

# ***ORIGIN OF BAUXITE***

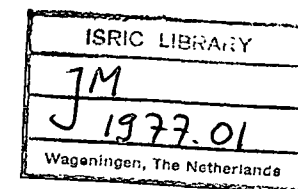
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the Journal of the Geological Society of Jamaica**

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The present work is an overestimate of the removal time as it is concerned solely with the solutional erosion of the limestone and discounts entirely other forms of erosional activity that are operative on limestone and non-limestone terrain alike. Material is transported from the White Limestone by processes other than that of solution such as suspended and traction stream load. The removal of material from a unit area of White Limestone by means other than solutional erosion is probably less than is the case for a comparable area of non-limestone terrain. This would be particularly true for material removed by normal river transport as traction (or bed) load. The subterranean nature of the drainage lines in the White Limestone would probably carry less traction load due to the restricted cave passages and sumps through which the streams flow. A sump situation would tend to act as a setting pool for coarser grades of sediment. It is not possible to give any realistic measure of this overestimate.

#### CONCLUSION

The assumptions present difficulties in stating an absolute value for the time necessary for the removal of the 780 feet of White Limestone suggested by Sinclair as necessary for the formation of the bauxite deposits by a residual hypothesis. If the major assumption is permitted that climatic conditions, especially rainfall, have remained relatively constant over the period, the limestone could have been removed by solutional processes alone in a period of 3 1/2 to 6 million years. Fluvial transport of material other than of a solutional nature would cause this estimate to be reduced but to some extent this is balanced by Sinclair's assumption that none of the weathered insoluble residue of the limestone was removed from the region.

It would seem a valid overall conclusion that the removal of the thickness of White Limestone necessary for the residual weathering of bauxite genesis in Jamaica is possible in the time since erosion is presumed to have commenced in the mid-Miocene. The most reliable absolute age for the mid-Miocene is 12 million years for the upper boundary and 18-19 million years for the lower (Funnell, p.190, 1964). This would seem to allow an ample margin to cover the assumptions and errors likely to affect the figures presented.

#### ACKNOWLEDGEMENT

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## PREFACE

The genesis of bauxite, and Jamaican bauxite in particular, has been the subject of much scientific deliberation over the past two decades. Many of the earlier papers published in *Geonotes*, which later became the *Journal of the Geological Society of Jamaica*, are not readily accessible because the original publications are now out of print. This reprint volume is an attempt to make these papers more generally available.

The papers, and discussions contained in this volume, provide interesting arguments as to whether the various Jamaican bauxites originated from a residual limestone source, or were formed from volcanic-based materials transported to the present sites of deposition. None of the authors in this volume support windblown volcanic ash as a source material for Jamaican bauxites. Some workers in the 1970's have provided evidence compatible with such a derivation, although the quantum of bauxite thus formed may be relatively small.

The debate continues.

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Substitution of these figures in the formula of Corbel with its modifications by Williams gives the following values for the thickness of limestone removed.

Albert Town	68.5 mm/1,600 yr.
Stepney	39.8 mm/1,000 yr.

Using these figures the time necessary to remove the 780 feet of White Limestone postulated by Sinclair is  $3.47 \times 10^6$  yr. for Albert Town and  $5.98 \times 10^6$  yr. for Stepney.

### ASSUMPTION AND MAJOR SOURCES OF ERROR

#### (a) Climate.

In presenting any estimate concerning the rate of erosion in the past the major assumption relates to an assessment of previous climatic conditions. Rarely it is possible in tropical latitudes to do other than assume that conditions in the recent past were similar on balance to those of the present. No detailed outline of the palaeoclimatology of Jamaica or the Caribbean exists for the period of the last five million years or so. In calculating the evapotranspiration estimates the precipitation figures are more critical than those of temperature. The generalised climatic situation for the recent past of the tropics indicates that temperature figures are unlikely to have changed significantly. Any major errors in the suggested time period are most likely to be due to unwarranted assumptions regarding precipitation.

#### (b) Hardness figures.

If climatic conditions changed in the past it is possible that the hardness figures would have shown some sympathetic variation. This is not thought to have been the case within the range of climatic change likely to have been experienced in the last million years.

There is also a possibility that the drainage from the White Limestone area under consideration does not all emerge at the surface to flow from the spring sites sampled. A proportion of the flow may emerge in submarine springs the existence of which is known around the coasts of the island (personal communication, Geological Survey). This is not thought to be a major source of error as such water would probably have a similar hardness to that emerging at inland spring sites. The constancy of the hardness figures can be interpreted as indicating a form of 'saturated' value with the prevailing processes responsible for the solutional erosion of limestone in the region.

#### (c) Erosion other than that of a solutional nature.

In Sinclair's work the implicit assumption is made that none of the insoluble residue of the weathered White Limestone is removed by erosional processes. This is clearly not the case as some of the insoluble residue is removed as suspended load by the water emerging at the springs sampled. No quantitative estimates are available for the sediment removed in this manner although attention was drawn to this process by Zans (1959, p.127-129). It is difficult however, to see how a reliable estimate of the insoluble residue removed in this manner could be obtained. This omission indicates that the thickness of limestone necessary to yield the suggested residue is an underestimate by a factor that is indeterminable.

RECENT VIEWS ON THE ORIGIN OF BAUXITE

V. A. Zans

To understand the composition, properties and mode of occurrence of a mineral deposit, it is essential that its genesis be fully understood. In the case of bauxite deposits it is particularly important to determine the source rock or the source beds from which these deposits derive.

According to their mode of occurrence and host-rocks the bauxite deposits of the world can be classified into two major groups: (1) those associated with and obviously derived from igneous or other rocks rich in aluminium silicate minerals, and (2) those occurring on or closely associated with limestones and dolomites, i.e. calcareous rocks, carrying only a very low alumina content in the form of impurities, or being in places practically non-aluminous. Bauxites of the first group are usually called lateritic bauxites or laterite bauxite, also silicate bauxites, while those of the latter group have been designated as "terra rossa" bauxites, limestone bauxites or karst bauxites. To the former group belong the important deposits of the British and Dutch Guianas, India, West Africa, Arkansas in U.S.A. and many others. The well known examples of the "terra rossa" bauxites, or bauxites proper, are the Mesozoic and early Tertiary deposits of the Mediterranean countries (Southern France, Italy, Greece, Yugoslavia, Hungary) and the large late Tertiary ferruginous bauxite deposits of the West Indies (Jamaica, Haiti and the Dominican Republic).

Since the discovery of laterite and bauxite early in the last century a great deal of chemical mineralogical and geological research work has been carried out in many countries in order to assess the origin of these deposits. As a result, the formation of bauxite deposits from parent rocks rich in aluminium silicates is now sufficiently well understood (Fox, C. S., 1932; Allen, V. T. 1948; Harder, E. C., 1949, 1952; Eyles, V. W., 1952). A number of theories have been advanced in the past, some of them implying processes of solution and chemical precipitation or even replacement of host-rocks by hot aluminium-bearing solutions etc. Many of these theories have been abandoned and today apart from minor differences in opinion, most geologists are agreed that laterite bauxites are nothing but residual products derived from aluminium-bearing source rocks by deep tropical weathering. This process involves decomposition of the aluminium silicates of the source rock, gradual removal of alkalies, lime, magnesia, etc. by leaching, followed by removal of silica leaving behind hydrated aluminium and iron oxides in addition to titania and other minor insoluble impurities. The concentration of these elements in residual deposits is in agreement with their geochemical behaviour as determined by their ionic potential (Goldschmidt, 1937).

The climatic conditions necessary for bauxite formation are: (1) A temperature above 20°C and (2) alternating wet and dry seasons which favour chemical processes of leaching and removal of silica and concentration of iron oxide and alumina. Thus laterite bauxites (and indeed all bauxites) are now recognised as typical terrestrial or continental deposits formed under the conditions of a tropical (tropical-savannah), or sub-tropical climate during prolonged breaks of marine sedimentation, when old weathering surfaces develop at or near the peneplain stage of a geomorphic cycle. Most of these deposits are no doubt eluvial in their nature or formed in situ, although some of them can also be allochthonous or alluvial.

It is now considered that any kind of basic or intermediate igneous rock as well as metamorphic or clastic-sedimentary derivatives of these rocks can produce bauxite under suitable climatic and drainage conditions, provided there is sufficient time for the completion of the alteration process. Of the aluminium silicate minerals of igneous rocks, the calcic plagioclase feldspars appear to be those which most readily yield bauxite. The principal stages of alterations involved can be briefly summarised as follows:-

Aluminium silicate minerals of the parent rock  
Kaolinization

This is particularly the case when individual months have a moisture deficit i.e. the potential evapotranspiration is in excess of the precipitation. The figures obtained using two formulae for the calculation of potential evapotranspiration (Table 3) are obtained by the methods described by Khosla (1952) and Holdridge (1959). A method for the calculation of effective run-off that does not rely solely upon considerations of potential evapotranspiration is given by Thornthwaite and Mather (1957, p. 185-311). This method allows for the effects of monthly moisture deficits, soil moisture storage, cover type of vegetation, latitude and its effect regarding length of daily sun hours. All the values for potential or actual evapotranspiration presented below in Table 3 are summations values for individual months to give an annual figure. In all the calculations the temperatures used are the long term monthly means for Lorrimer's Banana Research Station (Anon., 1965, p. 39) which is situated at an altitude of 2,847 ft. These temperature figures have been used as the altitude of this station is comparable to the elevation of the major part of the White Limestone under consideration. The results for effective run-off as obtained from Khosla (1952), Holdridge (1959) and Mather (1957) are given in Table 3.

Table 3: Potential Evapotranspiration and Effective Run-off Figures at two stations in Jamaica.

	Potential Evapotranspiration		Effective Run-off		
	Khosla	Holdridge	Khosla	Holdridge	Thornthwaite & Mather
Albert Town			30.28	28.92	37.72
	48.84	50.20			
Stepney			11.97	10.61	21.91

All figures are annual means and are in inches.

The values used in the calculations for the rate of solutional erosion of the White Limestone are those obtained by using the Thornthwaite and Mather method which is considered to be the best available method applicable to the area and data available.

RATE OF LIMESTONE EROSION

The mean density of the White Limestone as obtained by Sinclair was 2.42 g/cm<sup>3</sup>. The mean calcium hardness value, T<sub>c</sub>, is taken as 150 p.p.m. CaCO<sub>3</sub>. The mean magnesium hardness value, T<sub>m</sub>, is taken as 23 p.p.m. MgCO<sub>3</sub>.

The effective annual run-off value for the precipitation figures for Albert Town obtained from the Thornthwaite and Mather formula is 37.72 in. (9.58 dm). The corresponding figure for Stepney is 21.91 in (5.57 d.m.).

Lithomarge (a transition rock consisting essentially of hydrated silicates of alumina or clay minerals of kaolinite group)

#### Laterization

Laterite (a mixture of hydroxides of iron and aluminium in varying proportions plus some titania and other residue left behind after the elimination of alkalies, lime, magnesia, and partly silica)

#### Bauxitization

Bauxite (a largely desilicated end product characterised by the predominance of hydrated aluminium oxides in addition to iron hydroxides, remaining silica and other impurities).

It should be noted, however, that all these stages are not always encountered and plagioclase feldspars may alter directly into gibbsite (aluminium trihydrate of bauxite) without passing through the lithomarge or kaolinite stage. This, for instance has been found to be the case of the Arkansas bauxites lying directly on nepheline syenite, and has recently been confirmed by investigations of bauxite occurrences of Kauai, Hawaiian Islands (Abbot, A.T., 1958), where gibbsitic bauxite is derived from olivine basalts.

Turning now to the problem of origin of bauxites associated with limestone, difficulties are encountered as in this case it is problematical as to whether the source can be attributed to the host-rock which does not contain aluminium silicates and usually carries only a very low sesquioxide content. The main question is, what is the source of alumina and iron in these bauxites? Can they be derived solely from the residue left behind after the dissolution of large portions of limestone rock, or might there be other source rocks involved? Are these deposits lying on limestone substratum, formed in situ (eluvial) or are they alluvial? Unfortunately, we have to admit that up to now a fully satisfactory solution to these questions has not been arrived at and consequently the origin and the question of the ultimate source of limestone bauxites is still a controversial problem.

The first investigators of the Mediterranean bauxites advanced the theory of the residual origin of these deposits due to solution of limestone. Mention should be made here of the invaluable work of Kispatic (1912) and Tucan (1912) who said that such deposits were derived from "terra rossa" which in turn they thought to be nothing but an accumulation of insoluble residue left behind after the decalcification of limestone. In fact, the last-named author found that "terra rossa" and bauxite are practically identical products. According to him bauxite should be an advanced or older stage of "terra rossa" and "terra rossa" an undeveloped bauxite. Indeed the chemical analysis of Mediterranean "terra rossa" shows 10 - 40%  $Al_2O_3$ , 5 - 17%  $Fe_2O_3$ , 20 - 60%  $SiO_2$ , up to 1.5% MnO, 1 - 3%  $TiO_2$  and 7 - 20% combined water, CaO and alkalies, while the average composition of the Mediterranean bauxite is as follows: 57-60%  $Al_2O_3$ , 12-25%  $Fe_2O_3$ , 2-7%  $SiO_2$ , 2.5 - 3.5%  $TiO_2$  and 12-14% combined water. It is apparent from these analytical data, that the main difference between the two lies in the silica content, which is appreciably higher in "terra rossa", thus demonstrating its argillaceous composition, while the bauxite is a far more desilicated product.

The views of Kispatic and Tucan were subsequently adopted by many other authors and in fact up to the present, the solution residue or "terra rossa" theory of the origin of limestone bauxites is still the most widely held view among geologists. This view became more established after the work of De Lapparent (1930) in France, and was more recently revived by De Weisse (1948, 1949) for the bauxite deposits of Dalmatia and Hungary. This orthodox view has not, however, remained unchallenged; a number of authors have opposed it, pointing out that enormous thicknesses of limestone rock would have to be dissolved to produce such thicknesses of "terra rossa" and bauxite as actually occur in the deposits and in many cases it has been considered that this is quite impossible. Objections have also been raised from the geochemical point of view and there is reasonable doubt as to the formation of these deposits in situ. It has also been pointed out that no such process has actually been demonstrated to be now in progress in tropical countries.

given in Smith (1969, Table 5.2 and Figs. 5.9 and 5.10). For example the spring near Dromilly (grid ref. 299533) has a mean total hardness figure of 172 p.p.m. calcium hardness 154 p.p.m.  $CaCO_3$  and magnesium hardness of 18 p.p.m.  $MgCO_3$ . The ratio of calcium to magnesium from the sites in eastern St. James and from the sites listed in Table 1 from St. Ann is remarkably constant. This may indicate that the ratio of calcium to magnesium in the bedrock is comparable to that obtained from an analysis of the water samples. The difficulty in verifying this statement is the paucity of published data relating to the calcium to magnesium ratio of the bedrock. However, work undertaken by the author on the limestones of western Scotland (Smith, in litt) for which both water and bedrock analyses are available demonstrates that in that region there is close agreement between the two ratios.

#### EFFECTIVE RUN-OFF

The remaining variable necessary to obtain an estimate for the rate of limestone solutional erosion is a measure of the effective run-off. Effective run-off can be defined as the precipitation less the actual evapotranspiration, for the purposes of this paper measured in terms of mean annual figures. For the areas of White Limestone outcrop there is virtually no surface run-off. The effective run-off is by means of subterranean flow of which a proportion at least appears at spring sites listed in Table 1. Full discharge records for the sites sampled are not available and if they were it would not be possible to delimit the catchment area of any individual river as there is no simple method of obtaining information on the extent of the subterranean drainage net. It is possible to calculate values for the effective run-off although it should be stressed that such values are best considered as estimates.

A number of rainfall recording stations are located in the White Limestone area under consideration. The long term mean monthly rainfall figures for these stations are given in the Handbook of Jamaica (Anon., 1965, 42-62) and a rainfall atlas for Jamaica is also available (S.R.C. Jamaica, 1965). Additionally Sweeting (1956, p.2) in a study of the hydrology of the White Limestone states that the mean annual rainfall for this part of the island varies between 75 and 100 in. per year. The calculations for evapotranspiration described below necessitate monthly mean rainfall figures but of the rainfall stations for which such figures are available most are located at altitudes below that of the main White Limestone surface. This lower altitude leads to a rain shadow effect and the rainfall totals of such stations are an under-estimate of the rain falling on the greater part of the White Limestone catchment. With this problem two rainfall stations have been selected, namely Albert Town and Stepney. The former has a mean annual rainfall of 79.12 in. (Anon., 1965, p.44) and the latter a mean annual rainfall of 60.81 in. (Anon., 1965, p.46). The mean annual rainfall for the area as a whole is thought to fall within the rainfall range of these two stations.

Evapotranspiration is a difficult quantity to measure or estimate. Various workers have outlined empirically derived formulae for the calculation of potential evapotranspiration (Khosla, 1952, Holdridge, 1959) but considerable differences may exist between the actual and potential evapotranspiration values, (Thorntwaite and Mather 1957).

Table 2: Detailed analyses of calcium and magnesium hardness of samples collected from the sites listed in Table 1.

