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Subsurface geology and genesis of the bauxites in the area east of Brignoles in Provence

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Although bauxite mining appears to have commenced in the area east of Brignoles some 100 years ago, up until 1961 prospecting for bauxite consisted mainly of finding outcrops and then digging pits, shafts or stopes into them. Drilling was confined mainly to erratically spaced shallow mine development drill holes. Since 1961, when bauxite deposits in France were classified as mineral deposits requiring an exploitation permit to explore or exploit them or a mining concession, considerable exploration drilling on regular grids has been carried out by bauxite mining companies. This deep exploration drilling, which has proved up sufficient tonnage of bauxite in the vicinity of the old mines to justify the exploration programs, has in addition provided noteworthy geological information. The bauxites which form part of an extensive bauxitic mantle filling the chemically eroded Bathonian limestone synclines in the area east of Brignoles exhibit many features similar to the bauxite mantle, still in the process of formation, on the chemically eroded Miocene and Oligocene limestone synclines in Jamaica. However, in the area east of Brignoles the bauxitic mantle filled synclinal valleys were covered also by Santonian marls or Campanian sandstones and marls and during the Eocene were intensely folded, overthrust, underthrust and faulted. Often one side of a Cretaceous synclinal valley was inverted before the overthrusting. Some of the overthrust blocks appear to have travelled several hundreds of meters; sometimes the inverted portions of the bauxitic mantle and the limestones originally underlying them were thrust into the Upper Cretaceous sandstones, although often wedges of the bauxitic mantle were plucked out and driven forward into other beds to form "écailles".

Bauxite mines in the area east of Brignoles commenced nearly 100 years ago, originally by digging pits and inclined shafts in the outcrops by the many different owners of the surface rights or their agents, working adjacent small parcels of land. Although some deep drilling was done, exploration was confined mainly to shallow mine development drill holes or pits. In 1961, when bauxite deposits were classified as mineral deposits, the numerous small adjacent mines were consolidated in large concession areas and exploration drilling on regular grids has since been carried out by the bauxite mining companies, proving up a substantial tonnage of bauxite and furnishing precise information on the complicated structure and confirmation of the bauxite deposits.

The bauxite outcrops in the area east of Brignoles form an almost continuous double line ringing the northern and southwestern sides of a wedgeshaped Triassic inlier between

Brignoles on the west and Vieux Cannet 23 km to the east. The outcrops in the northeastern section represent the surface exposures of an extensive bauxite bed that accumulated within a chemically eroded westerly pitching unsymmetrical synclinal valley of Bathonian limestones and dolomites (the Vins syncline), which was later filled with a thin bed of Santonian marls, in the western part, and thick accumulation of Valdonian fluviatile arkosic sandstones and Fuvellian and Maestrichian limestones and clays. Outcrops of bauxite occur on both sides of route D 24 from 5 km east of Brignoles down the valley of the Caramy, which here flows east, in the opposite direction to the pitch of the Vins syncline, to the artificial Lac de Carcès. In this section of the area generally the southern line of outcrops are exposures of the bauxite resting on the southern, less inclined, down faulted limb of the Vins syncline, the "couche sud" of the miners, and the northern line of outcrops are surface exposures of the overturned and overthrust, more inclined limb of the syncline, the "couche nord" of the miners. In this area are the bauxite mines of St. Christophe, Vins and Brauch (near the Lac de Carcès). The St. Christophe mine is in the widest part of the Vins synclinal valley, the axis being probably 1 km north of the Caramy under the overthrust "couche nord". The "couche sud" here rests on Bathonian dolomite and is covered by at least 100 m of Valdonian, Fuvelian and Maestrichian deposits. The outcrops of bauxite continue up the Vins syncline mainly on the north side of route D 79 to La Gagère mine (3 1/2 km east of the Lac de Carcès). In this part of the Vins synclinal valley flows the Issole river in the same direction as the pitch of the syncline. East of the Lac de Carcès are located the mines of Doze Ouest and Doze Est, Dauphin, Combecave and La Gagère. The Issole river has broken through the Montagne de la Bouissière, which forms the southern limb of the Vins syncline south of Combecave mine, and has partly eroded the "couche sud" from its point of entry into the Vins synclinal valley to its junction with the Caramy at the Lac de Carcès. Between Doze Ouest and Doze Est mines the overthrust northern, more inclined, limb is almost vertical and three or more thrust faults above the synclinal axis have produced three or more "écailles". Several north striking faults separate the Doze Ouest and Doze Est mines from the Dauphin mines, one of them causing a small waterfall in the Issole. In the Dauphin mine complete overfolding and overthrusting along three or more thrust planes above the axis have broken the "couche nord" into three "écailles" which now dip to the south [1]. East of Dauphin the more inclined limb of the synclinal valley becomes less overturned in the Combecave mine to less than vertical in La Gagère. Thrusting below the synclinal axis has produced a prominent "écaille" of the "couche sud" and there are indications of thrusting below the main "couche sud" bed. The axis of the Vins syncline can be seen in the center of La Gagère mine. The bauxite outcrops continue to the northeast of La Gagère mine, mainly on the south side of route D 79 to Le Thoronet. This area is also a bauxite filled unsymmetrical syncline and was probably the continuation of the Vins syncline. Here the south limb of the synclinal valley is steeply inclined against a fault and the north limb only slightly so with the result that the bauxite and sometimes portions of the underlying Bathonian limestone have been plucked out without overfolding and pushed south by an overthrust rock sheet of Keuper Rhaetic and Hettangian beds into the Valdonian sandstones, which originally filled the valley above the bauxite. In this area north from La Gagère mine are located on the west side of route D 79 the mines of La Derobade and on the east side Maron, where there are several plucked out "écailles" thrust into the overlying Valdonian. Farther east and south of route D 79 are the Blanquette and Peygros mines. In the area, in addition to piled up "écailles" thrust into the overlying Valdonian, an almost horizontal thrust has developed in the bauxite in the—here almost flat—center of the syncline under the Keuper-Hettangian rock sheet. On the north side of route D 79 the old mine of La Petite Darboussière represents a small undisturbed outlier of the bauxite filled syncline.

