	− 0·71	2·65	0·72	− 0·72
K_2O	0·52	0·44	− 0·15	0·60	0·70	+ 0·16	0·30	0·46	+ 0·53
H_2O+	2·50	28·85	+10·74	2·28	27·06	+10·86	0·95	24·65	+24·94
TiO_2	2·63	8·76	+ 2·33	0·88	5·33	+ 2·28	2·27	11·69	+ 4·14

BRITISH GUIANA.[2]

	Set No. 4.			Set No. 5.			Set No. 6.		
	I.	II.	$\frac{(I-II)}{I}$.	I.	II.	$\frac{(I-II)}{I}$.	I.	II.	$\frac{(I-II)}{I}$.
SiO_2	52·00	3·33	− 0·98	49·06	3·13	− 0·93	51·09	2·71	− 0·94
Al_2O_3	17·29	46·80	+ 1·70	18·86	56·42	+ 1·99	15·70	64·86	+ 3·76
Fe_2O_3	12·08	26·40	+ 1·18	6·91	11·59	+ 0·67	11·20	0·85	− 0·93
MgO	6·95	nil	− 1·00	10·95	0·20	− 0·98	7·74	0·36	− 0·93
CaO	8·80	nil	− 1·00	11·70	0·13	− 0·98	9·11	0·33	− 0·99
Na_2O	2·81	nil	− 1·00	0·97	0·13	− 0·86	2·38	nil	− 1·00
K_2O	0·18	nil	− 1·00	0·06	0·10	− 0·66	1·55	0·15	− 0·90
H_2O+	0·35	22·96	+64·02	0·43	27·84	+63·74	0·35	30·47	+86·05
TiO_2	0·53	0·69	+ 0·30	0·88	0·83	− 0·05	1·70	0·75	− 0·50

[1] For these analyses of Indian basalts occurring in the same localities as the laterites, vide H. S. Washington, The Deccan traps and other plateau basalts. Bull. Geol. Soc. Amer., 1922, vol. 33, p. 765. The ferrous iron in these analyses has been converted into ferric iron.

[2] For these analyses of both the original rocks and the laterites, vide Sir J. B. Harrison, Rep. and Corres. relating to the bauxite of 'British Guiana, 1919. Colonial Office Publication. In set no. 4 the original rock is basalt, in no. 5 epidiorite, and in no. 6 diabase.

It is shown above that it is possible to trace a relationship between some of the constituents of the original rock and those of the laterites derived from it. In each of the above sets of tabular statements the first vertical column gives the chemical composition of the original rock occurring in the same locality as the corresponding laterite, the second that of the laterite itself, and the third the proportion of gain or loss of each of the constituents.

It will be noticed that the proportion lost of silica and oxides of calcium and magnesium is identical, or in other words the proportion of these constituents present in residual laterites is invariably constant. If so, when these proportions are reached, these constituents should become invulnerable to the further action of the lateritizing agents. It is then possible to surmise that the process of lateritization, which in the main consists of the leaching out of silica, magnesia, and calcium oxide from rocks is limited in its scope. It may also be possible to trace this relationship between the original and altered rocks of other countries— of course only if the laterites are primary.

In a pamphlet on lateritization Chautard and Lemoine [1] have indicated a method of calculating the amount of silica, alumina, and other constituents involved during this type of alteration on the assumption that all the titanium present in the original rock is left unaffected in the altered product. But chemical and microscopic examination of low-level laterites and calculation based on the amount of titanium oxide present in the original rock have proved that an appreciable amount of titanium is invariably removed, and as such much stress should not be laid on the methods suggested by these workers.

It was not found possible to represent the constituents of laterites in the form of a variation diagram.

VII. *Mineral Composition of Laterites.*

Attention may now be directed to the consideration of the several minerals occurring in laterites and their correlation with the chemical composition.