Date.	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Nov. 19th	150 23	168 21	170 27	153 23	133 23	158 21	160 25	123 42	133 38
Dec. 28th		163 30	163 30	153 19	133 25	163 21	153 15	130 34	138 21
Jan. 9th		163 21	160 27	150 25	138 23	163 23	158 23	138 23	138 23
Feb. 25th	163 27	165 13	163 30	148 25	145 15	163 21	145 19	135 23	133 21
Feb. 26th		163 21	168 23	155 27	133 23	160 21	180 23	140 21	140 25
Apr. 2nd	153 19	160 23	150 21	153 19	133 19	140 23	138 17	138 17	143 19
Apr. 30th	158 17	158 23	173 21	148 23	135 25	138 25	148 19	150 30	130 21
May 24th	150 15	155 21	158 23	153 30	125 19	138 23	148 17	160 30	120 23
June 8th		158 19	168 27	145 27	123 25		138 23	173 23	130 19
June 17th		153 23	168 23	140 23	120 25	138 25	135 19	200 34	123 23
July 10th		153 23	164 23	145 24	131 24	163 30	150 21	183 25	135 27
July 23rd		156 26	152 29	142 28	128 24	163 26	145 19	178 17	130 29
July 27th		151	167 24		131 26	162 21			124 21
Aug. 5th		144		156 15	141 23				120 26
Aug. 21st	161 34	161 22	159 27	149 21	132 26		167 29		150 18
	Ca Mg	Ca Mg	Ca Mg	Ca Mg	Ca Mg	Ca Mg	Ca Mg	Ca Mg	Ca Mg

All hardness figures are in p.p.m.

In France the eluvial origin of the Langue doc "terra rossa" has been criticised by V. Agafonoff and P. Graziansky (1933), M.B. Geze (1947) and others. Several objections on the same matter have also been expressed by E. Vadasz (1946, 1956) in Hungary. In the last mentioned paper Vadasz has even gone as far as to assert that the "terra rossa" of Hungary is a degraded bauxite, thus reversing the earlier assumptions.

Recently M.H. Erhart (1956) and M.E. Roch (1956, 1957) in France have strongly opposed the eluvial theory and claim that the bauxites of Provence and Languedoc are of alluvial origin and that the source of alumina in this case should be looked for in the aluminium silicate rocks of the Central Massif of France, which has been subjected to denudation since the Albian. While Erhart suggested transport of weathering detritus by running water, Roch proposes aeolian transport of weathering fines. According to him aeolian dust accumulations (very much like loess) were retained in pockets and solution depressions of previously karstified limestone country, where under suitable climatic conditions they subsequently evolved into bauxite. Roch also points out that in many French bauxite mines bauxite can be seen separated from the limestone wall-rock by discontinuous layers of manganeseiferous red clays, breccias or conglomerates containing fragments of rocks often foreign to the immediate wall, and thus proving the independence of the bauxite relative to its wall-rock.

Of the other European authors who have recently arrived at the conclusion that the sources of the Mediterranean bauxite are rocks other than limestone, mention should be made of St. Miholic (1956), who finds that the bauxite deposits of SW Croatia are derived from the Eocene shales and not from limestone as generally believed. In Italy, the results of the geochemical and geological investigations of certain bauxite deposits of Terra d'Otranto by V. Mineri (1954) are also at variance with the conventional theories on the origin of these deposits.

When the discovery was made in 1942, that the red ferruginous earth of the Tertiary limestone areas of Jamaica was bauxitic and in fact so rich in alumina as to rank as a commercial grade bauxite, it was soon realised that these deposits are nothing but a more recent equivalent of the Mediterranean bauxite. Identical deposits were located a few years later in Haiti and Dominican Republic. Both in Jamaica and in Hispaniola large deposits of this type of bauxite are found as surface deposits resting on very pure Tertiary limestone with an average alumina content of less than 0.1 per cent. As to their origin, the first workers on Jamaican bauxite (Schmedeman, 1948, Hose 1950, Harder 1949, 1952) adopted without more ado the limestone residue theory. However, the detailed work on these deposits in Haiti and the Dominican Republic led Goldrich and Bergquist (1947, 1948) to the conclusion that they "may be an inherited soil derived from source material other than the limestone on which the deposits now rest."

In their latter paper Goldrich and Bergquist (1948, p. 104-105, 109) submitted more evidence in favour of this view and were able to state that the chemical and mineralogical composition of these bauxites in particular the ratios of  $Al_2O_3:Fe_2O_3:TiO_2$  suggest an igneous parent material of intermediate or andesitic composition. It was noted by the authors that such rocks are of widespread occurrence in the West Indies but no effort was made to explain in what manner and by what geological agencies the weathering products of such andesitic rocks were introduced into the limestone environment. It was considered that beds of volcanic ash or tuff were once overlying the limestone series and have been subsequently eroded. In Jamaica there is, however, no evidence of any sizeable occurrence of such deposits in the preserved late Tertiary sequence overlying the White Limestone Formation, but extensive beds of andesitic rocks and pyroclastics are known to occur widely in the stratigraphical horizons underlying the White Limestone Formation.

Considering the youthfulness and the surface occurrence of the Caribbean bauxite deposits, it would appear that these should provide a clue or an excellent example for the elucidation of the origin of this type of bauxite. However, subsequent mineralogical and chemical investigations carried out on Jamaican bauxites by V. G. Hill (1955) and J.A. Hartman (1955) did not introduce any new evidence and both authors retained the conventional view that the immediate source of these bauxites is the White Limestone Formation. Calculations were made as to what thickness of limestone has been dissolved and it was considered that the small amount of sesquioxides contained in the White Limestone in form of impurities were sufficient to yield large deposits of red earth and bauxite attaining in places a thickness of over 140 feet. While Hartman (1955, p. 746) admits that



the ultimate source of the impurities in the limestone may be a volcanic ash that settled into the basin of limestone sedimentation Hill (1955, p. 687) pointed out that clay minerals of the montmorillonite group should be present in the bauxitic clays if a volcanic ash was the source material.

Thousands of analyses made from various deposits of red earth in the course of prospecting for commercial bauxite have revealed that in Jamaica there occur all the transitional grades from the high silica argillaceous "terra rossa" to good grade bauxite of less than 3.5 percent  $\text{SiO}_2$  and over 50 per cent  $\text{Al}_2\text{O}_3$ . It was also found (Zans 1954) that the best low-silica deposits of uniform grade occur as a rule at higher altitudes of say over 750 feet a.s. Actually, the height above sea level is less important than the height above the water-table and the drainage conditions of the deposits. Deposits lying at lower altitudes close to or within the range of the fluctuating water-table have remained argillaceous and usually carry a high silica content, while those at higher levels are much more desilicated. But even in large deposits of commercial bauxite the total silica, iron and titania are as a rule slightly above the average in the extreme upper and lower layers of the deposit so that the cores of such deposits invariably show a better grade bauxite. (See Fig. 1, Zans, 1954, p. 315). There is at present little doubt that the bauxites of Jamaica are derived from the argillaceous "terra rossa" by the process of desilication which quite probably still goes on under the existing conditions of tropical-savannah climate. However, the question still confronts us as to what actually is "terra rossa" and what is its source.

The present writer (Zans, 1951, 1956) approved the problem by studying the actual process of karst development and karst hydrology in Jamaica. These studies reveal that in the late maturity and old age stages of the karst cycle when rocks of the karst basis are laid bare in upland areas, these supply a large amount of weathering detritus which is carried into the cavernous limestone environment by sinking karst streams. This load including certain amounts of limestone residue is being trapped in solution pockets partly underground or more often in the depressions and karst valleys where these streams rise at lower levels. When subsequently uplifted and subjected to the effects of tropical savannah climate these clayey sediments evolved into "terra rossa" and bauxite. A theory was put forward (Zans 1956) thus advocating the alluvial origin of "terra rossa" due to the action of karst streams or free karst ground-water flow.

In Jamaica the karstification of the thick Tertiary calcareous series, comprising the Yellow and White Limestone Formations, has reached a very advanced stage, particularly at higher levels where these limestones have been exposed to denudation since the Miocene uplift. In the "Cockpit Country" on both flanks of the anticlinal range of the island, not only is the surface dotted with thousands of sinkholes absorbing the surface water, but the whole thickness of limestone is penetrated by innumerable underground channels and caves allowing a free sub-horizontal flow of karst water governed by the incline of the impervious karst base. This latter consists of tuffaceous shales or other andesitic rocks and is at present exposed in many inliers along the central axis of the island at elevations ranging up to 3,000 ft. a.s. (Fig.1). All these inliers, being essentially outcrops of lateritic weathering tuffaceous and andesitic rocks, are drained by streams which enter the limestone terrain on the flanks either as normal surface streams or more usually as underground rivers disappearing in shallow holes at the rim of the limestone outcrop and reappearing in low-lying interior valleys or karst depressions several miles away. In fact all the large rivers of the limestone areas of Jamaica have their sources or "heads" in the inliers of Cretaceous or early Eocene andesitic rocks which due to the anticlinal structure of the island are or were exposed at higher levels than the limestone beds on the flanks.

The study of such subterranean streams reveals that an enormous amount of lateritic weathering material from the andesitic and tuffaceous beds of the inliers is brought into the cavernous limestone every year particularly during the rainy seasons when the subterranean karst flow is at its maximum. Much of the coarser sandy material derived from this source is trapped in the caves and irregular underground conduits and, if one examines the bottom sediments of the now dry tunnel caves in the Cockpit Country, considerable accumulations of quartz sand, and sand rich in magnetite etc. can be found flooring much caves. Deposits of similar material foreign to limestone environment are found not only in the caves but more often at the outlets of large underground streams miles away from their original source beds. The fine clayey fraction as well as all the material

Table 1: Mean hardness values.

Sampling Site..	$\text{CaCO}_3$ in p.p.m.	$\text{MgCO}_3$ in p.p.m.	Total Hardness in p.p.m.	Number of samples.
1. White River.	156	23	179	6
2. River at The Ruin, Ocho Rios.	158	21	179	15
3. River to the West of Ocho Rios.	163	25	188	14
4. Cave River	149	24	173	14
5. Dunns River	132	23	155	15
6. Roaring River	154	23	177	13
7. River to West of St. Ann's Bay	151	21	172	13
8. River near Mile Post 49.	154	27	181	12
9. Laughlands Great River. Llandovery	131	24	155	15

There was little variation in the hardness values at any individual site throughout the period of observation. (Table 2). The samples were collected under a variety of discharge conditions including a number at times of storm discharge. Unfortunately no absolute discharge records were available for any of these rivers. The base flow of the rivers sampled varied very considerably from site to site but there was no significant relationship between size and hardness.

Figure 2 illustrates the total hardness values obtained for two of the sites, namely the Laughlands Great River at Llandovery and the Cave River to the east of Dunn's River. These two examples are considered typical of all the sites sampled.

Thus it would seem a tenable hypothesis to suggest that the mean of the values given in Table 1 could be assumed to represent the hardness values necessary for substitution in the formula (outlined above) to obtain a value for the rate of erosion. The mean total hardness for the rivers draining the White Limestone of this section of the island is 173 ppm consisting of 150 p.p.m.  $\text{CaCO}_3$  and 23 p.p.m.  $\text{MgCO}_3$ .

#### CALCIUM HARDNESS IN RELATION TO MAGNESIUM HARDNESS

It is worth noting that the hardness figures for other spring sites associated with the White Limestone in other parts of Jamaica appear to be similar to those given above. Results related to the White Limestone of the eastern parts of the parish of St. James are

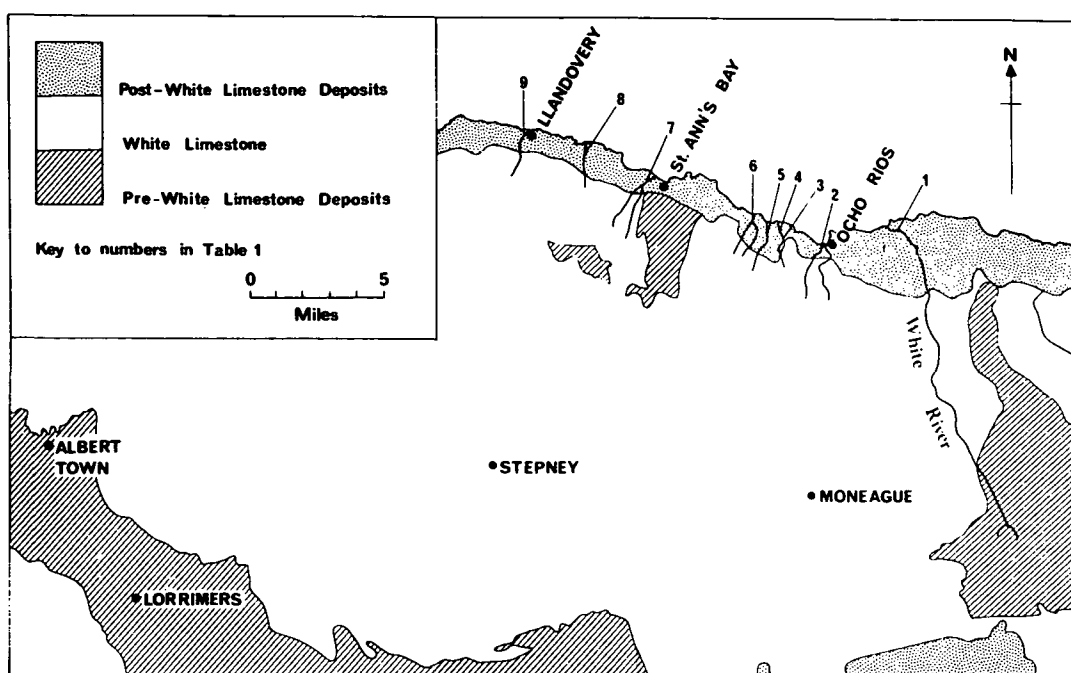


Fig. 1: Sample Locations.

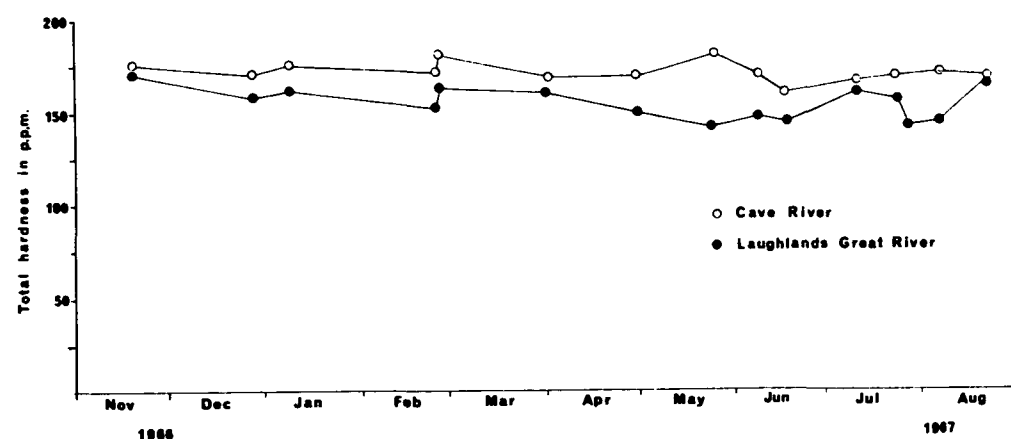


Fig. 2: Plot of water hardness.

in suspension is naturally carried much further or becomes only partially trapped in smaller cavities and pores of the limestone. The bulk of such load is brought to the surface in lowlying areas where the karst streams rise, and is spread out over the floors of karst depressions of various sizes. This phenomenon can be observed in Jamaica at the mouth of practically every large karst spring or vauclusian rise, the best example being the Fontabelle spring at the foot of the Cockpit Country in Lower Trelawny. The head of this water lies in the Warsop area of the Central Inlier. This "boiling" karst spring, emerging along the major fault in White Limestone (Duanvale fault) brings up a considerable volume of yellowish brown clayey material when in spate and distributes it over a large area of the broad Fontabelle valley. This is particularly conspicuous after the heavy rainy seasons. Above the inundation level on the slopes of the valley the same clay can be seen merging into typical "terra rossa" and still higher up into bauxite.

Another good example illustrating the alluvial nature of the clay deposits in limestone country is the area of the Moneague lakes in St. Ann. On several occasions in the past following exceptionally heavy rainy years a depression in the limestone area east of Moneague has been the scene of temporary rising karst lakes. These persist for a year or two and then gradually disappear, the most recent rise having taken place in 1933-34. The highest strand-line of these temporary lakes can still be traced on the slopes of the Moneague depression at 956 feet above sea level. The lakes then covered an area of approximately two square miles. The dry lake bottom is floored with clay sediments directly overlying the White Limestone. Higher up the slopes the clay can be seen grading into "terra rossa" which, still higher up, is bauxitic. The karst stream, which in this case is responsible for the contamination of the ground water with argillaceous matter is the "Great River" of the Guys Hill inlier. It originates in the red weathering Middle Eocene tuffs of the inlier, flows over this formation for a distance of about 3 miles and sinks at Middlesex. After 4 miles of underground flow it reappears at Riverhead as Rio Hoe and sinks again in the Moneague depression. Similar occurrences are quite frequently encountered in other karst areas of Jamaica and in each instance it is possible to trace the source of the karst streams causing such inundation to one of the inliers where lateritic weathering andesitic rocks are exposed producing the bulk of the clay-load of such streams.

These observations demonstrate clearly the alluvial or allochthonous character of argillaceous deposits at present found filling the low-lying karst depressions in the limestone. It is also quite clear that in the course of subsequent uplift which brings these deposits high above the water table they are altered to "terra rossa" and bauxite. It cannot be denied that the residue left behind after the solution of the limestone constitutes a part of these deposits but the bulk of the material obviously originates from the weathering aluminium silicate rocks present in the inliers.