Bauxite outcrops continue from Le Thoronet to 3 km northeast of Le Vieux Cannet. On the south side of route D 17 are the small outcrops of Les Ubacs and the mines of Rigoulier, Les Cadouls and Le Recou. The mines are in four main "écailles" on dolomite dipping 40-60° SW into the Montagne des Ubacs. They appear to be faulted portions of the overturned south limb of the Vins syncline thrust over Campanian breccia against the Hettangian and Keuper. On the south side of the Triassic inlier and route N 7 from 4 to 6 km east of Brignoles more bauxite outcrops indicate another bauxite filled synclinal valley. In this area, where the mines of Pelicon, Merlançon, Fontlade and La Rouge are located, an unsymmetrical synclinal valley pitching to the west appears to have been ruptured at the axis and the southern more inclined, limb of bauxite, Portlandian and Bathonian dolomites, Bajocian and Keuper limestones and marls has been thrust over the northern, less inclined, limb in a series of upward curved thrust planes carrying plucked out "écailles" of bauxite of the lower limb near the axis forward over the unmoved portion of the bauxite bed on the northern limb of the syncline. Small outcrops of bauxite also occur at Maunier east of La Rouge mine north of route N 7.

The general tectonics of the bauxite area east of Brignoles is covered in the explanatory notes and 1: 50 000 geological map of the Draguignan district 1966 edition, on which are marked the locations of some of the deep drill holes [8]. Many hundreds more exploratory and exploitation holes have been drilled on regular grids during the past decade, which for obvious reasons are not shown on the geological map. These are concentrated mainly in the vicinity of the old mines and have proved up more than 20 000 000 tons of additional bauxite reserves. Apart from satisfactory economic results, much geological information has emerged regarding the probable genesis of the bauxites in the area.

In general, these holes appear to confirm many of the conclusions reached in 1930 by Professor Jacques de Lapparent in his monumental monograph [7], namely that the mines and outcrops east of Brignoles formed part of a more or less continuous "eluvial" bauxite bed in a karsted Bathonian syncline, the Vins syncline, the northern limb of which had been overthrust to the south. There now seems to be little doubt that the bauxites of the area east of Brignoles were formed in place from the insoluble residue left after chemical erosion of the Bathonian limestones at one or more times within the Aptian or Albian periods.

The recently formed bauxites that were discovered in Jamaica in 1942 supplied more concrete evidence in support of the "eluvial" theory. Reports on the bauxites on Jamaica by the economic geologists who undertook the original exploration there show that there is substantial evidence that the bauxites in Jamaica are the residual product of the chemical erosion of the Lower Miocene and Oligocene limestone on which they lie [11], [6]. This chemical erosion has continued probably from the Middle Miocene to the present time, or some 15 000 000 years, and, in spite of their low insoluble residue content, about 1 %, there was sufficient volume of these limestones to account for the tonnage of bauxite in Jamaica [5].