Alumina.—Hydrated oxide of aluminium is the dominant constituent of laterites, and the consideration of its nature and mode of occurrence is the prime object of this paper. Aluminium hydroxide has so far been known to occur in the form of three compounds, two of which, viz. gibbsite and diaspore, are easily determined by their definite physical, chemical, and

[1] J. Chautard and P. Lemoine, La latérisation. Bull. Soc. Industrie Minérale, Saint-Étienne, 1908, ser. 4, vol. 9, reprint 87 pp.

mineralogical properties. But there is a great divergence of opinion regarding the consideration of bauxite as a definite mineral. Gibbsite occurs as a secondary mineral and forms only a very small proportion of laterites. Diaspore has never been known to occur in laterites but is found associated with minerals of thermodynamic origin, signifying that mere conditions of lateritization are not conducive to its formation; consequently it cannot be expected to occur as a normal constituent of laterites.

Bauxite.—During the description of specimens of laterites it was repeatedly pointed out that the thin sections and the crushed grains of the rock contained an opaque material having a milky-white appearance when not stained by iron. Microscopic examination did not reveal any further information regarding its optical and mineralogical properties.

The specifically light residue obtained from a bromoform separation of the crushed grains of the rock proved on microscopic examination to consist mostly of these milky-white grains. Further, it also formed the bulkier part of the bromoform separation and had the following chemical composition. The light residue of laterite no. 9 from Netarhat, Bihar and Orissa, India (184), gave the following results on analysis:

SiO_2.	Al_2O_3.	Fe_2O_3.	MgO.	CaO.	Alkalis.	H_2O+.	TiO_2.	Total.
0·40	62·96	8·94	0·38	0·85	n.d.	25·04	5·25	98·82

Recalculation of the above analysis after excluding the minor constituents shows that there is 71·74 % of alumina and 28·26 % of water, and this proportion is not near to a mono- or trihydrate of alumina. Evidently the aluminium hydroxide forming the dominant constituent of laterite is neither diaspore nor gibbsite and must be nothing other than bauxite.

Composition of bauxite.—With a view to determine the composition of bauxite Arsandaux[1] carried out some interesting work with certain highly aluminous rocks occurring in France. By digesting several specimens of these rocks with concentrated hydrochloric acid on a water-bath for about an hour, he seems to have succeeded in removing all the iron and obtaining residues consisting mostly of alumina, some titanium oxide, and a trace of silica. On chemical analysis these residues were found to contain alumina and water in a proportion sufficient to form only a monohydrate. In about thirty cases treated in this fashion he found only one instance of variation and all the rest agreed. The comparatively small amount of water present in the French specimens described

[1] H. Arsandaux, Compt. Rend. Acad. Sci. Paris, 1909, vol. 148, pp. 986, 1115.

in the present paper also goes to support Arsandaux's conclusions. But the proportion of alumina and water present in specimens from other countries are not in favour of his views. The following table gives the results of chemical analyses of two typical specimens of laterites, one from India and the other from the Gold Coast, after they were treated with hydrochloric acid. Since an hour's treatment had not removed much of the iron, they were digested on the water-bath till the acid began to attack the bauxite of the rock.

	India (no. 12).				Gold Coast (no. 32).	
SiO_2 ...	0.77	...	...	...	1.17	
Al_2O_3 ...	65.63	(70.9)[1]	...	...	63.62	(71.7)[1]
Fe_2O_3 ...	2.51	...	...	...	2.12	
$H_2O +$ ...	25.64	(29.1)	...	...	27.09	(28.3)
TiO_2 ...	3.13	...	...	...	4.15	
	97.68	100.00			98.15	100.00

Comparison of these two partial analyses with those of the original specimens (vide p. 420) shows the rather surprising result that very little of the alumina has been attacked by the acid, though the treatment was quite a severe one; nor is there much change in the amount of water. The proportion of alumina and water in both cases is nearer to that of a dihydrate than to the other two known aluminium hydroxides. The percentages of alumina and water in all the laterites, whose chemical composition is given on p. 420, also on recalculation after excluding the accessories correspond to a dihydrate and never to a monohydrate. Obviously the specimens described by Arsandaux and the two French ones described in this paper do not contain any bauxite, but probably some other hydroxide of alumina corresponding in composition to a monohydrate. For reasons already given this monohydrate cannot possibly be diaspore. Thus there arises the probability of the occurrence in nature of aluminium hydroxide minerals other than the three now known, and the fact that there are laterites (C. S. Fox, loc. cit.) containing still less water than a monohydrate lends further support to this view.

Doubt may arise as to whether the mono- or the dihydrate, both being found in France, should be called bauxite. The following analysis made by Berthier in 1821 will help to clear that doubt.