This process of allochthonous clay material being brought into the limestone environment has been continuous since the Miocene uplift and the breaching of the basement anticlines where the andesitic rocks became exposed. In the past when the base level of erosion was much higher than it is today, the rise of clay-charged water in limestone terrain was encountered at much higher levels. The wide occurrence of "terra rossa" and bauxite deposits in the degraded karst areas of Dry Harbour Mountains and elsewhere in Jamaica now lying at altitudes ranging from 1,000 to 2,000 feet, is the result of this process. Due to the subsequent faulting and uplift in some places "terra rossa" and bauxite deposits are now encountered even as high as 3,000 feet.

This theory advocating the alluvial origin of "terra rossa" and implying aluminium silicate rocks as the ultimate source leads us to a much better understanding of a number of facts which cannot be satisfactorily explained by conventional residual theory. It explains for instance why the bauxite deposits in Jamaica are confined to the cavernous and highly karstified Tertiary limestones and dolomite beds flanking the Central Inlier and other inliers of weathering Cretaceous andesitic rocks. The largest deposits are found mainly in the karst depressions at or near the foot of the Cockpit Country. They do not occur, however, on the less cavernous and less karstified chalky marly Montpelier limestones where the free underground flow is impeded. It also explains the fact why there are no bauxite deposits in many limestone areas of tropical countries, as for instance in Yucatan, where there are no sources of aluminium

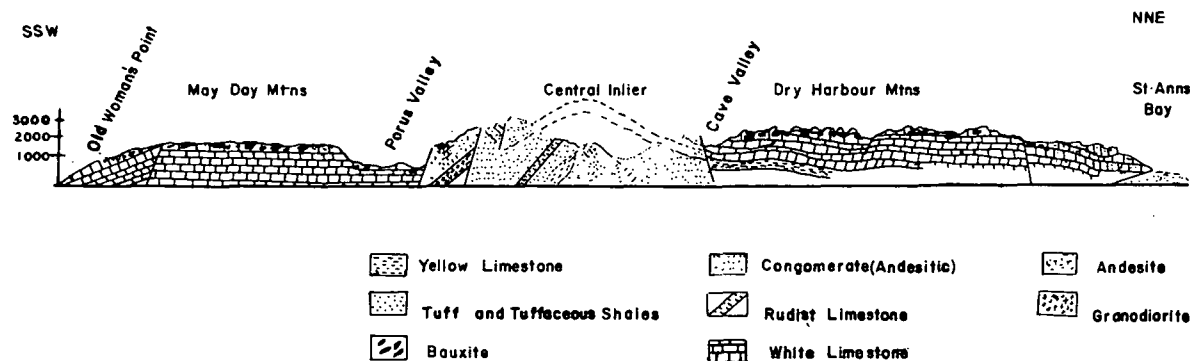


Fig. (1) Diagrammatic section through Central Jamaica showing the breached Central Anticline and the flanking Tertiary Limestones

silicate rocks exposed in the immediate vicinity. In such areas, where the karst base is not exposed, only a relatively small amount of residue is left behind after the solution of the limestone which evidently does not yield bauxite.

As regards the occurrence of pure limestone residue and its relationship to the "terra rossa" and bauxite, and interesting observation recently made in Jamaica should be mentioned here. In 1957 Dr. V.A. Eyles, examining the freshly exposed base of bauxite deposits in some of the open pits of Alumina Jamaica Ltd. at Shooters Hill discovered that in places the bauxite is separated from the limestone substratum by a dark yellowish band of phosphatic clay containing a number of small fossil fish teeth. This layer represents, undoubtedly, a residue of limestone solution. However, it differs considerably from the overlying bauxite which carries no fossils of marine origin. On a subsequent visit to this locality with Dr. Eyles, we examined the occurrence more closely to find that the phosphatic band was discontinuous coating mainly the flat tops of certain pinnacles and was only about one inch in thickness. This shows that: (1) the true limestone residue, where occasionally preserved in situ, is of insignificant thickness as compared with the great thickness of overlying bauxite; (2) the residue is of quite a different nature and has not been altered into bauxite but is highly phosphatic, its phosphate content being derived either from the organic fish remains or from phosphates (bat guano) typically found in the caves of limestone areas. It appears indeed very doubtful that such a residue ever could produce bauxite.

Thus, from our present knowledge of the geological processes involved in the formation of the Caribbean "terra rossa" and bauxite, it appears that the principal source of these deposits is aluminium silicate rocks of the karst base, which owing to the structural features both in Jamaica and Hispaniola are exposed to tropical weathering in many areas topographically above the extensively karstified limestones. The free karst water flow is most probably responsible for the invasion of this parent material into the limestone environment. If this is true, the conclusion may be reached that the identical Mediterranean bauxites could also be derived from similar sources, rather than solely from limestone residue. This will mean that, in fact, all bauxites are derived from the aluminium silicates of igneous rocks or their disintegration products.

The close association of large deposits of bauxite with limestone suggests that the calcareous facies provides in many ways a favourable environment for their formation. First of all it favours the coagulation of clayey suspension brought into this environment and secondly the karst depressions, cavities and pockets of various sizes provide very suitable traps. Furthermore the alkaline environment and excellent drainage conditions are conducive to the desilication of "terra rossa". It has however, to be admitted that a number of points in this connection still remain obscure and a good deal of further research, both geological and geochemical, is still needed to elucidate the problem. For this purpose the bauxite deposits of Jamaica and Hispaniola certainly offer a most favourable example and it is hoped that in the not too distant future investigations carried out on these deposits will lead to more specific and final deductions as their origin.

A measure of the solutional erosion of a limestone region can be obtained by considering the amount of calcium and, in many cases, magnesium carried off in solution by the waters draining the area. If the density of the limestone and the run-off from the region are also known it is possible to calculate the volume of limestone removed. Corbel (1959, p.98) produced a simple formula which permits the volume of limestone transported from an area in solution to be calculated. The original formula considered only the calcium and ignored the magnesium which is also removed in solution. The formula was later modified by Williams (1963, p. 435) to take account of both calcium and magnesium. This is a necessary modification as the majority of limestones are dolomitized to some degree.

Thus to obtain a figure for the time required to remove the 780 feet of White Limestone postulated by Sinclair as necessary to account for the observed Jamaican bauxite deposits three quantities are necessary.

- (i) the density of the limestone
- (ii) the quantity of calcium and magnesium removed in solution per unit volume.
- (iii) a figure for the run-off of the area concerned.

The formula as proposed by Williams (1963) for a catchment composed solely of limestone is as follows:

$$X = \frac{E(T_c + T_m)}{10D}$$

10D

Where X = amount of limestone removed by solution in cubic metres/ year/ sq. kilometre.

$T_c$  = mean  $\text{CaCO}_3$  content in parts per million (hereafter p.p.m.)

$T_m$  = mean  $\text{MgCO}_3$  content in p.p.m.

$D$  = mean density of limestone in  $\text{g/cm}^3$

$E$  = effective annual run-off in decimetres (dm)

Sinclair (1966, p.28) obtained a figure for the mean density of the White Limestone of 151 lb./cu.ft. ( $2.42 \text{ g/cm}^3$ ).

#### CALCIUM AND MAGNESIUM HARDNESS

During the period from November 1966 to September 1967 water samples were collected from nine sites along the north central coast of Jamaica. These sites were located between the White River to the east of Ocho Rios and the Laughlands Great River at Llandovery (see Fig. 1). All of these rivers drain from the White Limestone region of the parish of St. Ann and it is assumed that the whole catchment of these rivers is composed of White Limestone. The samples were analysed for their calcium and magnesium content by means of titration with E.D.T.A. (Schwarzenbach, 1957, and Smith and Mead, 1962, 209-211). The number of samples analysed and the mean calcium and magnesium values for each of the sites are presented in Table 1. The calcium and magnesium values are expressed in terms of calcium carbonate and magnesium carbonate as well as total hardness (the sum of calcium and magnesium carbonate).

THE RESIDUAL HYPOTHESIS FOR THE FORMATION OF JAMAICAN BAUXITE

- A CONSIDERATION OF THE RATE OF LIMESTONE EROSION.

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Abstract

Sinclair has recently suggested that the Jamaican bauxite deposits originated as an insoluble residue resulting from the solutional erosion of the White Limestone. A figure of 780 feet is given for the thickness of limestone erosion necessary to give the required volume of bauxite deposits.

The present work give figures for the concentration of calcium and magnesium for a number of streams draining from the White Limestone of north-central Jamaica. Considerations of the current rate of evapo-transpiration are also given. The contemporary rate of erosion expressed in terms of overall surface lowering is between approximately 70 and 40 mm/1,000 years. If this rate is projected into the past the bauxite deposits could have resulted from the solutional erosion of the White Limestone in a period of between 3 1/2 and 6 million years. A discussion of the most likely major errors and assumptions is also presented.

INTRODUCTION

Recent work by Sinclair (1966) considered the details of the genesis of the Jamaican bauxite deposits. An estimate of the overall bauxite reserves and associated deposits was expressed as equivalent to a layer of terra rossa approximately eight inches thick over the surface of the White Limestone outcrop (Sinclair, 1966, p. 29). Figures for the insoluble residue and density of the White Limestone were also presented (Sinclair, 1966, tables 1 and 2). If the Jamaican bauxite deposits represent a residual soil formed by the weathering of the White Limestone it is then possible to calculate the thickness of limestone necessary to produce eight inches of residual soil. Calculations presented by Sinclair (1966, p.30) give a figure of 780 feet as an estimate of the White Limestone removed. Further (Sinclair, 1966, p. 30) states that the erosion of this thickness of limestone since the Middle Miocene uplift is a reasonable postulate.

Sinclair does not cite any specific figures for the rate of erosion of the limestone either under present conditions or estimates of the rate of erosion in the past. The results presented below discuss the rate of solutional erosion of the White Limestone under contemporary conditions.

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#### Addendum

In a note published in the November 15th, 1958, issue of "Nature", V. A. Eyles describes in detail results of the examination of the above-mentioned phosphatic band underlying bauxite deposits near Mandeville. The band is found to be highly phosphatic, so that some layers could be designated as collophanite (colloidal hydrated calcium phosphate). Another typical feature is the rather high concentration of rare elements including Ag, Ba, Be, Cd, Cr, Cu, Ni, Pb, Sn, Y, Zn, Zr. It exhibits a higher radioactivity than typical terra rossa and bauxite. Its further characteristic is a quite considerable concentration of fish teeth among them teeth of small carcharinid sharks, chaetodonts, sparids, labrids, and scarids.

In the conclusion of his note, Eyles (1958, p. 1368) tentatively classifies the band as a marine phosphorite comparable to those of the Bone Valley formation in Florida. The characteristics of the band indicate clearly, however, that this is not a normal marine sediment. The concentration of rare elements, its high radioactivity, and in particular the concentration of fish teeth are infallible indications of its residual nature. Fossil shark teeth are known to occur occasionally in the White Limestone Formation of Jamaica and have been recorded from two localities, Prospect estate in Portland and Bath estate in Westmoreland, as far back as 1848 (A. G. Johnson, 1848). The abundance of these teeth in the band supports the view that this is nothing but a residue originating from a great thickness of limestone. It must, however, be emphasized that this band differs markedly from the volume of bauxite which overlies it, implying different modes of origin.

If Eyles' correlation of this phosphatic band with the Bone Valley formation is accepted, then the inevitable conclusion is that all Jamaican bauxite deposits which overlie such phosphates are of Post-Pliocene age. There is however, no other evidence to support such a view.

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TABLE 3: pH, Eh and chemical analyses of bauxite and bauxitic clay samples.

Location	pH	Eh	L.O.I.	Silica	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	Al <sub>2</sub> O <sub>3</sub> by diff.	Available Alumina
		Volts							
A <sup>1</sup>	7.60	0.069	21.4	10.6	27.2	2.3	0.6	37.9 <sup>2</sup>	14.8
C	7.52	0.122	27.2	0.6	23.0	1.9	0.8	46.5	30.2
D	7.65	0.142	29.8	1.0	18.4	2.0	0.5	48.3	31.1
F	7.40	0.147	26.7	0.7	23.0	2.5	1.0	46.1	37.3
1	7.10	0.127	25.0	1.8	22.6	2.1	0.9	47.6	39.2
2	6.02	0.163	25.0	0.4	23.9	2.3	1.0	47.4	37.2
3	6.25	0.232	27.4	0.4	18.5	2.0	0.5	51.2	48.8
4	6.40	0.197	25.0	0.4	19.8	2.1	1.1	51.6	43.4

<sup>1</sup> The location letters refer to points on the cross-section, while the numbers refer to tests in Reynolds mining area.

<sup>2</sup> Probably includes some CaO.

#### ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance given by Reynolds Jamaica Mines, Ltd., in providing the equipment and analytical data, and to thank Dr. V. G. Hill of the Scientific Research Council for helpful advice regarding the redox potential measurements.

(Paper originally presented to the 3rd Caribbean Geological Conference, Jamaica, 1962.)

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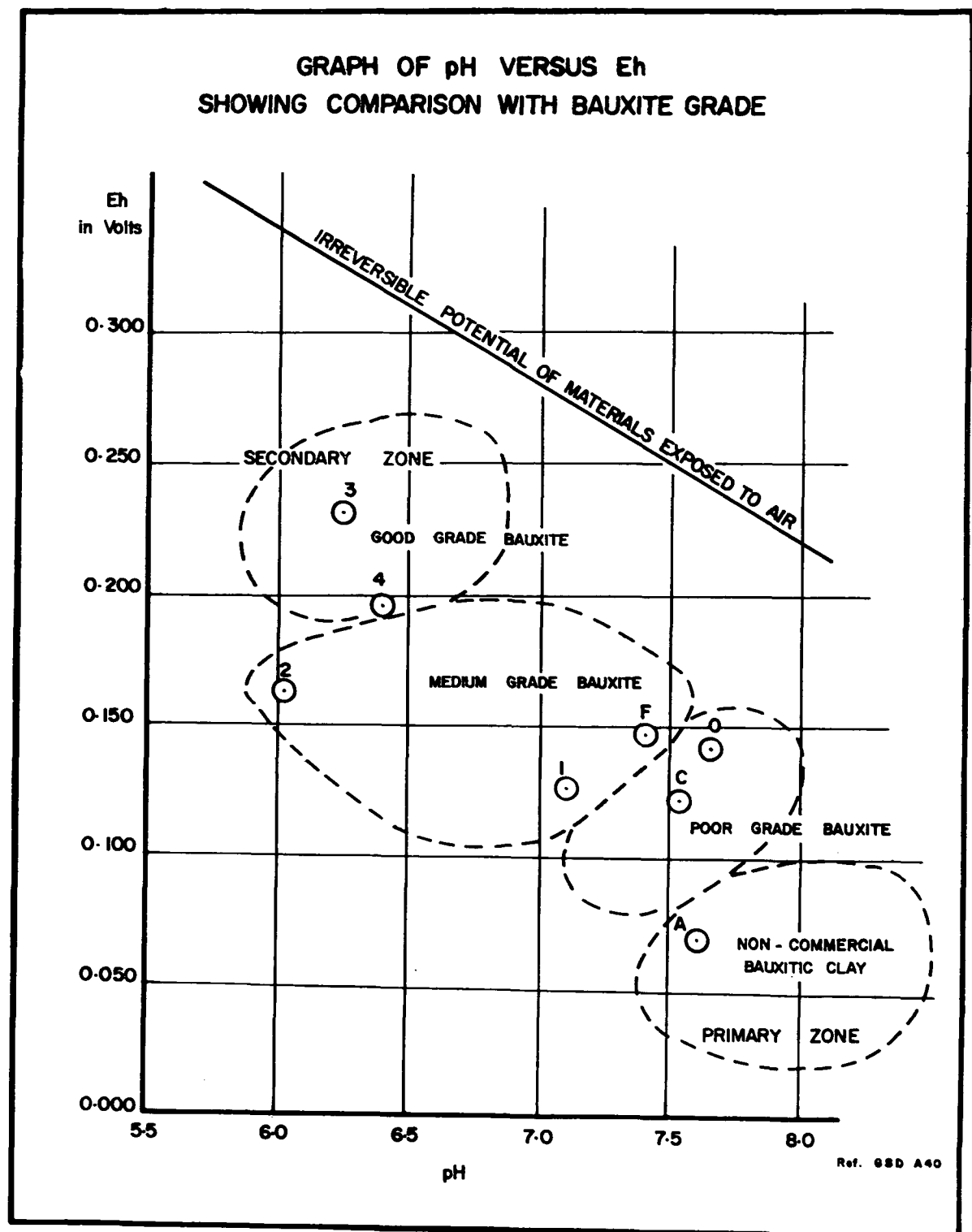
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Fig. 2

NOTE ON A PHOSPHATIC BAND UNDERLYING BAUXITE DEPOSITSIN JAMAICA

by H.G. Kugler  
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V. A. Eyles (1) reports the occurrence of a thin band, generally less than one foot thick, of a phosphatic rock separating the Tertiary limestone of Jamaica from the overlying bauxite. The rock shows the presence of a "considerable number of rare or uncommon elements", amongst which "zinc, cadmium, beryllium and yttrium were found to be present in surprisingly high concentration in certain samples". The band was also found to be considerably more radioactive than the overlying bauxite. The most characteristic feature of the phosphatic rock in the common occurrence of small fish teeth (10 mm.) comprising carcharinid sharks, chaetodonts, sparids, labrids and scarids of possibly Tertiary or younger age.