These conclusions were based not on the results from one or two solitary deposits of a few million tons but on deposits aggregating a billion proved tons of bauxite, which had been blanketed by grids with thousands of holes drilled down to the limestones and also deep holes drilled into the underlying limestones. Many complete analyses have been made and they show that, although these limestones are very pure, containing from under 0.01 % to 0.12 % SiO_2 and from under 0.01 % to 0.23 % Al_2O_3, the ratio of SiO_2 to Al_2O_3 is always about 1: 1 and similar to the Bathonian limestone underlying the bauxites in the Vins synclinal area.

Because of the low alumina content of both the Jamaican and Bathonian limestones some geologists have proposed other source materials for the bauxites and complicated means of transportation of this material by rivers or subterranean channels into the main karst areas [12], [10], [9]. In the case of Jamaica, hydrological and physical conditions under the bauxite deposits refute these hypotheses. Kaolinitic clays and terrestrial deposited volcanic ash have been proposed as source materials. But the former contains a higher ratio of silica to alumina than the limestones under discussion. Moreover, it appears from studies in Malaya on the concretionary bauxites and kaolinite clays derived from the weathering of metamorphosed rhyolites and andesites that the kaolinite clays develop under different hydrological conditions from the bauxites [5]. Terrestrial deposited volcanic ash as a source material for Jamaican bauxite is unacceptable as no deposits of ash have been found on the Tertiary limestones. Studies of recently weathered terrestrial deposited volcanic ash on Hawaii indicate that it is chemically and physically different from both Jamaican and French bauxites. Fine volcanic ash or dust in minute quantities is of course widespread in oceanic deposits and mineralogical studies indicate that in minute quantities it is a constituent of the Tertiary limestones in Jamaica [3]. It probably accounts for much