SiO_2.	Al_2O_3.	Fe_2O_3.	H_2O.	Total.
—	52.0	27.6	20.4	100.0

[1] Numbers in brackets indicate percentages of alumina and water exclusive of the minor constituents.

After excluding the iron there is in the above analysis 71·8% of alumina and 28·2% of water, and this approximates to the dihydrate in composition. Evidently Berthier gave the name bauxite to the dihydrate. Whether analysed in the manner suggested by·Arsandaux or otherwise, the proportion of alumina and water in the specimens whose composition is given on p. 420 (France excluded) also corresponds to a dihydrate. Thus as there is a definite dihydrate occurring in nature, there is no justification in giving the name bauxite to any other aluminium hydroxide. These French specimens corresponding in composition to a monohydrate may provisionally be considered as an amorphous variety of diaspore.[1] Further, Berthier has a claim for priority and hence it does not seem proper that a name given by him for a particular mineral should be given to any other.

The definite chemical composition of bauxite, as seen from the examples given above, also settles the question of its being a distinct mineral. As a further proof, an experiment was carried out to see if bauxite would behave in a manner similar to other minerals. It has already been pointed out by previous workers (Fox and Arsandaux) that laterite on heating gave off water at uneven rates; but the significance of this feature had not been fully realized. Samples of laterite, gibbsite, and limonite were separately heated in an electric furnace to different temperatures, and curves were plotted showing their different rates of dehydration. As can be seen from fig. 4, none of the specimens gave off its combined water at a uniform rate.

It is too much to expect that the uneven nature of the curve for laterite,[2] which is so pronounced, is due to the small amounts of gibbsite and limonite that may be present in it. So it would not be unsafe to consider that bauxite, which forms the dominant constituent of laterite, should also have contributed to its unevenness. This uneven rate of dehydration would serve as a further proof of bauxite being a definite mineral and not a colloid (cf. Lacroix, loc. cit.).

It is also clear by now that bauxite is not a mixture of gibbsite and diaspore, since the former is of subsequent formation to bauxite and the latter never occurs in laterites.

Silica.—Occurrences of silicate minerals and quartz in laterites have already been recorded. Rational analysis[3] revealed the fact that silica

[1] A crystalline aluminium mohohydrate in French bauxite has recently been named 'boemite' by J. de Lapparent, Compt. Rend. Acad. Sci. Paris, 1927, vol. 184, p. 1661 [Min. Abstr., vol. 3, pp. 369, 430].

[2] This differential method has to be adopted as it is never possible to obtain bauxite free from gibbsite, limonite, or both.

[3] For a detailed account of the estimation of the different forms in which

was present in laterites in colloidal form also.   Felspar, kyanite, musco-
vite, biotite, zircon, sphene, tourmaline, and amphibole are the important
silicate minerals present.   The quartz present may be primary if derived
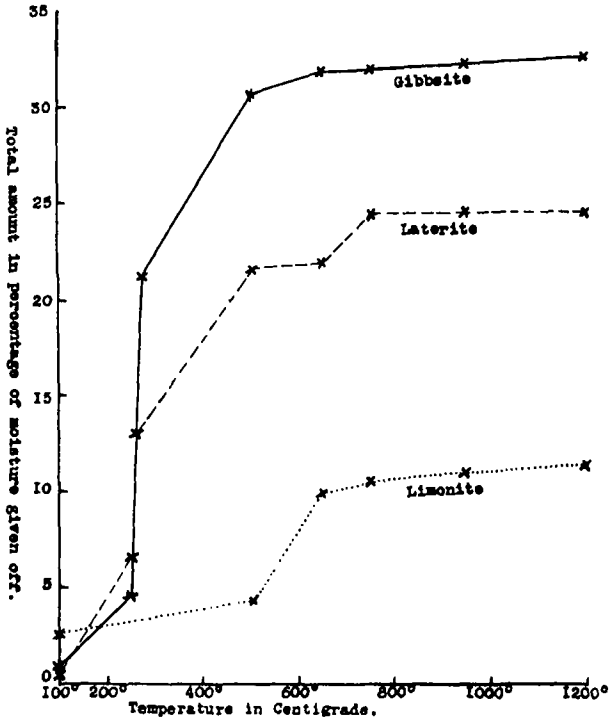from the original rock or it may be secondary.   The silica that is not

FIG. 4.   Curves showing the different rates of dehydration of laterite, gibbsite,
and limonite.

included in any of the above forms is present as a colloid—the form in
which it should have separated out of the rock before it formed secondary
minerals.