Eyles classified the sedimentary band as a marine phosphorite and compares it with the Bone Valley formation in Florida. He visualises the possibility of "attenuated and re-sorted remnants of a once more extensive phosphatic deposit, younger than the karstified white limestone (Upper Eocene to Lower Miocene) on which it rests". Evidence of Plio-Pleistocene submergence to heights exceeding 1500 feet are considered to be responsible for the formation of these marine phosphates.

V.A. Zans (2) refers to the note of Eyles and is of the opinion that the dark yellowish band of phosphatic clay "represents undoubtedly a residue of limestone solution", originating from a great thickness of limestone. He sees in the fish teeth a residual part of the limestone which happened to become mixed with the phosphates derived from bat guano commonly found in the limestone caves of Jamaica.

Eyles observed the fish teeth to be small (10 mm.) with no report of any of the large *Carcharodon* or *Lamna* teeth one should expect if the fish teeth would represent a residue of a great thickness of limestone.

The living fish-eating bat *Noctilio leporinus* of Trinidad rarely catches fishes of more than sardine size. The remains of these fishes are a common sight in the limestone caves of Gaspar Grande island off Trinidad. A deposit of fish guano could be formed by this bat and thus explain the accumulation of rarer elements. However, the fish teeth of Jamaica appear to be much larger than those of fishes caught by *Noctilio* of Trinidad. It is suggested that the fish remains of Jamaica could derive from guano of an extinct fish-eating bat of larger size than the present one.

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Pointe-a-Pierre,  
Trinidad, W.I.  
18th August, 1959.

DISCUSSIONS ON THE ORIGIN OF BAUXITE ASSOCIATED WITH LIMESTONE

The article entitled "Recent Views on the Origin of Bauxite" by V. A. Zans published in GEONOTES, Vol.1, No.5, January 1959, pp.123-132, has attracted considerable interest among bauxite geologists in many countries, and has stimulated widespread discussions on the subject. As readers will remember, the article contains both a review of current opinions and a full account of Prof. Zans' own views on the origin of limestone bauxite. Since the appearance of the article both its author and myself have received a number of comments in letters from bauxite geologists and other experts in various parts of the world, including the U.S.S.R. As these are of great general interest and deal with the basic problems of the sources and origin of bauxite associated with limestone, I have thought it appropriate to publish here the views expressed in this correspondence which I hope will stimulate yet further discussion on the problem raised.

EDITOR.

1. DR. V. A. EYLES, Geologist, Oxford, England.

Well known for his studies on the composition and origin of the Antrim laterites and bauxites, Dr. Eyles spent several months in Jamaica in 1957 studying the local bauxite deposits for Alumina Jamaica Ltd. In the course of these studies the phosphatic band rich in fossil fish-teeth was discovered underlying bauxite in some of the open pits at Shooter's Hill, (Eyles, "Nature" Vol. 182, No.4646, pp. 1367-1368).

In a letter to Dr. L.J. Chubb dated 28 January, 1959, Eyles comments on the problem of the origin of Jamaica bauxite as follows:-

"I am, and always have been in sympathy with Zans' attempt to derive the bauxites from some other source than the limestone, but after seeing the ground I could not convince myself that the materials of the Inliers provide a likely source. In my approach to the problem I tried to keep an open mind; and I attempted to collect all the field evidence bearing on the question. Since my return I have given the question much thought, and I don't know that I have arrived at any satisfactory explanation. I think the only course as far as publication is concerned, is to place on record all the field evidence, and leave others to draw their own conclusions.

Please convey to Zans my thanks for his Geonotes paper on the Origin of Bauxite, which I am glad to have. It is a very interesting and useful summary of the present day position.

I also note in the addendum to Zans' bauxite paper in Geonotes he states if my correlation of the phosphate bed with the Florida Bone Valley formation is correct the conclusion is the Jamaica bauxite beds are post-Pliocene in age; but, he states, "there is no evidence to support such a view". What is the evidence for a pre-Pleistocene age, any way? Zans writes of yellowish clay in the Fontabelle Valley merging into terra rossa and then into bauxite - surely this bauxite must be post-Pliocene in formation?.

To me, it seems exceedingly difficult to formulate any theory of origin which is consistent with all the known facts. I wish I were on the spot to discuss the problem with Zans and yourself".

have resulted in the formation of different grade material. It was necessary to measure both pH and redox potential (Eh) and to plot graphically Eh versus pH in order to compare the stability relations of the various grades from clay to bauxite, (Fig. 2).

The equipment used to measure the pH and redox potential consisted of a Beckman Model "G" pH Meter, a combination glass and reference electrode (Beckman No. 39142) for measurement of pH, and a combination platinum and reference electrode (Beckman No. 39186) for Eh. The platinum surface of the Eh electrode must be frequently cleaned by polishing with fine emery paper in order to obtain consistent results. The reference electrode (silver-silver chloride) has an EMF of 0.203 volts relative to the standard hydrogen electrode at 25°C. This figure must be subtracted from the meter reading to give the true redox potential of the material in each case.

It was found that useful readings of pH, and in particular Eh, were only possible by direct measurement in soil or bauxite in place. The measurements were taken by using a small auger to drill into the ground to a depth of two to three feet, the combination platinum electrode was then lowered on a rod and pressed into the material at the bottom of the hole, while at the same time, the hole was plugged with a rubber cork. It is essential to place the electrode in material which has not been exposed to air, as the oxygen in the atmosphere has an oxidizing effect that quickly spoils the true reading.

After the Eh reading was completed, the pH electrode was connected to the meter and inserted into the hole. In order to compare the pH and Eh readings with a laboratory analysis of the material, a sample was taken from the tip of the auger used to drill the hole. Table 3 shows the results obtained and these are recorded graphically in Fig. 2.

CONCLUSIONS

From the graph (Fig. 2) it can be seen that as a general rule, the higher potentials correspond with the higher grade bauxite. It is not yet known which minerals are affecting the redox potential, but it does appear that pH and Eh readings in situ could be a useful tool for the immediate field determination of bauxite grade, and further experimental work is planned.

It appears that the material which has been below the water table for a longer time in alkaline and reducing conditions (giving a lower Eh potential) coincides with a primary zone of clay and terra rossa. Where neutral or acid oxidizing conditions (higher Eh potential) exist in areas of good drainage, a secondary zone is established with resulting high grade bauxite.

TABLE 1: Typical analyses of low grade bauxitic clay (hole B on plan and section).

Feet From	Feet To	Loss on Ignition	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> by diff.	Available Alumina
0.5	5.0	26.38	12.37	12.00	2.32	46.93*	20.66
5.0	10.0	21.60	16.92	18.40	2.03	41.05	21.27
10.0	15.0	20.95	18.00	15.90	1.82	43.33	21.54
15.0	20.0	22.33	15.77	16.70	1.62	43.58	23.45
20.0	25.0	21.01	17.82	16.75	1.85	42.57	21.31
25.0	32.0	19.57	22.92	14.25	1.68	41.58	16.93
Limestone Bedrock							

\* Probably contains CaO from calcareous tufa on the surface.

TABLE 2: Analyses of the high grade bauxite (hole E on plan and section).

Feet From	Feet To	Loss on Ignition	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> by diff.	Available Alumina
0.5	5.0	29.30	0.73	17.00	2.20	50.77	38.93
5.0	10.0	27.50	0.34	19.10	1.81	51.25	43.82
10.0	15.0	27.69	0.42	19.20	2.04	50.65	43.99
15.0	20.0	28.11	0.40	17.45	2.24	51.80	44.82
20.0	25.0	28.13	0.50	18.10	2.23	51.04	45.25
25.0	30.9	27.58	0.36	14.90	1.92	55.24	41.82
Limestone Bedrock							

#### pH AND OXIDATION/REDUCTION POTENTIAL

##### MEASUREMENTS.

The solution, transportation, deposition and alteration of elements in various states of oxidation are strongly influenced by the oxidation/reduction or redox potential of the environment. It was considered that useful information could be obtained by comparing measurements taken in bauxitic deposits where different environmental conditions

2. G.I. BUSHINSKY, Senior Geologist, Geological Institute of the Academy of Science, U.S.S.R. Moscow, one of the leading Russian experts on bauxite and the Editor of the Symposium "Bauxites, their Mineralogy and Origin". Moscow, 1958.

In a comprehensive paper "On the Genetic Types of Bauxite" published in the above Symposium (pp.176-263), Bushinsky gives a full account of the bauxite problem. In reviewing all the existing publications on the bauxite deposits of Jamaica and Haiti, he states:-

"Of all the views expressed on the origin of Jamaican and Haitian bauxite those of Zans appear to be the most plausible. As regards the occurrence of heavy mineral fraction in both White Limestones and bauxites, this can be explained by assuming that the ultimate source for both could be the rocks of the Lower Eocene and Cretaceous".

Elaborating on the problem of the genesis of the red bauxites of the Urals (pp. 253-256) he arrives at a similar concept - namely, that these deposits accumulate in the same manner as the Jamaican deposits in conjunction with karst development. Intermittent streams inundating karst depressions deposited their suspended load of clayey material derived from nearby areas of lateritic weathering alumino-silicate rocks. Circulating warm ground-waters brought about the decomposition of the aluminium silicates into free alumina, removed carbonates and silica, leaving behind oxides of Fe, Ti and Al. Thus the process of lateritisation commenced in the weathering mantle of silicate rocks continued and was completed in the karst pockets.

In a letter to Prof. Zans dated 17th February, 1959, he comments on the two of his papers as follows:-

"I have read with great interest the copies of two of your papers which you kindly sent me. You have indeed been fortunate to have the opportunity of observing and investigating such remarkable deposits as the bauxites of Jamaica.

Although the International Geological Congress (1956, Mexico) is long past, having now read your paper I would like to share with you some of my impressions on the subject.

1. You mention in the Summary that the alkaline environment of limestone favours desilication and the transformation of terra rossa into bauxite. It is doubtful if this is so. Limestone provides alkalinity inadequate to raise the solubility of silica. Research has been done on this question by Okamoto, and I have dealt with his results in my paper which is due to appear soon, and which I will send you.

Further this your suggestion seems to be in contradiction to your factual data - the low silica varieties of bauxite occur within the deposits not in the immediate vicinity of the limestone walls, but in the centre of lenses. What causes the migration of silica towards the periphery of the deposit is not yet clear (p.12).

Limestone could rather be regarded as: (1) a kind of stabilizer or buffer in keeping the reaction of the environment slightly alkaline or neutral which retards the removal of alumina; (2) providing traps for the capture of bauxite in the karst pockets and possibly (3) as a coagulator of suspensions.

2. It is also somewhat difficult to agree with you (p.4) that bauxites are not formed in the absence of an alkaline environment. In the paper I sent you can be found data on the formation of bauxite in laterites which are characterized by an acid environment. Unfortunately you do not provide pH determinations of your bauxites. Such determinations are incidentally not very complex, and would be of substantial value if carried out on sample from various parts of the deposits, and from various types of bauxite.

3. Table I, (p.5) is not very convincing. The variations in chemical composition are so small that it is difficult to appreciate them. It would perhaps be better to select other profiles and investigate them chemically, mineralogically and structurally petrologically.

4. Table II (p.10) is very interesting. To make it more impressive and to stress the conclusions, it would be desirable to accompany it with a sketch or a photograph.

5. The discovery of the phosphorite band is significant; are there any such bands in limestone?

6. For the elucidation of the role which water plays in filtering through the bauxite - both groundwater and rainwater - it is important to determine the content of dissolved silica in both of them. The absence of silica in the rainwater favours the disintegration of aluminosilicates and the formation of bauxite.

7. Is there any new data on pisolites and oolites?

I hope you will excuse my comments, but the attention of all the workers on bauxite in Europe is now focussed on you and Jamaica, and we are eagerly anticipating your future scientific contributions in this field".

3. PROFESSOR ALAN M. BATEMAN, Professor of Geology Yale University, U.S.A. a well known economic geologist and Chief Editor of "Economic Geology" in a letter dated March 17, 1959 following his brief visit to Jamaica writes:-

"I was very glad indeed to hear your views and to read your paper regarding the origin of the Jamaican bauxite. I was particularly glad to have the chance to read it before visiting Mandeville. I found some differences of opinion existing there. One group favoured your general idea of introduced clayey material and the other, of the formation of bauxite in situ".

4. DR. EDOUARD ROCH, Professor, Faculté des Sciences, Laboratoire de Géologie à la Sorbonne, Université de Paris, France, the author of the aeolian theory of origin for the red bauxites of France, writes on 19th April, 1957 to Prof. Zans:-

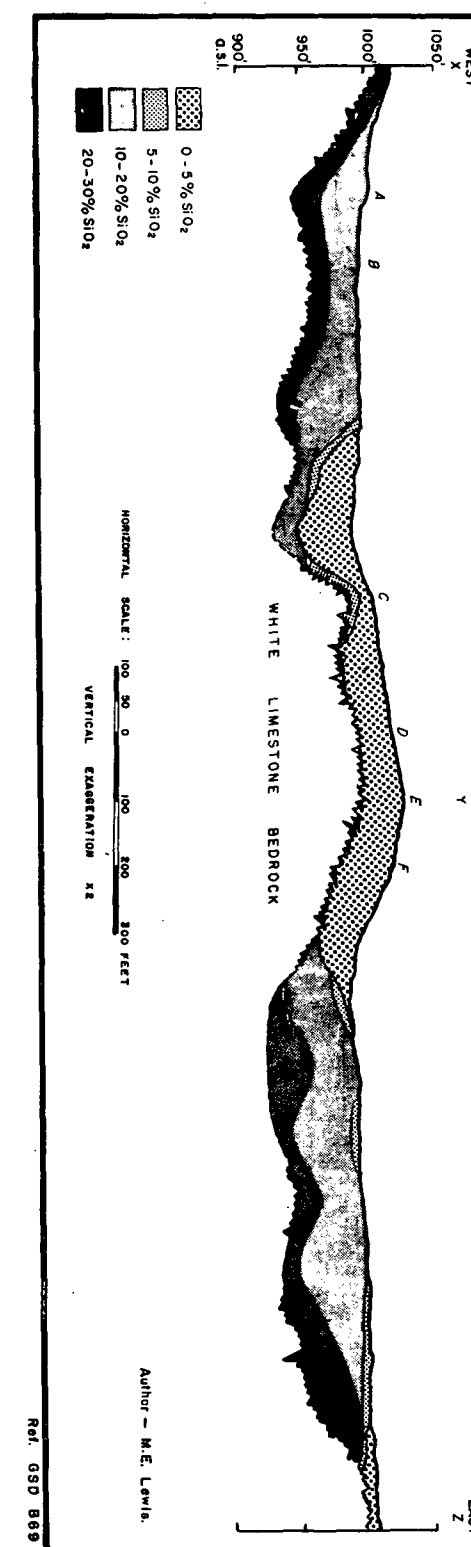
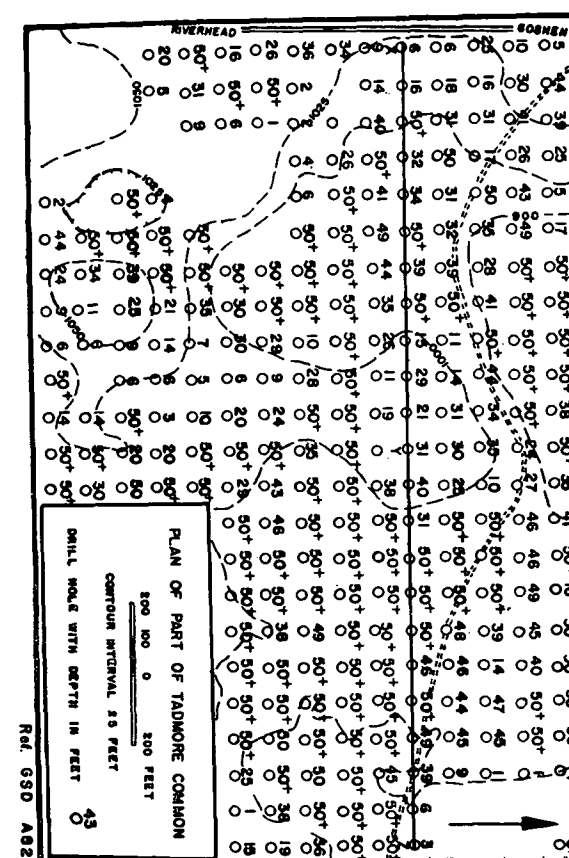
"I am happy to see that in a particularly clear way you show that the bauxites of Jamaica and Hispaniola derive from aluminosilicate rocks. I am delighted at your conclusion that all bauxites have their origin in eruptive aluminosilicate rocks or their alteration products.

Your point of view seems to me excellent and your explanation of the transport of the altered andesitic material through the body of the limestone is extremely ingenious.

Very modestly you say that much remains to be done on the subject. I think this reflection would apply to the majority of geological problems but as far as the Greater Antilles are concerned I believe that you have answered the most important questions.

What you say of Jamaica and Haiti induces a strong inclination to come at the earliest opportunity and study the bauxite deposits under your direction".

Fig. 1



the areas which have recently been covered by the lakes a bed of white or yellowish calcareous tufa, up to 5 ft thick, occurs.