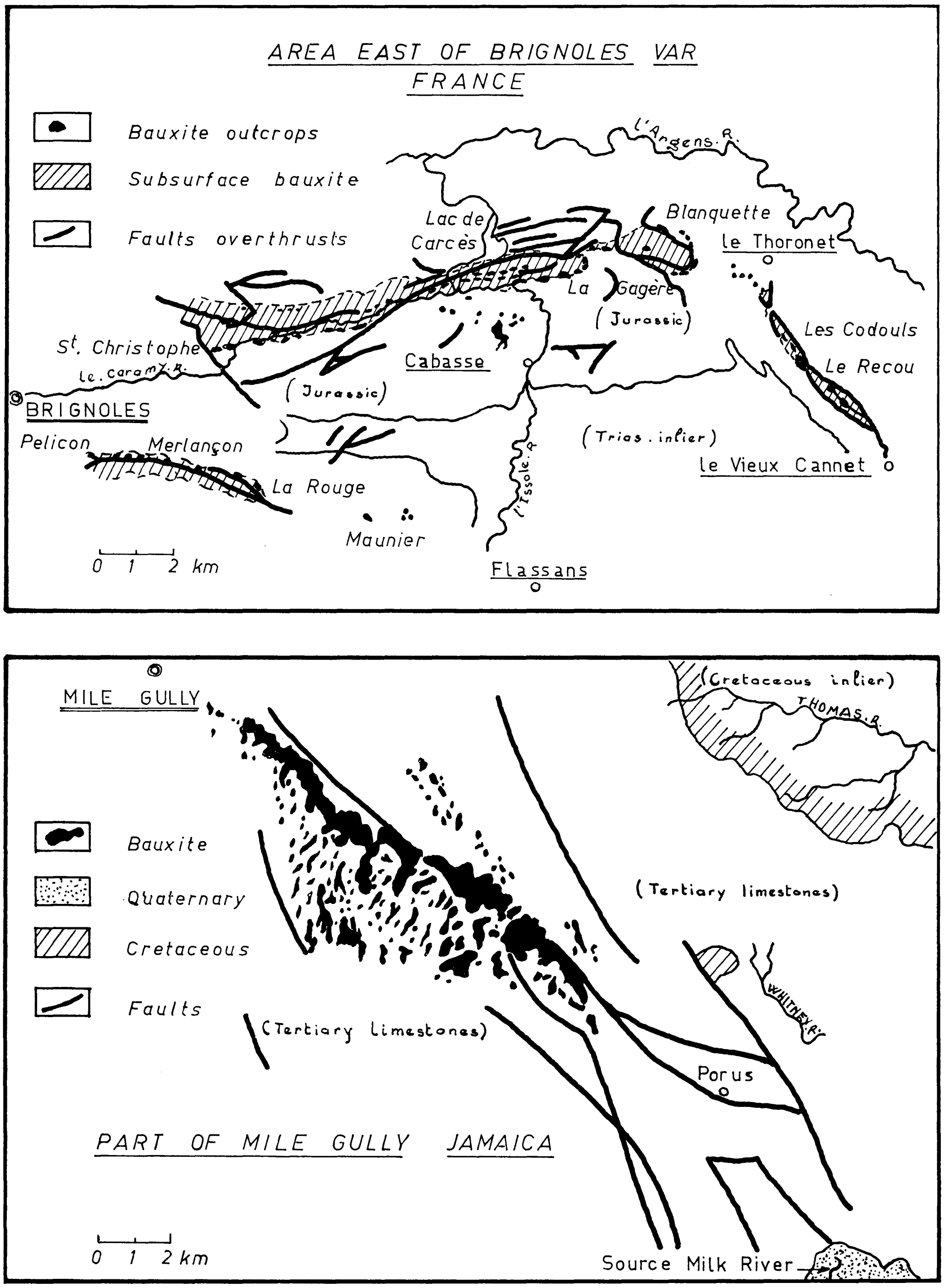

Fig. 1. — Synclinal areas east of Brignoles, France and part of Mile Gully valley

of the titania and iron oxides, soda and silica as glass and quartz found in the insoluble residue. However, since the limestone residua has a ratio of Al_2O_3: SiO_2: Fe_2O_3: TiO_2: P_2O_5 of 4: 3: 2: 1: 1, the bulk of the Al_2O_3 and P_2O_5 must be in another material, probably in the skeletons of the abundant shallow water foraminifera in the limestones. Modern species of the same genera have a ratio of Al_2O_3: SiO_2: P_2O_5 of about 2: 1: 3 in their skeletons [4]. Volcanic dust is probably also the source of much of the heavy trace elements found in the limestones and bauxites in Jamaica and France. However, local large increases in P_2O_5 minerals above the normal content in Jamaican bauxites may be due to the collapse of caves and the high nickel coated ovoid bodies found in the bauxite at Les Cadouls might be of meteoric origin [2].

Jamaican bauxites and those of the area east of Brignoles are true bauxites. Bauxite production now exceeds 12 500 000 tons a year in Jamaica and 1 500 000 tons a year in the area east of Brignoles.

Both the Vins synclinal area and the one southeast of Brignoles can be matched with the synclinal Mile Gully valley in Jamaica to a remarkable degree. In southwest Jamaica the Mile Gully valley has resulted from the chemical erosion of a down faulted unsymmetrical synclinal Tertiary limestone trough. The floor of the valley from its head at 380 m elevation northwest of Mile Gully village declines to 150 m elevation in 25 km and then opens out southeast of Porus into the plain of Quaternary alluvium in which the Milk River issues from a spring at 75 m elevation. The southwest side of the valley rises at about 5 degrees to the 750 m high Manchester plateau and the northeast side abruptly with a 15° slope to 900 m elevation, where the Tertiary limestones have been chemically eroded away to form the Cretaceous inlier of central Jamaica.

On both sides of the valley there are several longitudinal faults 3 to 15 km long parallel to the valley floor. Deposits aggregating over 100 million proved tons of bauxite have accumulated in the valley. They are concentrated as an irregular 1 km-wide belt lining the whole 25 km of the valley bottom. On the more gently sloping southwest flank the deposits cover a smaller area, are less thick and cccupy either oblong or oval solution pockets with the same orientation on the steeper northeast flank. The bauxite filled solution pits vary in depth from 5 to 30 meters and the largest deposits are concentrated in the longitudinal center of the valley between 400 and 450 m elevation. There are no streams in the valley, and no other deposits apart from 30 cm of bauxitic soil cover either the bauxites or limestones (fig. 1).