   Iron.—Of the various oxides and hydroxides of iron, haematite, mag-
netite, and limonite are the only ones to be definitely identified.   Grains
of pyrite are also of occasional occurrence.   Of these iron-bearing minerals
only the pyrite and a portion of the magnetite are primary.

   Titanium.—The form in which this constituent occurs in laterites has

silica occurs in laterites, vide J. W. Mellor, Treatise on quantitative inorganic
analysis, 1913, pp. 658 and 668.

so far been a matter of speculation. Maclaren is probably the first to point out the occurrence of ilmenite and doubtfully of rutile in laterites. Lacroix is of opinion that it is in the form of ortho- and metatitanic acid. Wysor[1] seems to have identified pseudobrookite besides ilmenite in the specimens examined by him. Fermor[2] denies the occurrence of any titanium-bearing minerals in the laterites of India. Fox thinks that it is in the form of a gel. Although an attempt made to estimate accurately whether all the titanium present in laterites was in a crystalline form was unsuccessful, the present investigation has definitely proved the occurrence of ilmenite, rutile, anatase, sphene, and titaniferous magnetite.

Alkalis.—Felspar, micas, and some of the other silicates present in laterites would account for the alkalis, but it is not certain if all of them are in the form of minerals. The role played by them in the process of lateritization has already been discussed.

Water.—There is a fairly wide range in the amount of water present in laterites. Bauxite accounts for most of it, but some may also be due to the colloids, gibbsite, and hydroxides of iron that may be present.

Colloids.—Rational analysis has afforded evidence of the occurrence of colloidal silica in laterites. Under favourable conditions it forms secondary minerals, else it is left unaltered in the laterite. If so, colloid in laterite is only a transitional stage between the minerals of the original rock and those of the resultant type. These remarks apply as much to the other constituents as to silica.

From the foregoing considerations the relation between laterite and bauxite is clear. Laterite is a rock largely composed of the mineral bauxite together with certain accessories such as silicates, oxides and hydroxides of iron, and oxides of titanium ; those constituents that have not altered to give rise to secondary minerals are left as colloids.

VIII. *Spherulitic Structure in Laterites.*

As is the case with several features, no two workers are agreed in their opinions regarding the formation of this structure in laterites. Campbell thinks that spherulitic structure in laterites is only an instance of molecular aggregation, and Fermor (loc. cit., p. 514) allocates this type provisionally to lake deposits, thus doubtfully attributing the agency of water for its formation. According to Lacroix a homogeneous medium with few or no solid elements insusceptible to concretion is the condition necessary for its formation.

[1] D. C. Wysor, Econ. Geol., 1916, vol. 11, p. 44.
[2] L. L. Fermor, Econ. Geol., 1916, vol. 11, p. 689.

The formation of spherulitic structure in laterites, especially those showing a banded structure, afford good instances of Liesegang rings. According to Freundlich [1] the formation of these rings depends on the velocity of formation of a nucleus and the coagulation velocity of the gel, and for satisfactory results a small amount of impurity is desirable. With these conditions may be included the amount of concentration of the constituents of the mixed colloid. Now supposing there is a mixed
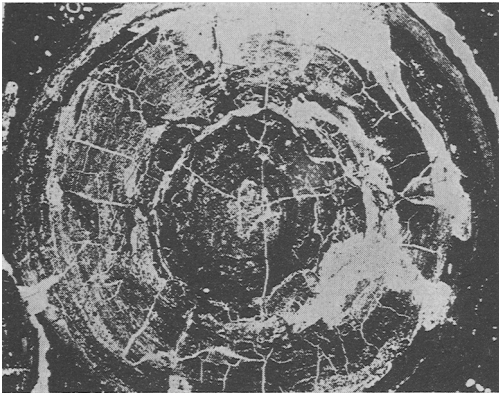