It is suggested that the Rio Hoe brought the older argillaceous material into the Basin. The tufa represents precipitated carbonate derived from the White Limestone. The Rio Hoe originated as the Great River in the Guys Hill Inlier and passes over the red weathering Middle Eocene or Cretaceous tuffs for a distance of about three miles and then sinks into the ground near Middlesex. It is from the rocks of the Guys Hill Inlier that the clays were probably derived. Subsequent weathering changed the argillaceous deposits into terra rossa and bauxite where there has been a relative lowering of the water table. Such changes may result from tectonic uplift or lowering of the water table due to the opening of solution channels in the limestone basement.

#### ANALYSES OF THE CLAY, "TERRA ROSSA" AND BAUXITE

##### OF THE TADMORE SECTION OF THE MONEAGUE BASIN.

A number of holes have been drilled through the bauxite and clay sediments in the proving of ore reserves by Reynolds Jamaica Mines in the Tadmire Common area.

A plan of part of this area and cross-sections through the area (along the line XYZ indicated on the plan) are shown in Fig. 1. The sections are based on drill holes placed 100 ft apart with samples taken for each 5 ft of depth. Where the limestone bedrock exceeds 50 ft below ground level, the contact is only assumed as the drilling was limited to 50 ft using a hand auger.

Cross-sections (Fig. 1) show that the high grade bauxite is generally confined to areas of higher elevation within the Basin. In almost all cases the depressions in the hill slopes surrounding the Basin are filled with good grade bauxite. It therefore appears reasonable to suppose that in areas of good drainage, the desilicification of the bauxitic clay has taken place.

Table 1 lists the typical analyses of specimens of low grade bauxitic clay, taken at various levels in borehole B, Fig. 1. Table 2 gives the details of the analyses of specimens of high grade bauxite taken at various levels from borehole E, Fig. 1.

5. PROFESSOR DR. STANKO MICHOLIC, Geologist, Zagreb, Yugoslavia, in a letter dated 21 April, 1959, writes:-

" I have just received a reprint of your very interesting and instructive review "Recent Views of the Origin of Bauxite" containing a valuable list of publications for which I thank you very much.

I am currently studying the genesis of bauxite in its dependence of the pH of the percolating waters and the Eh of the immediate environs. It seems that with high Eh and high pH ordinary red bauxites are formed, with low silica and high iron, while with low Eh and low pH, white bauxites originate, having a high silica and low iron content".

6. DR. GY BARDOSSY, Geologist, Budapest, Hungary, author of a number of papers on Hungarian Bauxite in a letter dated 30 July, 1959:-

" In the meantime I received the copies of your papers and I studied them with great interest. Your paper of 1952, "Bauxite Resources of Jamaica and their Development" was already known to me, but the others were not. I find your paper "Recent Views on the Origin of Bauxite" to be an excellent summary of this complicated subject. It was very useful to read your outline of recent karst-bauxite literature. I was acquainted with the greater part of it, but did not know about the work of Minier (1954). Fortunately I found this work in our library and have studied it already.

It was very interesting to read in your work about recent bauxite formation, which takes place in Jamaica. I think that this process is wholly valid also for Hungarian bauxite formation in the Cretaceous age. As you will see from my paper now in press, I have made similar conclusions as you for our bauxites.

The yellowish phosphatic clay mentioned on page 129 is of special interest to me; namely, in some of our deposits we have also yellowish clay at the base of the bauxite body. I should be glad to know the chemical composition of this clay, especially how much  $P_2O_5$  it contains. I think it is also of great importance to know what is the chief clay mineral of this layer".

7. DR. H.G. KUGLER, Chief Geologist and Consultant, Texaco Trinidad Inc., Pointe-a-Pierre, Trinidad W.I., an authority on the geology of Trinidad and the West Indies in general. In a letter to Prof. Zans dated 10th August, 1959:-

" I read with the greatest interest your "Recent Views on the Origin of Bauxite" in 'Geo-Notes', Vol.1, No.5. Your explanation of the origin of the "terra rossa" bauxite is convincing and agrees with the observations I made in Trinidad and Venezuela when many samples of "terra rossa" from limestone areas were investigated without finding any abnormal content of  $Al_2O_3$ . I congratulate you on this excellent paper." (See also Kugler's note elsewhere of this issue).



DISCUSSIONS ON THE ORIGIN OF BAUXITE ASSOCIATED WITH LIMESTONE

VARIATIONS IN THE BAUXITE DEPOSITS OF THE MONEAGUE BASIN,

ST. ANN, JAMAICA.

M. E. Lewis.  
Reynolds Jamaica Mines Ltd.

8. DR. WILLIAM C. KELLY, Assistant Professor of Geology, the University of Michigan, U.S.A., in a letter to Prof. Zans dated 25th November, 1959:-

" I was surprised in studying the literature to find as much discussion of the limestone as a source based on so little actual data on the  $Al_2O_3$  content of this rock. Aside from Schmedeman's data the only published  $R_2O_3$  breakdowns I could find were those of Goldich and Bergquist for Hispaniola. Perhaps, if any further calculations of required limestone thickness are to be made, these Kendal Core analyses will help. Based on the 29 samples, the mean  $Al_2O_3$  content is 0.036%. This agrees closely and coincidentally with Goldich's average of 0.035% for five samples. Inserting this value in Hartman's calculations would double the required limestone thickness.

Finally, I would like to say that I am in wholehearted agreement with your recent hypothesis regarding origin of these ores. It makes sense geologically and in the light of the recent experimentation by Carroll and Starkey, the leaching of the clays makes sense chemically. Based on our work here I think that whatever  $Al_2O_3$  the limestone may have contributed to the soils was as a direct release of gibbsite from the bedrock itself but the Kendal Core analyses suggest that this contribution could not have been quantitatively adequate to account for the ores.

Sam Goldich was also pleased with our confirmation of his low  $Al_2O_3$  value for he is still, as you know, a staunch advocate of sources other than the limestone bedrock".

9. MR. H.R. HOSE, Chief Geologist, Aluminium Laboratories Ltd., Arvida, Canada, one of the first investors of Jamaican bauxite and an adherent of the solution residue theory, in his recent paper on "The Origin of Bauxites in British Guiana and Jamaica" presented to the 5th Session of the Inter-Guiana Geological Conference, October-November 1959, elaborates on the problem as follows:-

"The Oligocene and lower Miocene limestones (of Jamaica) are particularly pure and although the alumina content is low, the silica and ferric iron content is also low. The average composition of these limestone is shown as No.3 (Table III).

Abstract

Soils within the confined area of the Moneague Basin range from low grade terra rossa to high grade bauxite. Oxidation/reduction potential and pH measurements made on 8 borehole samples of varying grade show that higher oxidation potentials and lower pH correspond with higher grades of bauxite. pH and Eh readings in situ could be used for the immediate determination of bauxite grade in the field.

INTRODUCTION

The Moneague Basin, covering an area of about six square miles is one of several deep depressions within the mature karst topography of the White Limestone of the Parish of St. Ann, Jamaica. Its deepest points are less than 1,000 ft above sea level. A broad undulating plateau comprising chalky nodular Upper Eocene limestone and varying in elevation from 1,200 to 1,500 ft occurs to the north. The hills surrounding the Basin are formed of hard crystalline limestone, probably of Oligocene age, with the chalky Upper Eocene limestone exposed in the deeper cockpits and glades. To the south of the Basin lies the high ground around Mount Diablo (2,500 to 2,700 ft) which forms part of the main watershed of northern Jamaica.

The Rio Hoe which rises at Riverhead at Blue Hole, 1,040 ft above sea level, is the only surface stream in the Moneague Basin. It flows north-west for a distance of two miles and disappears below ground at Waltons Sink. In the Tadmire area normal rainfall is 85 in per annum but after abnormally heavy rainfall, exceeding 105 in per annum, lakes rise and may cover an area of 2 to 3 square miles for many months. This phenomenon is known as the Moneague Lakes. Records show that the lakes rose in 1886 (110 in), 1916 (124 in) and 1933 (128 in).

The Moneague Basin lies near the axis of a broad north-west trending syncline. The limestones of the coastal ridge dip to the south and south-west and those in the Mount Diablo area dip north and north-east. Superficial deposits of clay, terra rossa and bauxite lie unconformably on the White Limestone. The terra rossa is found on the lower ground and grades into bauxite on the higher slopes. In the Tadmire Common or Lake Tadmire section of the Basin, which is the part investigated, the soil ranges from clay through terra rossa to bauxite. Within

It is not claimed that the figure of 780 feet arrived at in the above calculation is an accurate one but it is likely to be of the right order; the erosion of an average thickness of White Limestone of this amount since the Middle Miocene uplift is considered a reasonable postulate.

The information presented here is not, in itself, proof of the validity of the residual theory but it serves to demonstrate that this theory cannot be dismissed as untenable solely because of the purity of the White Limestone.

#### ACKNOWLEDGEMENT

The writer is grateful to the bauxite companies for permission to sample limestone in their pits.

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Calculations show that there were sufficient of these oxides present to account for the quantity of bauxite which has accumulated since the lower Miocene. The limestones, on which the bauxites lie, cover an area of some 1,000 square miles and if, on the average, half of the 700 to 900 feet thick Oligocene and lower Miocene limestones have been dissolved away since the lower Miocene, this is 600 to 900 billion tons of limestone. If these limestones contain 0.03 percent  $Al_2O_3$ , which is the average content of uneroded portions of these limestones, then they contained 175 to 250 million tons of  $Al_2O_3$  equivalent to 350 to 500 million tons of bauxite containing 50 percent  $Al_2O_3$ . Since there is probably between 300 and 400 million tons of bauxite with an average content of 50 percent  $Al_2O_3$  on the limestones in Jamaica it appears that the Jamaican bauxites could have been derived entirely from the insoluble residue remaining after solution of the limestones. Most of this insoluble material was probably present in the skeletons of fossils and microfossils such as corals and foraminifera which make up the bulk of the limestones. A small amount may be derived from altered volcanic ash and some of the higher phosphatic portions of the bauxites may be derived from included cave debris. However, the quantity derived from weathered volcanic ash must be small as even under ideal drainage conditions volcanic ash usually weathers to high silica bauxitic material. Recently formed bauxitic material derived entirely from a weathered volcanic ash on the island of Hawaii contains on the average 13 percent  $SiO_2$  and only 29 percent  $Al_2O_3$ . Moreover, limestones which do contain some included volcanic ash such as the consolidated dune limestones on Kauai (Hawaii), which contain 0.63 percent  $R_2O_3$  and 0.28 percent  $SiO_2$ , weather to terra rossas with 18 percent  $SiO_2$  and 30 percent  $Al_2O_3$ .

It appears that the insoluble residue left after solution of the limestones, weathered to bauxites in the area of the deposits because the drainage was good, the alkaline earth content of the rocks high, and because the ratio of  $SiO_2/Al_2O_3$  in the insoluble material was low.

In Jamaica, deposits of terra rossa have accumulated mainly in low lying badly drained areas, and only in a few cases do they occur below the bauxites, as in Greece, Yugoslavia and France. Terra rossa is a residual material in which the hydrous aluminium silicates predominate. They are found on limestone in many parts of the world and are not always associated with bauxites. When kaolinic, they probably represent the insoluble residue remaining after solution of limestones where the drainage is bad, or where the ratio of  $SiO_2/Al_2O_3$  in the limestone is high. When halloysitic, and found bauxites, they may represent an intermediate stage or primary residuum from which the bauxites have formed. Low lying terra rossa such as those which occur at elevations of 500 feet in Trelawny parish may, however, be mixtures of partly bauxitized terra rossa and fine alluvium deposited from underground rivers which come to the surface in that area. Analyses of these terra rossas and of a terra rossa which occurs below the bauxite in the Kendal area are shown as Nos. 4 and 5 (Table III). X-ray diffraction analyses show that the low lying terra rossas contain kaolinite and probably halloysite, goethite, anatase and quartz, while the terra rossa found below the bauxites at Kendal consists mainly of halloysite with smaller amounts of quartz, goethite and anatase.

## ESTIMATION OF REQUIRED THICKNESS

## OF LIMESTONE

TABLE III - Chemical Analyses of Limestone and Derived Residual Material, Jamaica

	Per Cent				
	1	2	3	4	5
H <sub>2</sub> O	25.0 - 31.0	28.2	0.65	11.6	15.6
SiO <sub>2</sub>	0.3 - 3.5	0.4	0.03	46.5	22.3
Fe <sub>2</sub> O <sub>3</sub>	16.0 - 23.0	16.6	0.04	9.1	16.8
TiO <sub>2</sub>	2.0 - 3.0	2.1	0.01	1.7	1.9
Al <sub>2</sub> O <sub>3</sub>	45.0 - 55.0	52.7	0.03	27.2	43.4
CaO	0.1 - 1.2	-	55.40	1.7	-
MgO	- -	-	0.48	-	-
CO <sub>2</sub>	- -	-	43.30	-	-
MnO	0.1 - 0.2	-	Trace	0.1	-
P <sub>2</sub> O <sub>5</sub>	- -	-	0.03	0.1	-
SO <sub>3</sub>	- -	-	0.03	-	-
Total		100.0	100.0	98.0	100.0

1 - Average composition of bauxites in Jamaica

2 - Analysis of bauxite filling a narrow pipe in limestone, Trelawny parish, Jamaica.

3 - Average analysis of Oligocene and lower Miocene limestones, Jamaica.

4 - Analysis of terra rossa below bauxite, Kendal, Jamaica.

5 - Average analysis of terra rossa in low lying regions, Trelawny parish, Jamaica.

Analyses by Aluminium Laboratories Limited, Arvida, Canada.

The following data are the basis of this calculation:

1. The limestone occupies an area of some 3,000 square miles.
2. Bauxite reserves are estimated at 600 million long tons by the Department of Mines. To allow for sub-economic deposits and terra rossa, as well as some loss by erosion, we may increase this amount to, say, 1,500 million tons; this figure is equivalent to a layer of terra rossa about eight inches thick over the entire limestone surface.
3. The mean acetic acid-insoluble residue of the limestone is 0.070 per cent (q.v. Table 1). It can be argued that the median rather than the mean value of the figures in Table I should be used in the calculation below so that the exceptionally high value of samples 24, 29 and 32 will not unduly affect the result. However, the writer believes that the existence of the less pure beds represented by these samples is of considerable importance and that it is unrealistic to minimise their influence.
4. The average Al<sub>2</sub>O<sub>3</sub> content of the insoluble residue is about 25 per cent (Burns, *op. cit.*). Therefore the average Al<sub>2</sub>O<sub>3</sub> content of the limestone is about 0.0175 per cent.
5. Average Al<sub>2</sub>O<sub>3</sub> content of the bauxite is about 50 per cent (Hose, 1963).
6. Average density of limestone is 151 lbs./cu.ft. or 1.8 long tons/cu.yd. (q.v. Table 2).

Calculation:

From 4 and 5 the potential bauxite content of the limestone is about 0.035 per cent. Therefore one ton of bauxite is equivalent to 2,900 tons of limestone.

Therefore  $1.5 \times 10^9$  tons of bauxite is equivalent to  $4.4 \times 10^{12}$  tons limestone.

One cubic yard of limestone weighs 1.8 long tons

Therefore volume of limestone required is  $\frac{4.4 \times 10^{12}}{1.8}$  cu.yds.

Area of limestone is 3,000 square miles or  $9.3 \times 10^9$  sq. yds.

Therefore required thickness of limestone =  $\frac{4.4 \times 10^{12}}{9.3 \times 1.8 \times 10^9}$  yds.

= 260 yds. or 780 ft. *239 meters*

TABLE 2: Density of Limestone Specimens

Specimen number	Density lbs./cu.ft.
1	155
2	146
3	148
4	148
5	156
6	149
7	152
8	148
9	155

Mean Density = 151 lbs./cu.ft.

## Location of Specimens:

- No. 1: Quarry half-mile north of Walderston on Christiana road.
- No. 2: Far Enough corner, Williamsfield-Christiana road.
- No. 3: Alcan Mines, Faith Pen.
- No. 4: Red Hills road one mile south-east of Rock Hall.
- No. 5: Mt. Diablo road quarter mile north of St. Ann/St. Catherine parish boundary.
- No. 6: Quarter-mile north of Mizpah, Williamsfield-Christiana road.
- No. 7: Spur Tree Hill, near gateway to Kaiser offices.
- No. 8: Old Stony Hill road, quarter-mile north of intersection with Junction road.
- No. 9: Shenstone Drive, Beverley Hills.

10. Professor V.A. ZANS, in a letter to GEONOTES dated 15th December, 1959:-

"I am indeed pleased that my paper on "Recent Views of the Origin of Bauxite" has met with such a response and that the whole problem of the origin of limestone bauxites had been taken up and is being reconsidered with a fresh approach. A number of authors have referred favourably to the idea that the chief source of limestone bauxites is not the limestone wall-rock but argillaceous weathering material of aluminosilicate rocks.

This concept is of course, not a new one, and in fact has been adopted in the past by quite a few geologists who found it difficult to explain all the facts in terms of the limestone residue hypothesis. In many instances it was however not clear as to where the original material came from and what the main transporting agents were. In my hypothesis based on the study of Jamaican karst I was able to show that under the conditions of mature tropical karst the weathering products of silicate rocks are being brought into the limestone environment by subterranean karst streams. These deposit their suspended load in the periodically inundated poljes and other karst depressions several miles from the outcrop of aluminosilicate rocks, first in the form of clayey deposits which then subsequently under favourably drainage conditions alter into terra rossa and eventually into bauxite. It is admitted that limestone residue contributes to the formation of these alluvial parent deposits of bauxite but its share is small and it is evidently not the main source of alumina.