Deep drilling in the center of the valley at 406 m elevation penetrated 23 m of bauxite, then 395 m of Lower Miocene, Oligocene and Upper Eocene limestones and 60 m of impervious Middle Eocene marls and clays, and bottomed at 72 m below sea level. The water table in the limestone was at 102 m elevation. The rainfall in the valley area is from 760 to 2 410 mm a year and the level of the water table fluctuated within a range of 6 meters, about 48 h. out of phase with the rainfall fluctuations during a three-month test period in the rainy season before closing in the well. The Lower Miocene and Oligocene limestones for the first 150 m below the bauxite averaged 0.03% silica and 0.04% alumina, and the magnesium carbonate content was under 2% down to 130 m elevation; below this the limestone became increasingly dolomitic with a magnesium carbonate content of over 40% at 41 m elevation. Several caverns were encountered in the limestone above the water table.

The bauxite deposits in the Mile Gully valley are soft earthy, shaley and porous (free moisture 13-24%) and the contact with the underlying pinnacled fresh limestone surface is sharp, even when the surface has been softened by chemical decomposition. Stratification or other features characteristic of sedimentary deposition have not been observed. In some places, towards the base of the deposits they are weakly foliated. The direction of foliation is not consistent, although mainly vertical, and is probably the outcome of slumping caused by underground collapse and/or by avalanchal creep from the sides of the valley. The average grade of the deposits in the valley is: H_2O 26.5%, SiO_2 1.5%, Fe_2O_3 18.5%, TiO_2 2.5%, Al_2O_3 48.5% and minor elements 2.5%.

The silica content varies both laterally and vertically in the same deposit from 0.01 % to 3.0 % and there is a tendency for the phosphates (Crandallite 3 %) and manganiferous minerals (concentrated in black filmy scales and pisolites) to be concentrated at the base but not at the limestone contact, as is the case of manganese in the Vins synclinal area. Like other recently formed bauxites on limestones and other rocks, the bauxites are gibbsitic (gibbsite 61 %) with from 2 to 8 % boehmite. The latter is unequally distributed in Jamaican bauxites, while in Guinean and Australian bauxites derived from non-calcareous rocks the boehmite appears to be concentrated at certain levels. Jamaican bauxites are colloidal, up to 50 % of the particles are under half micron and pisolites, although frequent, are under 6 mm in size, in comparison with their abundance and large size, from 1 to 12 mm, in the French bauxites. Elimination of two molecules of water bound to the alumina in the cryptocrystalline gibbsite and ferro alumina hydrogels in the Mile Gully bauxites would give a boehmitic bauxite analysing H_2O 13 %, SiO_2 2 %, Fe_2O_3 23 %, TiO_2 3 %, Al_2O_3 59 %. This is identical to some of the best grade Combecave boehmitic bauxite, which contains 6 % gibbsite. It would seem that the dessication of a gibbsitic goethitic bauxite to a boehmitic hematitic bauxite may occur when the climate becomes drier, as would occur when elevated limestone plateaux are chemically eroded away towards the base level.

The residual material in the Miocene and Oligocene limestones in the Mile Gully valley has a ratio of SiO_2: Al_2O_3 of 3: 4. Hydrolysis of this material without desilication would yield a residual bauxitic clay analysing SiO_2 27 % and Al_2O_3 37 %. Bauxitic clays on low lying water saturated limestones with the same SiO_2: Al_2O_3 ratios in other parts of Jamaica average SiO_2 22 % and Al_2O_3 43 %.

The circumstances conducive to the genesis and accumulation of extensive deposits of good grade bauxite as exemplified by the Mile Gully valley thus appear to be a faulted unsymmetrical synclinal valley of very pure limestone with a silica: alumina ratio of about 1: 1, elevated sufficiently above sea level for the water table to have always been well below the surface along both the sides and center of the valley. Under these physical conditions and in the present climate of Jamaica the limestones are chemically eroded by carbon dioxide charged and oxygenated rain, which dissolves the calcium and magnesium carbonates and carries them down in solution to the water table, where the magnesium carbonate is precipitated. At the same time the non-calcareous residual matter, probably in the skeletons of foraminifera and other marine fossils and volcanic dust, is desilicated and hydrated to bauxite.

There are strong indications that these essential conditions developed in the area east of Brignoles in the Jurassic and Cretaceous, although much of the post-Jurassic tectonics is obscured by the Upper Cretaceous deposits and the Eocene tectonics. However, the pattern of the latter shows the influence of the post-Jurassic tectonics, which created the suitable conditions for the late Cretaceous karst topography to develop in the Vins syncline and the accumulation of a broad 25 km long belt of bauxite along the axis of the valley from the residual material in the Bathonian limestones.

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