FIG. 5. **Banded** spherule in laterite showing concentric and radial cracks. Samnapur, India. × 11.
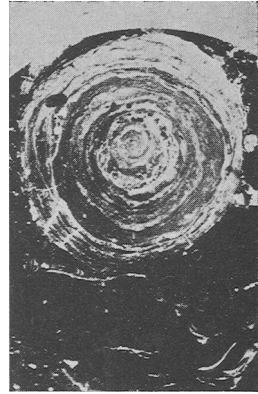
FIG. 6. Spherule in laterite showing concentrically banded structure and closely cemented by matrix. Ejuanema, Gold Coast. × 11.

colloid consisting of two constituents, the one less stable in the colloidal state would form a ring round a nucleus, say, an unaltered mineral of the original rock. The removal of a portion of the less stable colloid to form the first ring will increase the concentration and consequently the coagulation velocity of the second colloid in the mixture and thus enable it to form a second ring. The concentration and the coagulation of the less stable colloid that formed the first ring would now have increased, resulting in the formation of a third ring. In this manner spherules with a banded structure would be formed (fig. 6). The presence in the colloid of a third constituent of the rock would serve the function of the desired impurity and hasten the formation of this structure. The

[1] H. Freundlich, Colloidal and capillary chemistry (1923), English translation, 1927, p. 733.

formation of banded structure would, as pointed out by Lindgren[1], be accompanied by expulsion of water and reduction of volume, resulting in concentric and radial cracks (fig. 5) in which secondary gibbsite is sometimes formed.

The two sets of chemical analyses given below show the difference in composition between the spherules and their respective matrices in two specimens of laterites.

		Unlocalized (no. 46). (Analysed by T. V. M. Rao.)				Maddox, Georgia, U.S.A.[2]	
		Spherule.	Matrix.			Spherule.	Matrix.
SiO_2	...	1·01	0·64	...	...	3·74	0·62
Al_2O_3	...	54·78	62·91	...	...	52·36	64·91
Fe_2O_3	...	4·08	1·92	...	...	0·76	0·28
MgO	...	0·80	nil	...	...	nil	nil
CaO	...	0·79	0·68	...	...	nil	nil
Na_2O	...	0·27	0·36	...	...	nil	nil
K_2O	...	0·12	0·02	...	...	nil	nil
$H_2O(+)$	...	27·36	27·53	...	...	33·17	33·00
$H_2O(-110°C.)$	—	—	...	...	0·20	0·53
TiO_2	...	11·46	5·97	...	...	9·70	1·05
Total	...	100·67	100·03	...	...	99·93	100·39

The percentages of all constituents except those of alumina are greater in the spherules than in the matrices.

During the description of specimens of laterites it was pointed out that in some of the specimens the spherules were easily detachable intact from the matrix, while in others this was not possible. In the absence of any explanation for this feature, the following suggestion might be offered. If after the lateritization of the rock the spherules were to form and consolidate before the matrix, they would be easily detachable intact. But if, on the other hand, the matrix and the spherules consolidated simultaneously, the soft outermost walls of the spherules would become confluent with the matrix and when the specimen becomes indurated would be undetachable intact.

IX. *Summary and Conclusions.*

The chief points emerging from this paper are the following:

(1) The process of lateritization consists of the action of alkali carbonates on the aluminium silicates of rocks, when hydrated aluminium

[1] W. Lindgren, Bull. Geol. Soc. Amer., 1925, vol. 36, p. 254.

[2] Vide T. L. Watson, Amer. Geologist, 1901, vol. 28, p. 25, for this set of analyses.

carbonate is formed; this compound being unstable breaks down into hydrated aluminium oxide, which is deposited in the form of bauxite. This, together with the undecomposed minerals of the rock, forms laterites.

(2) Bauxite is a definite mineral having a composition corresponding to a dihydrate of alumina.

(3) The gibbsite present in laterites is of secondary origin formed by hydration of bauxite.

(4) Diaspore never occurs in laterites, as mere conditions of lateritization are not sufficient for its formation.

(5) Felspar, micas, kyanite, tourmaline, haematite, magnetite, limonite, pyrite, ilmenite, rutile, anatase, and sphene, some of primary and others of secondary origin, have been definitely found to occur in laterites.

X. *Acknowledgements.*