I am pleased to note that this concept in its entirety, with only minor modifications, has recently been adopted by Bushinsky for the explanation of the origin of the Devonian red bauxites of the Urals. Gy. Bardossy in his recent publication on "The Geochemistry of Hungarian Bauxites" Parts III & IV, Acta Geologica, Budapest, 1959, also arrives at the conclusion that these bauxites originated from sedimentary kaolinitic clays originally deposited in a tropical to subtropical climate in the periodically inundated karst basins. The primary substance was at the time of its deposition still of argillaceous nature, and its bauxitization took place in situ subsequently. He does not say, however, as to where the original argillaceous material was derived from and what its source rocks were.

It is but understandable that those authors who are familiar with the surface karst features only and have had no chance to study the karst subsurface drainage still adhere to the conventional residue hypothesis or eventually tend to keep an open mind and do not subscribe to any of these theories. Among these latter seems to be Dr. Eyles. He does however ascribe much importance to the phosphatic band sporadically found underlying the bauxite deposits of Jamaica. He considers this band to be a marine sediment of post-White Limestone age. Such an assumption would of course throw an entirely different light on the problem. It is, however, clear for us that this band is nothing but a remnant of a residual cave deposit enriched in phosphate derived from the guano of cave-dwelling bats (see Kugler, Geonotes, Vol. II No. 3, p. 93). The overlying bauxite was deposited in its original clayey form after the cave was opened by progressive karstification.

The adherents of the limestone residue theory must be reminded that their calculations of the volume of dissolved limestone necessary to produce the known quantities of bauxite (and terra rossa which they tend to forget) prove little or nothing, since it actually retained on the limestone and what has been transported into the sea. Hose's calculation that the dissolution of only a half of the 700-900 feet thickness of limestone would account for the quantity of bauxite known to occur in Jamaica is based on the assumption that all the residue produced since Miocene has been retained on limestone which is certainly far from being the case.

Although being a staunch supporter of the limestone residue theory in his recent paper Hose however admits that "a small amount may be derived from altered volcanic ash" and also that low lying terra rossa may be a mixture of partly bauxitized terra rossa and a fine alluvial material.

As regards the question of pH raised by Bushinsky, no doubt more work has to be done on pH determination in field to ascertain fully the environmental conditions under which the terra rossa and bauxite formation takes place. Of what we know at present it appears that the clayey and colloidal suspensions of bauxite parent material are transported in an acid medium and coagulated or precipitated upon arrival into the limestone traps under neutral or slightly alkaline conditions. The breakdown of the clay minerals and the desilication and alteration of terra rossa into bauxite most probably takes place under pH values of over 7, i.e. in an alkaline and oxidative environment.

It would be desirable that more workers on bauxite could give their opinions on these matters. In particular the experience and the views of the geochemists and soil scientists would be greatly appreciated."

#### Location of specimens:

- Nos. 1 to 22: These specimens were all collected in bauxite pits operated by Alcan in the Schwallenburgh-Faith Pen area. Details of their exact locations are on file in the Geological Survey Department.
- No. 23: Mt. Diablo road, quarter mile south of St. Catherine-St. Ann parish boundary.
- No. 24: Mt. Diablo road, quarter mile north of parish boundary.
- No. 25: Approximately one mile south-east of Rock Hall on Red Hills road.
- No. 26: Mile post 17, Falmouth to Wait-a-Bit road.
- No. 27: Mile post 18, Falmouth to Wait-a-Bit road.
- No. 28: Quarry half-mile north of Walderston on road to Christiana.
- No. 29: Quarry at Caines Shop, Williamsfield to Christiana road.
- No. 30: Approximately one mile north of Dover Castle on Devil's Race Course road.
- No. 31: Kaiser Mines, Pepper District.
- No. 32: Kaiser Mines, Pepper District.
- No. 33: Spur Tree Hill, near gateway to Kaiser offices.
- No. 34: Old Stony Hill road quarter mile north of intersection with Junction road.



## DISCUSSIONS ON THE ORIGIN OF BAUXITE ASSOCIATED

## WITH LIMESTONE - Continued

Most of the limestone specimens examined were collected in the Alcan mines at Faiths Pen; a few were collected from bauxite mines in other districts and some from fresh road-cuts and quarry faces. Particular care was taken during collection to ensure that specimens were free from visible bauxite contamination. In the laboratory, specimens were broken into small pieces and examined for bauxite contamination in cracks and vugs; contaminated material was discarded. Five hundred gram portions of the bauxite-free specimens were dissolved in warm, thirty per cent acetic acid and the insoluble residues filtered off on Whatman 542 ashless paper. After filtration the residues were ignited and weighed; Table 1 shows the results of this work.

Density determinations were carried out on nine specimens and the results appear in Table 2.

TABLE I: Insoluble Residue Contents of Limestone Specimens.

Specimen number	Wt. per cent residue	Specimen number	Wt. per cent residue	Specimen number	Wt. per cent residue
1	0.001	13	0.024	25	0.054
2	0.019	14	0.050	26	0.046
3	0.011	15	0.027	27	0.095
4	0.069	16	0.016	28	0.026
5	0.044	17	0.024	29	0.248
6	0.044	18	0.053	30	0.048
7	0.061	19	0.019	31	0.015
8	0.026	20	0.070	32	0.206
9	0.034	21	0.013	33	0.095
10	0.030	22	0.019	34	0.033
11	0.052	23	0.036		
12	0.067	24	0.691		

Mean value is 0.070 per cent

11. Dr. JACQUES BUTTERLIN, an authority on Antillean geology, in a letter to Prof Zans, writes:-

"I have received GEONOTES (Vol. II, No.3) and I see that following the publication of your very interesting article on the origin of bauxites it has become a subject for debate.

As you know, I do not share your views on the subject of the origin of these bauxites. I enclose a brief article which gives a resumé of my ideas on the matter (see below, Ed. ).

I am also venturing to remark on what seems to be an error in your article. You write (p.129) that there are no bauxites in Yucatan, because there are no sources of alumino-silicate rocks. The article which I have published under the title "Preliminary Reconnaissance of the Geology in the Tertiary of Quintana Roo" state that this is not the case.

Bauxites, or more exactly lateritic clays do exist in the peninsula of Yucatan. It is only the fact that they are very rich in silica which prevents them from serving as a commercial source of alumina. Over the major part of the State of Yucatan these clays have been lost through erosion consequent on indiscriminate tree-clearing, but in the Quintana Roo territory, where the forest has been conserved, they still occur. Clearing conducted for road-building operations along the line Chetumal - Carillo Puerto - Peto - Merida revealed accumulations of lateritic clays more than a metre thick in dolines.

My opinion is that these clays are found in only moderate thickness because the limestone plateau forming the Yucatan peninsula has only been recently uplifted. The marine deposits of the Upper Miocene and Pleistocene are found over a wide extent there, and this cover must have been still more extensive prior to erosion. Following this, vertical movements re-immersed the limestones, and the lateritization was not able to develop until recently. For the same reason the desilification has not been very far advanced. This is the same phenomenon that I observed on the limestone platforms of the Pleistocene reefs in Haiti, particularly on the North-west peninsula.

How do you explain the formation of lateritic clays on those plateaux or platforms of marine limestone, sometimes on elevated reefs, (plateaux of Bombardopolis, Haiti, or the platform in Yucatan) where the run off has been feeble as a consequence of the absence of relief? As for me, I think like Erhart, that the forest has played a leading role, but not the alluviation, which in these regions is probably negligible".

Dr. Butterlin's article:-

On the Origin of Bauxites in Tropical Limestone Countries

(Extract from the Proceedings of the Geological Society of France, 1958, p.121)

Recently, two great schools of thought have confronted us on the subject of the origin of those deposits of bauxite, the "wall" of which is composed of limestone. The first considers that they are formed in

situ, or at a small distance from the place where they are now found, by the alteration of the limestone on which they lie. The second believes that bauxites are derived from aluminosilicate rocks (igneous, metamorphic or detrital rocks) and owe nothing to the subjacent limestones. Certain authors, however, admit that the limestone has favoured the desilification which has produced the aluminium hydroxides. For this second school, bauxites enter the category of alluvial deposits. Its partisans support their argument essentially on the great difference in chemical composition between the bauxite and the limestone, and on the absence of a zone of transition between the two types of rock.

Erhart, in his recent presentation of his "biostasique - rhexistasique" theory, has been led to re-examine this question. He indicates first of all, and the author is of the same opinion, that the hydroxides of aluminium which characterise the bauxites could only be formed under a virgin forest in a humid tropical or equatorial climate. The migratory phase of soil formation would have given birth to the constituents of limestones later deposited, far from their place of origin, generally in the sea, whilst the bauxites constitute the residual phase of the pedogenesis, derived from the aluminosilicate rocks. The superposition of the bauxites on the limestones would be a secondary phenomenon very much later than the formation of the bauxites and connected with the alteration of the soil cover and its erosion and removal following the disappearance of the protecting forest.

In the course of the geological and pedological study of Haiti where one frequently meets the superposition of red ferrallitic soil on limestone, the author has been led to study the same problem, and has arrived at some very different conclusions. In Haiti, the red ferrallitic soils associated with limestones, certain of which are exploited as bauxites (plateau of Rochelois). Southern peninsula are only met with in those regions characterised by compact or, more often, crystalline limestones, sometimes very detrital, often coralline or with molluscs and generally full of large foraminifera which indicate an Eocene, and more rarely, Oligocene age. On the other hand in the regions where chalky limestones outcrop, generally with flint, one finds only black tropical soils of rendzina type. In the southern peninsula, where the bauxites are exploitable by reason of their low content of silica, the only aluminosilicate rocks more recent than the Eocene limestones on which the bauxite lies are some Miocene and Pliocene clays, marine or lacustrine, and alluvial Quaternary deposits. One could suppose that the bauxites are derived from volcanic Cretaceous rocks (dacites, andesites and above all, basalts). One could then explain only with difficulty that on one hand bauxites have the character of alluvial deposits and yet are devoid of minerals such as quartz, and on the other hand the red ferrallitic soils that one finds on the same volcanic rocks are too rich in silica to constitute exploitable bauxites.

In the island of Gonave, built entirely of limestone, with a fringe of alluvial deposits along the coast, the red ferrallitic soils are dominant except in the regions, built up of chalky limestone with flint, (region of Plaisance - Pointe a Paquettes). Finally, one observation which appears to be equally interesting is that all the regions made up of Pleistocene reef limestones are covered by red ferrallitic soils.

A geological reconnaissance in Quintana Roo (Yucatan Peninsula) has confirmed that the red ferrallitic soils are associated with clearly defined types of limestone.

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# AN ESTIMATION OF THE THICKNESS OF LIMESTONE REQUIRED TO PRODUCE THE JAMAICAN BAUXITE DEPOSITS BY THE RESIDUAL PROCESS

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## Abstract

Results of investigations of the insoluble content and density of the White Limestone formation are presented.

Using these results, the thickness of limestone required to produce the bauxite deposits is calculated as 780 feet; this is within the limits of the amount of erosion which is considered to have taken place since the Middle Miocene uplift.

It is concluded that the residual theory of bauxite genesis in Jamaica cannot be regarded as untenable solely because of the purity of the White Limestone.

## INTRODUCTION

When the first detailed geological investigations of the Jamaican bauxite deposits were made it was generally accepted that the bauxite represented a residual soil produced by weathering of the Tertiary White Limestone formation (Schmedemann, 1948; Hose, 1950; Zans, 1951; Hill, 1955). However, Zans after further field studies, developed the hypothesis that the bauxite deposits are largely made up of material transported onto the limestone surface from the inliers of Middle Eocene and Cretaceous volcanic, volcanoclastic and sedimentary rocks and that residual material from the limestone has made an insignificant contribution to the deposits (Zans, 1958). This hypothesis has been accepted by the majority of geologists working in Jamaica as the most likely explanation of the genesis of Jamaican bauxite and no detailed arguments against it have been published although Hose (1953) still prefers the residual theory.

Several supporters of Zans' ideas believe the residual theory to be untenable because of the high degree of purity of the White Limestone; they maintain that derivation of the bauxite by the residual mechanism involves the postulation of an original thickness of limestone much greater than is suggested by stratigraphic evidence (Burns, 1951). Information of fundamental importance, therefore, in any discussion of the relative merits of the alluvial and residual theories, is the mean percentage of insoluble residue in the limestone. However, values published to date have varied by a factor of more than ten, ranging from 0.5 per cent (Hill, *op. cit.*) to a minimum of 0.04 per cent (Burns, *op. cit.*). Burns' figure is based on seven limestone samples and Hill's on an unstated number.

This lack of consistency has made appraisal of the possible validity of the residual theory difficult; it was considered by the writer that a useful contribution to the problem would be to obtain more information about the insoluble content of the limestone and use it to make as realistic an estimate as is possible of the thickness required.

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The subsoil of this territory is essentially made up, in the southeast part of soft chalk and clayey limestones and in the central part of detrital limestone and massive limestone, crystalline and coralline, with molluscs and Archaias. They are stratigraphically higher than the chalk. Now, in the southeast section one finds mainly black soils of rendzina type, except in the rare zones where the massive, more recent limestones have been preserved from erosion, and where one finds the red ferrallitic soils. On the other hand, in the central section, one finds but little red ferrallitic soils, becoming thicker towards the north-west. All the territory is covered by a tropical virgin forest, and no climatic difference has been observed between the zones. Moreover, the boundary between the types of soil is so sharp that the climatic considerations are insufficient to explain it.

Thus the bauxites appear to be found in those areas where <sup>m</sup>limestones formed near coasts or on shallow banks outcrop, that is to say, in those areas where impurities of continental origin are deposited most readily.

If sometimes one finds bauxites on purer limestones, is it not because the process was halted by the purer bed? In any case all the authors who have studied bauxite - limestone contacts know that they show contours of such irregularity that it is not possible to suppose that they are ancient surfaces of continental erosion. They are clearly surfaces of pedogenetic alteration. Colour photographs of the Kenscoff region (Massif de la Selle, Haiti) which I have taken are typical from this view-point. Transport to a limited degree has always concentrated the bauxites in low-lying places, in particular in the dolines of the karst plateaux.

The author considers that the sum total of observation which he has been able to make can be formed by pedogenesis from certain types of limestones.

12. Mr. H.R. VERSEY of the Geological Survey Department, Jamaica in a letter to the Editor:-

"With reference to the recent discussions on the origin of bauxite associated with limestones, I would like to make a small point.

Throughout Jamaica, there are various dissected peneplains at high level. These have been tilted and block-faulted but the concordance of summit levels to the plane of tilt is quite marked. This is clearly seen in Fig.1 of Zans' "Recent Views on the Origin of Bauxite" (GEONOTES Vol.1, No.5) and in Pl. IV and V of Sweeting's "Hydrogeological Observations in Parts of the White Limestone Areas in Jamaica (G.S.D.Bull. No.2).

In view of this, the estimates of the amount of limestone removed seem grossly exaggerated. It is more than unlikely that the removal of half the thickness of Oligocene and Miocene limestones, as suggested by Hose (GEONOTES, Vol.II, Part 4, p.130) would leave the remnant peneplane intact.

In conclusion may I say that I am in agreement with the view that the bulk of the bauxite deposits of Jamaica are derived from argillaceous sediments which by the agency of underground drainage and Vauclusian springs were brought from the Cretaceous inliers into the limestone environment. There are, however, difficulties involved in ascribing all the bauxite and terra rossa to this process. Some high level occurrences are more probably derived solely from the solution of limestone, but only detailed geochemical work can decide this point."

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A COMPARISON OF SOME EUROPEAN  
BAUXITES WITH THOSE OF THE CARIBBEAN

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Abstract

In the majority of cases, European bauxites have been considered as eluvial. They would then be produced from the solution of their very pure limestone walls. Today we have enough data to indicate that many of them are alluvial. In Greece transport of material in several occurrences is proven by the presence of ferro-nickel and chrome, produced by the weathering of eruptive rocks further to the east. In Hungary the original material of the bauxites comes from the crystalline rocks of the Tisia. In Spain the bauxites result from deposition, in a lacustrine environment, of the finest materials torn from the emergent massifs of the Meseta. In France, finally, paleogeography reveals the existence of a limestone isthmus which united the granites and the gneiss of the Central Massif with those of Maures. So, it is no longer possible to imagine the transport, by fluvial agency, of clays derived from the surface of those regions: aeolian transport has been suggested.

The studies of V. A. Zans in Jamaica have shown more clearly than in Europe the genetic connections between the bauxites and the rocks of the inliers. There can be no question as regards Jamaica and Hispaniola that the stratification sometimes observed in the bauxites proves their transport and that the presence of an irregular bed of calcium carbonate between the bauxite and its wall shows their independence one from the other. V. A. Zans has shown the mechanism by which the original material is transported from the rocks of the inliers to the dolines. This material is a yellow clay which blankets the karst depressions at low altitude and represents the finest fractions of the weathering products of the older rocks. At higher altitudes this gives way to a mottled clay which is succeeded by the bauxite.

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"I have always loathed having to choose; choice to me has never been so much a matter of selection as a process of eliminating that which I did not select."

Andre Gide: Les nourritures terrestres,  
Livre quatrieme.

## INTRODUCTION

Over the past few years, I have made a study of a number of European bauxites and have also visited the main deposits in Jamaica, under the guidance of V. A. Zans, and Haiti, under the guidance of R. C. Lemoine. From this work, it very soon became apparent to me that certain peculiarities of the Caribbean bauxites could help in getting an answer to some of the questions that are still a matter of controversy among the geologists of the Old World.

From among these various questions, I propose concentrating on that concerning the origin of bauxites, with exclusive consideration being given to those bauxites with almost pure dolomite or limestone foot-walls, i.e. containing 99.5%  $\text{CaCO}_3$ , which basically means the type of rock described by P. Berthier at Les Baux village, in the Provence area of France, in 1821. Numerous other deposits of this type have been found during the last hundred years, all of them being along the northern shores of the Mediterranean and running through Turkey, Greece, Albania, Yugoslavia, the Adriatic slopes of Italy, Sardinia and as far as the north-eastern part of Spain, which accounts for their being called Mediterranean bauxites. However, some fifty years ago, similar deposits were found in the U.S.S.R. and the West Indies, so that it is preferable to refer to the Mediterranean variety as karst bauxites (Vadasz, E. - Zans, V.A.) on account of the particular sculpture of their foot-walls. It might be added that, throughout Europe, these bauxites are hard rocks usually red in colour but also yellow or white and, more rarely, green. They are oolitic and pisolitic, homogeneous or brecciated or speckled. Bedding is almost never found in the deposits and there is often an irregular layer of red clay between the bauxites and their foot-walls. All bauxites are basically continental deposits, so that their presence in a lithological series proves a time interval.

Without going into details of the somewhat extravagant theories put forward to explain their origin, it may be said that, up to about 1923-1930, the majority of geologists compared bauxites with laterites.



However, some of these latter have such a high alumina content that they are actually worked. They are the bauxitic laterites and they differ from the karst bauxites in that they rest on foot-walls that are invariably aluminosilicate, never calcareous. To such informed experts as A. Lacroix (1901) in France, therefore, it seemed normal that the Provence and Languedoc bauxites should also originate from laterites, themselves derived from the residual clays of such rocks as granites, basalts, gneiss and even shales. However, Lacroix abandoned the search for the original materials of these deposits in the South of France.

J. de Lapparent (1930) got round the difficulty that had stood in the way of his predecessors by maintaining that, in spite of the low clay content, large bauxite formations could have occurred at the expense of limestones if considerable volumes of these latter had been dissolved "in situ". An eluvium would then have developed in a similar way to that in which the terra rossa, which is so developed over the white limestones of the Mediterranean coasts, is said to have done during the Quaternary. Actually, J. de Lapparent's ideas seemed to be confirmed by his identification of bauxite ores in clay obtained in the laboratory by the dissolution of limestones from the foot-walls. This would make bauxites clearly autochthonous.

In order to accept de Lapparent's views, it is first of all essential to be certain of the eluvial character of terra rossa, which is today disputed, and also that bauxite ores form an integral part of limestones, which is also open to discussion. We are more inclined to the opinion that these minerals were brought along in the limestones, after the bauxite deposits, as these can be seen to have an infinite number of fissures, some of them microscopic, which have been filled per descensum by red clay or even by bauxite from the overlying deposits.

Brilliantly put forward, the eluvial or absolute autochthony theory was accepted by almost all geologists. Over the last few years, however there has been a noticeable swing back to former ideas, including those that said that karst bauxites came from such rocks as the granites etc., the weathering products of which would have been transported, often over large distances, to the point where the bauxites are now found. This is the allochthony theory, according to which bauxites are consequently alluvial.

Between these two opposite views there is yet a third, more intermediate theory, according to which clay from the neighbouring

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be rigorously applied to Europe, but it can at least be used as a guide, and several processes can be considered. On account of this, until further knowledge comes to hand, I accept the idea of a land cut by rivers to explain the occurrences in the Parnassus, Hungary and Catalonia, and for the French deposits, the idea of wind transport. There is still the problem of the Lutetian bauxites, for which no satisfactory theory exists, unless one is prepared to consider total reworking. Perhaps it might be possible to accept the theory of relative autochthony for the bauxites in the Dalmatian zone and in the central Italian area, which are far removed from any outcrops of plutonic rocks or schists.

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carbonate rock was carried a short distance to join the red clay of the foot-walls. This is what is called the theory of relative autochthony.

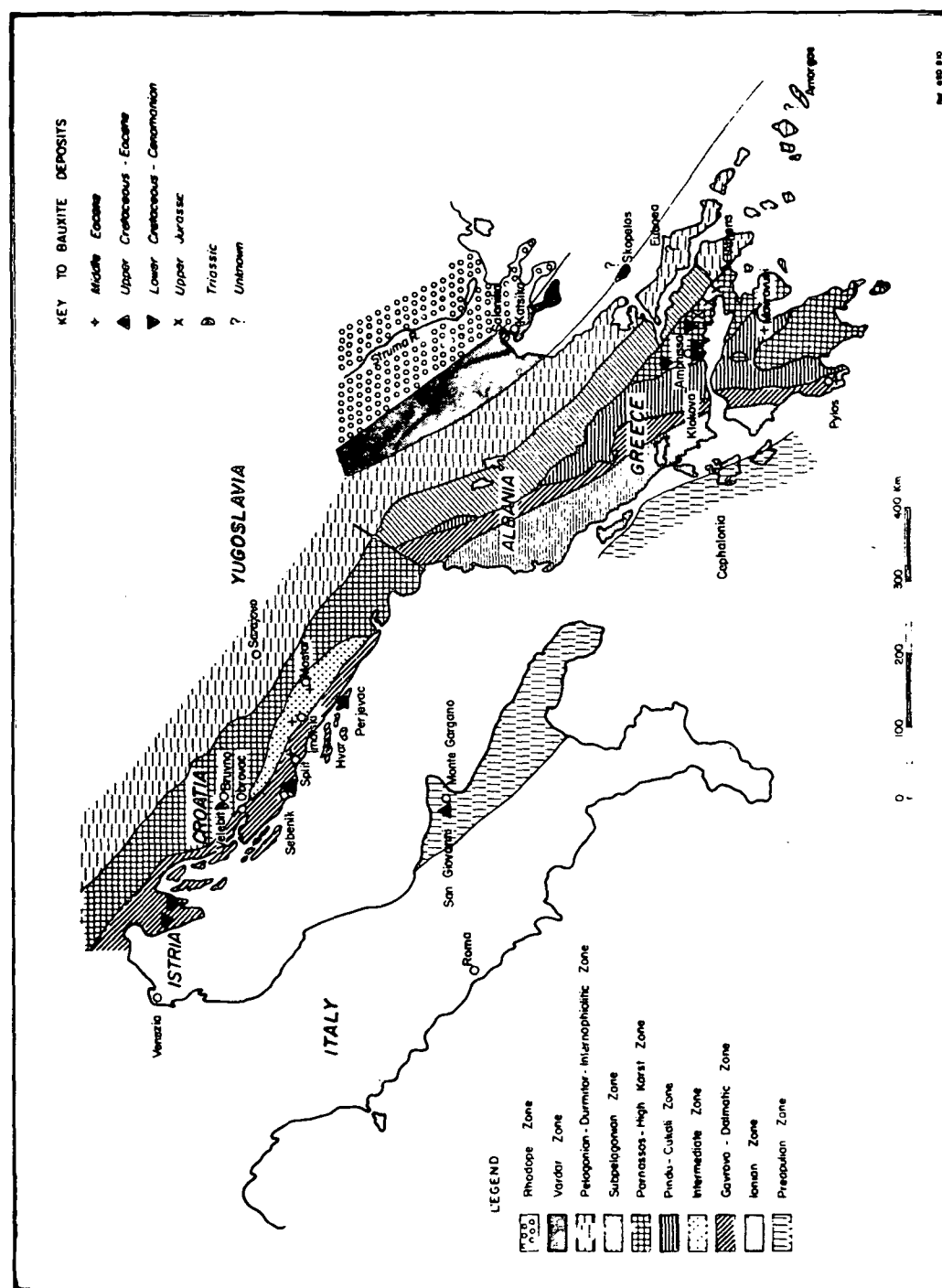
Since the absolute autochthony theory is no longer generally accepted, the choice would seem to be limited to the relative autochthony and allochthony theories. It is now proposed to see what recent work in Greece, Yugoslavia, Hungary, Spain and France can tell us from this point of view. In the following discussion references to authors have been grouped alphabetically under their respective regional headings at the end of the paper.

## GREECE

(Fig. 1)

The main Greek deposits are in the Parnassus-Ghiona area, in the central part of the peninsula. There are two distinct levels, the first being in the upper Jurassic and the second between the lower Cretaceous and Cenomanian. The remarkable thing about these bauxites is that they often contain small amounts of nickel-iron and cobalt, with traces of chromium. The subpelagonian and pelagonian zones to the east of the Parnassus area are sufficiently rich in stocks of green-stones for the iron and nickel to be worked at their weathered horizons. Not only has there been a concentration of minerals in these autochthonous deposits but the alumina has also increased to a point where it is twice that of the unweathered rock. Proceeding westwards towards the allochthonous deposits with karstic limestone foot-walls, a progressive reduction in the nickel iron content is found. Only minute quantities are still to be found in the bauxite deposits.

As proof exists that the characteristic metals of the green-stones have been transported, it is reasonable to think that this is also true of the aluminous earth. In fact, it is difficult to see how they could be considered as an eluvium since the foot-walls only contain 0.465% of  $Al_2O_3$ . This means that the Parnassus bauxites are alluvial. As to the alluvium transport and sedimentation processes, it is thought that watercourses ending in littoral marshes are responsible, because the presence of pyrite near the hanging wall indicates a reducing medium.



extremely fine, glaring white powder made up entirely of calcium carbonate. The join between this powder and the overlying red earth is quite clear. If this were a stage in the dissolution of the limestone, one would have expected the powder, which is an eminently loose material, to have disappeared, leaving behind the residual clay.

In addition, the affiliation between the bauxites and the plutonic rocks is easily reconstructed when the following facts are noted. Under the effect of the moist, tropical climate of the Caribbean, the eruptive rocks first of all underwent a granular disintegration into sand and then weathered into yellow sandy clay "in situ". It is found that this clay is carried by streams, some going to the sea and some into the karst sink-holes, which it fills up. Yellow clay is found up to a height of about 200 metres above sea level. Above this height, and especially in the range up to 400 metres, the depressions in the limestones are filled, not with a yellow clay, but with one that is veined with red and green streaks, which already shows signs of laterisation. Finally, above 400 metres, only bauxites remain.

Age, as indicated by the altitude, had therefore played its part in the evolution of the various earths, i.e. the older the bauxites, the more lateritic they are. The extent of the process was, in fact, governed by the successive settings of the hydrostatic level as the ground progressively rose. The climate, which should have been similar to the present one in the Miocene, plus easy drainage conditions and the alkalinity of the water, all contributed towards elimination of the silica. As regards the absence of detritus in the bauxites, this is explained by filtration of the flowing water in the karstic network. This accounts for the passages and grottoes near the plutonic massifs being clogged with quartz sands and stones.

In this way, the clay left the inliers and piled up in the sink-holes, whereupon bauxitisation gradually took place. This means that the bauxites are surely foreign to the limestones that contain them.

In my opinion, the conclusions to be drawn from this study of the West Indian deposits should be applicable to most of the karstic occurrences, if not to all of them.

Actually, I do not think the process revealed in the Caribbean should

picture of the eluvium of the Massif Central or the Maures. However, the dusts that reached the karstified parts of the Durancian Isthmus developed into bauxites "in situ". It is probable that there was subsequently some slight transport and reworking and that the material was deposited in the marshes, but the most important thing from our point of view is that it is necessary to look for the original material a long way away, i.e. in the aluminosiliceous rocks.

This brief review of the European bauxites finishes with a doubt as to their relationship with the aluminosiliceous rocks, except in the case of the Parnassus bauxites, where the ferro-nickel and chrome confirm this relationship clearly. Fortunately, the Caribbean bauxites have a number of important points to offer in favour of our ideas.

#### JAMAICA AND HISPANIOLA

These karst bauxites are the most recent ones known, being later than the lower Miocene. As usual, the foot-walls are of very pure limestone, i.e. 99,7% CaCO<sub>3</sub>, and are frankly karstic, as in Europe. On the other hand, instead of being in the form of a compact rock, the ore appears as a clay that is powdery when dry but plastic when moist. Beneath the limestones, there are igneous rocks, pyroclastic tuffs and andesitic or basaltic conglomerates.

We are certain that the bauxites are linked to these by a common origin. First of all, the bedding that is sometimes visible indicates that they have been transported. Then, their independence of the foot-walls is suggested by the following facts:-

- a) The foot-walls are rich in large shells, all separated and all preserved a few centimetres from the bauxites, in which they are never found, even as casts.
- b) Between the foot-walls and the bauxites, there is quite often an

There are other bauxite deposits in Greece including, first of all, those further westwards in the Gavrovo area, namely those of Pylia (or Pylos) and Mavrovuni to the west of Argos, both in the Peoponese, and Klokova, east of Missolonghi, which are more recent than the previous deposits, being interbedded between two Lutetian marine limestones. Although G. Aronis has not put forward an explanation of their origin, it might be possible to suggest one after describing their counterparts in Yugoslavia. Finally, mention may be made of the Euboean bauxites in the Pelagonian area, east of the Parnassus, and those of the Skopelos and Amorgos islands, as well as those of the Katsika area near Salonika, in the Vardar zone.

#### YUGOSLAVIA AND ALBANIA

In Yugoslavia, the Parnassus zone can be compared with the High Karst zone, in which there are three layers of bauxites. The earliest of these layers, between the limestones of the Ladinian and Norian ages, are derived from the Carnian, as is confirmed by the fact that they are sometimes seen to go over laterally into clayey rocks of the same age as the Raibl beds. They are worked in Croatia, in the Velebit ridge and in the Bruvno area.

The next two layers date from the same time as the Parnassus ones but, in spite of nearby green stone massifs in the inner ophiolitic zone, they contain no nickel-iron. The Jurassic and Cretaceous levels only exist in Montenegro and, in Istria, only the Cretaceous level exists, which de Weisse (1949) is inclined to accurately date as being of the Barremian. Analysis of the rocks shows them to be more akin to terra rossa than a true bauxite.

The most widespread and, perhaps, the richest occurrences in Yugoslavia are in the Dalmatian zone, which is homologous with the Gavrovo zone. To start with, there is a first bauxite included between the uppermost Cretaceous and the extreme base of the Eocene. It can be followed from Albania, through central Dalmatia to Istria.

It is particularly apparent in the region of Sebenik and is also to be found in the Quarnero islands, such as Hvar and Perjevac. According to C. d'Ambrosi (1940), some Istrian bauxites are Valanginian (Orsera).

The other bauxites of the Dalmatian zone are contemporary with those of Pylia (or Pylos) and Klokova, i.e. Lutetian, and with the bauxite deposits at Mostar, Imotski, Split, Zadar and Obrovac.

Most authors think that the Yugoslavian bauxites originate from a paleosol, i.e. from a terra rossa derived from impurities contained in the limestone foot-walls. But all of them give the same description of the structure of the sometimes very deep cavities in the karst. The Carvene Ornice cavity is 65 metres deep, whereas the Kalun one is worked at a depth of 330 metres and more than 2,000,000 tons have been extracted. A rough diagram would show (a) the foot-wall surfaces irregularly coated with red clay, (b) a fairly continuous zone of a yellow, siliceous bauxite and (c) the centre of the deposit, where the upper third is of good aluminous bauxite. Finally, there is a terra rossa in the hanging wall which often contains lumps of bauxite and whose formation is probably due to weathering of the ore. Generally speaking, therefore, writers have come down on the side of the relative autochthony theory.

It is not proposed to criticise this opinion since I have not so far examined the sites myself, though I would like to make the following four points.

- 1) It is striking to see how short the time intervals are, during which the bauxites are said to have formed, i.e. the Carnian age for the Trias bauxites, the Barremian age for some of the Istrian ones and only a small part of the Lutetian age for the other deposits. This of course, suggests that at least some, if not all, of the original material was transported. In the first case, is it possible to distinguish the bauxites formed "in situ" from those that are allochthonous? And, in the second case, there is the question of where are the source rocks of the terra rossa to be found. It would seem that the strictly Lutetian bauxites can only be completely allochthonous.
- 2) I am suspicious of the relative autochthony of the Upper Karst bauxites because the Parnassus ones, which are the Southern homologues, are clearly allochthonous.

point of fact these rivers must have had a steep slope and should have deposited lenses of pebbles at the same time as the clays, which should have been stratified. However, the clays are not stratified and there is a complete lack of pebbles.

We are now forced to look for the bauxite origin material in the weathered products of the emerged massifs of the Durancian Isthmus in its final form i.e. in the rocks of aluminosilicates, granites, gneiss, etc. that made up these massifs. But these eluvia could not have been carried by running waters since a hydrographic system lying along the main axis of the isthmus is out of the question. The only possible remaining carrier, therefore, is the wind. This implies that winds blew dust that was already slightly lateritic off the crystalline massifs and deposited it on the surface of the isthmus.

This theory takes into account:-

- i) the fineness of the bauxite grains.
- ii) the absence of detritics in the largest sense of the word, i.e. quartz pebbles, which would certainly have occurred at least in the deposits nearest the Maures.
- iii) the absence of stratification.
- iv) the homogeneity of the bauxites as a whole.
- v) their independence with respect to the foot-walls.
- vi) the fact that these last are invariably carbonate rocks already karstified, which acted as traps for the dust.

Finally, the existence of wind-borne deposits in the neighbourhood of bauxite occurrences has been proved by the Albian sands at Apt. These are marine sands of medium size, which contain ochre in the form of an argiloferruginous powder of very fine grain size, i.e. about a micron. There are no known transition members between these two constituents, so that it is reasonable to suppose that the dusts are an addition to a normal sand. The fact that these fell in the sea accounts for their not having developed, which means that we therefore have before us a true

the study of which resulted in J. de Lapparent rejecting the general train of thought followed by his predecessors in favour of the absolute autochthony theory. However, it is quite true to say that various other authors have since put forward developments like the relative autochthony theory, which brings us closer to the ideas of G. de Weisse and which is already quite encouraging.

There is often a little red clay between the foot-wall and the ore, and this could be interpreted as being a terra rossa liberated from the sub-jacent limestones which has not developed, whereas the bauxites would have come from another terra rossa which, due to the "refining" it was subjected to during transport, would have been the only material to be open to bauxitisation.

The transport of the bauxites is deduced from observation of the deposits themselves, which lie on a line 200 km. long, extending from Bedarieux to Toulon. Even though the foot-walls are of varying ages, the bauxites themselves are one and the same despite their diversity. Secondly, breccias and crusts impregnated with manganese often separate the ore from the foot-wall, thus providing proof that the former did not develop from the latter.

If this is admitted, however, it is felt that the theory of relative autochthony cannot be applied to the bauxites of Southern France, nor can the impurities in the Provence and Languedoc limestones be considered as being the original sources, since, in spite of the help these could have given, there would nevertheless appear to be too much bauxite. It should not be forgotten that, in addition to the known deposits, there are those still hidden below ground in the synclines and those that have disappeared from the anticlines during successive erosions. However, the volume of limestones likely to have been dissolved during the middle and upper Cretaceous was limited precisely on account of the paleogeography.

It will be recalled that a long, narrow, humped strip of emerged land once joined the Massif Central to the Maures, last remains of the Tyrrhenian mainland. This strip of land was the Durancian Isthmus and its outlines are quite clearly defined. Under these conditions, it is difficult to imagine slow flowing rivers unable to carry detritus. In

- 3) It is not possible that the Carnian bauxites are the result of weathering of volcanic tuffs and Ladinian green-stones? If this bauxite level is non-existent in Greece, is this not because the Triassic eruptive rocks they come from are also lacking?
- 4) G. de Weisse admits being surprised at the absence of bauxites in the southern part of the Dalmatian basin, which was completely above water between the Jurassic and Tithonian ages.

#### SOUTHERN ITALY

Authors agree that the Dinaric area was joined to the Apulia crest which, right from the Province of Bari to the Abruzzi, via the Monte Gargano, in southern Italy, has bauxite deposits with foot-walls of very pure limestone of the mid-upper Cretaceous and hanging walls, when there are any, of Eocene limestones of indeterminate age. Between the wall and the ore, there are occasionally breccias of very large lump size, and there is one point where the bauxite is bedded. The breccias and local bedding are two points in favour of the ore having been transported.

In Sardinia, as far as it is known, the deposit is an intercalated level in the upper Cretaceous limestones.

#### HUNGARY

Most of the deposits are on a line between the Sumeg and the Danube bend, which line follows the main direction of the tectonic



structure of this country. The hanging wall of the bauxites is frequently of Eocene limestones and their bed is usually of Norian limestones and dolomites.

Hungarian authorities, and also G. de Weisse, nevertheless do not think that the original substance of the bauxites formed during the long time interval, including the whole of the Jurassic and Cretaceous periods, on account of the numerous occasions when the sea encroached and receded during this time.

Subsequent sea floodings and recessions were apparently caused by disturbances and only affected certain areas, which accounts for the occurrences differing from one region to another.

The oldest deposits, such as the one at Hagyharsany, at the confluence of the Drava and the Danube in central Hungary, (which means that it is separated from the others), are included between the Malm with Diceras and the Valanginian with Valletia. However, the most important occurrences probably originate from the Barremian, including, for example, the one at Alsopere in the Eastern Bakony area, where the foot-wall and hanging-wall are respectively Dachstein and Aptian limestones. Others, like the Sumeg deposit, are included between the Senonian and the Eocene. de Weisse is of the opinion that the first two of these bauxites come from a transformation of the terra rossa and that the remainder are a late Cretaceous clay in conjunction with reworking of bauxites of earlier formation, since a lot of these latter are brecciated (Gant).

As regards the place of origin of the clay, de Weisse makes ingenious use of the paleogeographic charts based on the present very erratic distribution of the Jurassic outcrops. In his opinion, the present formation is only the remains of an important original extension and that a lot of the limestones, including some nodular limestones, would have liberated terra rossa by dissolution. This latter would then have been built up to the present occurrences.

Recent work, that of Vadasz in particular, offers a different interpretation. It is known that, during the Cretaceous age, the sea was confined in the south-western part of Hungary and that, extending out from the S.E. Bakony area, was a large Hercynian massif, sometimes called

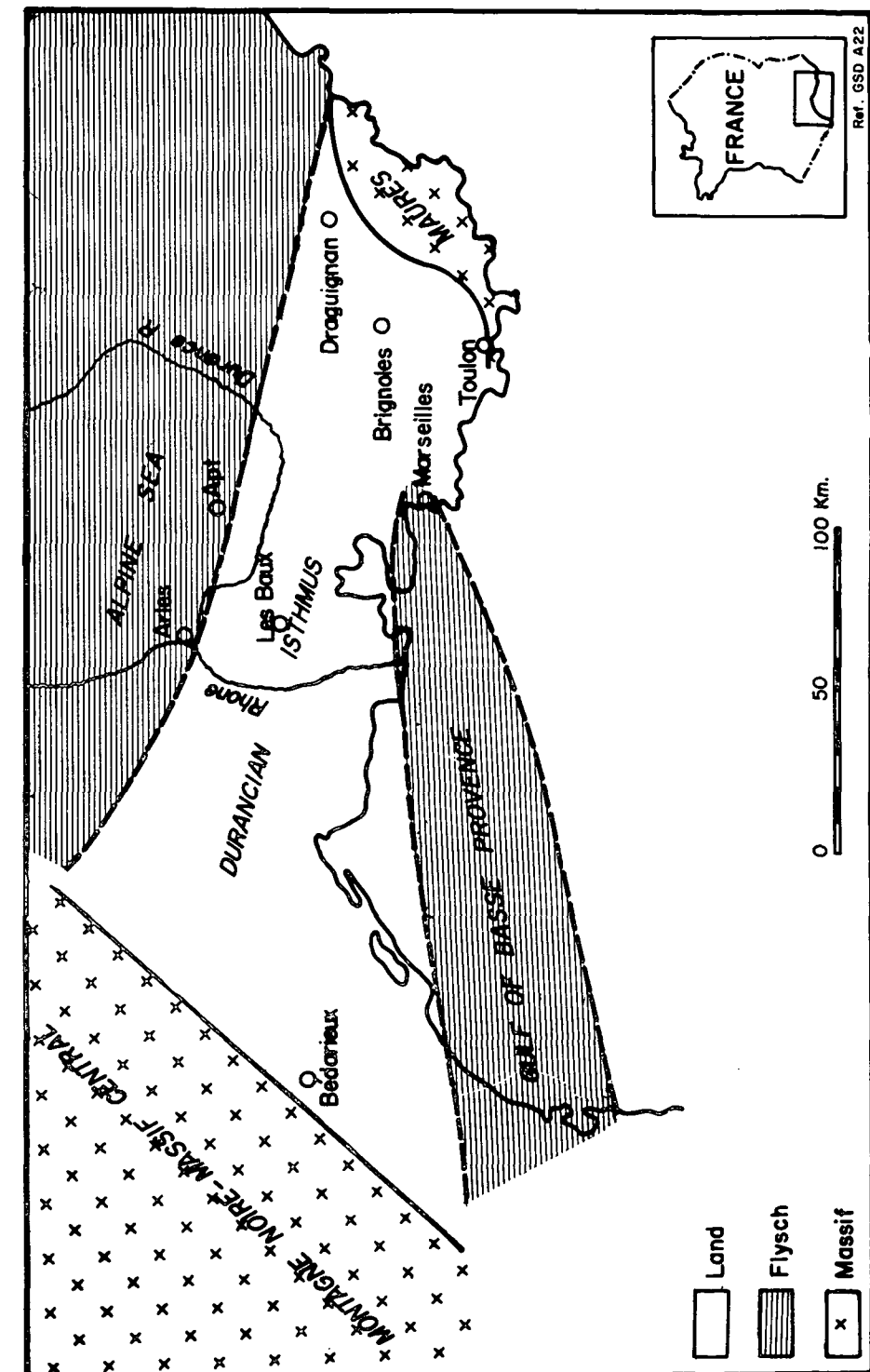


Fig. 3. Paleogeography of the French Bauxites.

During the Barremo-Aptian and a little of the Albian as well, the sea extended into the province of Teruel, where it deposited both Urgonian limestones and Lamellibranchiata layers at various times, each incorporating "glittering horizons", assumed to be continental products. Outside the Province of Teruel, Wealden and the Aptian sediments most probably continued to settle out North-West of a line through Montalban - Saragossa - Burgos and Vitoria. At the same time, the Atlantic was connected to the Mediterranean by a wide strait, which went from San Sebastian, Vitoria and Pamplona as far as Gerona, thus including a large part of the Pyrenees. The fact that the Aptian limestones do not contain any red strata indicates that they have never had any terrigenous products.

Opinions are unanimous that the continental formations represent a huge piedmont formation deposited by rivers flowing from the W.SW to E.NE. In this way, the heavy materials would have settled out progressively the further the rivers got from their sources, until only fine clayey particles were carried along. Only those particles that reached the karst of the Catalanian massif developed into bauxites. It will be found that, in some of the group "a" deposits, where favourable bauxitisation conditions probably did not prevail, there are "semi-bauxites", which Jungwirth calls lateritic clays. This is an instance of a transition stage between the unaltered Wealden rocks and true ore. It will be seen, therefore, that the general picture proposed for the origin of the Spanish bauxites bears quite a close resemblance to that put forward by Hungarian geologists for their deposits.

## FRANCE

We now come to the Provence and Languedoc bauxites of France,

Tisia, which collapsed at the beginning of the Miocene. Clayey shales in varying states of metamorphism are attributed to this massif together with phyllite, identified in boreholes, and the Velence mountain granite outcrops.

During the Secondary, all these rocks rich in aluminous ores underwent severe weathering of the clay and, probably, laterite types, since the existence of a hot and humid tropical climate is proved by the gastropod fauna. The finest particles of the eluvium would have been carried in the form of muds and colloids, by the watercourses and the subaerial currents, towards the North-west where the karst lay. Like the Parnassus bauxites, the Bakony ones often contain pyrite in their upper sections, thus indicating the presence of marshy conditions, which would have existed in at least the Eocene. On account of this, these levels are somewhat independent of those supporting them. In addition, the pyritic bauxites would be the parent rock of the speckled bauxites found in many occurrences in Europe and the West Indies. With their clear patches, the Hungarian bauxites would be areas where sulphur and iron have been decomposed by the action of vegetal roots, which are also responsible for the coal levels in the hanging walls. Finally, the pyritic bauxites may sometimes be the products of the reworking of bauxites deposited earlier and which have remained loose. These will have been subjected to resilication and should therefore be termed clay bauxites.

As regards the bauxites closest to the foot-wall, these are also relatively rich in silica and are therefore considered as being earth that is incompletely bauxitised. Finally, as in Yugoslavia, the best ores are found in the central section of the occurrences, or towards the upper third, where the bauxitising process would have been most concentrated.

By way of summing up, the finest, crystallised clay parts and the colloids derived from the weathered products would have been dragged by slow running rivers, during the Cretaceous, into the Triassic karst cavities, which were periodically under water. Under the tropical climate conditions that then existed, the bauxitising process, i.e. the elimination of silica combined with intense oxidation, then gradually took place from top to bottom. Reworking during the Eocene era has affected the upper sections of the deposits. Part of the Cretaceous bauxites were then transported as far as the marshy areas, where the reducing conditions created by the vegetation allowed the formation of the pyrite.

## SPAIN

The origin of the Spanish bauxites, which only occur in Catalonia, is easily explained, in my opinion, once their age and distribution are considered with respect to the paleogeography. This shows that the deposits are grouped as follows, from the South-West to North-East:-

- Fuentespalda-Beceite-Horta de San Juan, on the right bank of the Rio Ebro. The foot-walls are of the upper Jurassic and the hanging-walls of the Aptian;
- At La Llacuna, between Lerida and Barcelona, the bauxites are between the Trias-Rhetian and lower Eocene.
- In the Rio Segre basin, North of Lerida, they are between the indeterminate Jurassic and the Upper Cretaceous.
- Finally, in the Sierra del Cadi, south of Seo de Urgel, the bauxites are similarly bounded except that the hanging wall strata often start with continental sandstones that are probably Albian.

If all the Catalanian bauxites were formed at the same time, the deposits in group "a" and, to a less definite extent, those of group "d" indicate that they would be Neocomian and Bedoulian (lower Aptian).

If the general paleogeographical lines are now traced, it is found that, during the lower Cretaceous, the crystalline and Paleozoic massifs of the Meseta were emerged and extended over nearly half of western Spain. In addition, to the North-East, there was a Catalanian massif that covered the country between Pamplona, Saragossa, Barcelona and Gerona. During the Neocomian, these two continental masses were joined by an area of land bounded by Vitoria, Burgos, Valencia and Tortosa. At the surface of this land area, 1000 metres of sandstones, sands and multicoloured clays, often red and with Wealden facies have built up, which products are surely due to dismantling of the meseta rocks, and it is probable that they are lateritic in character.

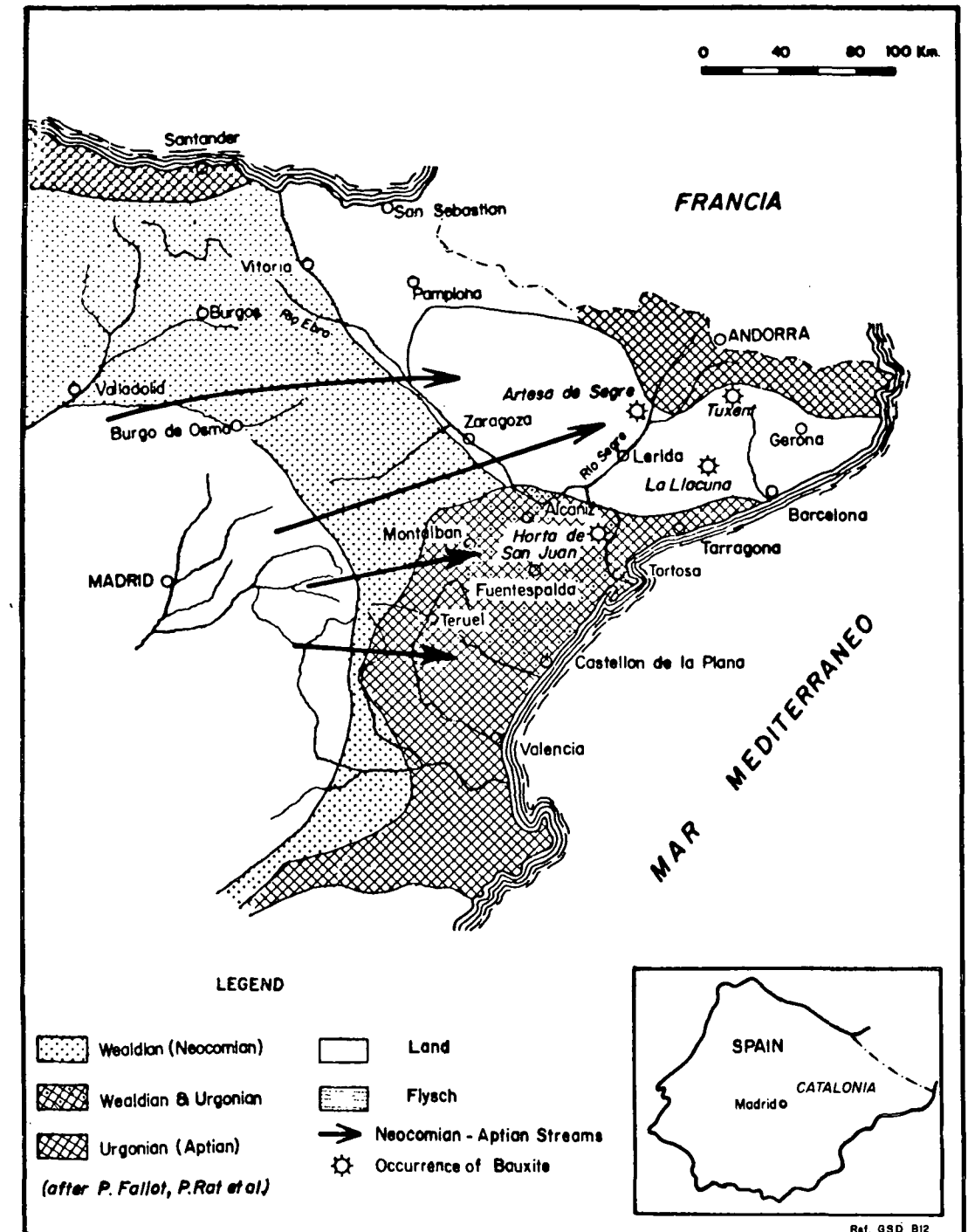


Fig. 2. The Provenance and Location of Spanish Bauxite.