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Record 1973/156

ORIGIN OF AUSTRALIAN BAUXITE DEPOSITS

by

K.A. Plumb and V.A. Gostin (Univ. of Adelaide)

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SUMMARY

Field and laboratory observations made as a result of an inspection of Australian bauxite deposits in the company of two USSR geologists are described. Theories of origin of the deposits are critically reviewed, and alternative hypotheses proposed. Criteria to aid further bauxite exploration are outlined.

The Gove deposit contains both detrital bauxite and residual, in situ bauxite. It was derived from bauxitization of Lower Cretaceous clay-rich sediments. Bauxite types comprise tubular bauxite, cemented pisolitic bauxite, and loose pisolitic bauxite.

The deposits on Marchinbar Island are of detrital origin, and are most likely to have been derived from a Lower Cretaceous parent rock.

The parent rock at Mitchell Plateau is Precambrian (1800 m.y. old) basalt, and the deposit is entirely of sedimentary origin; no original residual in situ bauxite is preserved. The bauxitic rock types include a complex of densely cemented conglomerates, breccias, and pisolitic material.

The Weipa deposit is characterized by immense quantities of very uniform loose pisolitic bauxite. It is essentially a residual deposit formed by a combination of in situ weathering or bauxitization, and down wasting and local redepositon of the surface layers. The parent rocks were permeable clay-rich sediments of Upper Cretaceous or Lower Tertiary age. The deposit is the result of an exceptional combination of conditions, perhaps unique to Weipa's position on the flank of the young stable Carpentaria Basin.

The Jarrahdale deposit contains both detrital and residual in situ bauxite, and comprises lithified and friable pisolitic and breccia-type bauxites. The parent rock was Archaean granite, gneiss and metasediments, and (?)Cretaceous aluminous sediments.

The deposits at Moss Vale, formed on mid-Tertiary basalts, contain pisolitic and tubular types, and are probably detrital.

All deposits are of middle to late Tertiary age, and all show modifications due to drier, more seasonal climates during the Quaternary.

The best guides to prospecting for bauxite are (1) proximity to the coast, (2) the presence of suitable parent rocks - intermediate to basic rocks or permeable aluminous sediments, (3) moderate elevation and relief within the lateritized surface, (4) strikingly different vegetation and air-photo pattern in areas of widespread thick laterite.

INTRODUCTION

During the period 1-15 April 1971, two USSR geologists, Prof. A.D. Shcheglov, Deputy Minister of the Ministry of Geology, and Dr V.A. Tenyakov, Specialist Geologist in Bauxite, Institute of Mineral Resources, visited and inspected Australian bauxite deposits at Jarrahdale, Moss Vale, Weipa, Gove, and Mitchell Plateau (Figure 1). Cobourg Peninsula and Wessel Islands were briefly inspected from the air. During the visits they were accompanied by both authors, Plumb as BMR representative and guide to north Australian regional geology, and Gostin as interpreter. Plumb was not present in Perth and Jarrahdale, where the BMR was represented by G.F. Mead.

The opportunity to discuss the deposits with our visitors brought an awareness of valuable new concepts on the origins of these deposits and stimulated the senior author (K.A.P.) to carry out further literature research and laboratory study of the deposits. Unfortunately there has been no opportunity to augument these studies with further field work, and the field visits were very brief.

This report describes the field and laboratory observations made during the study, augumented by the senior author's previous knowledge of the region. Both published descriptions and theories and the views of the USSR visitors are critically analysed in detail, and alternative hypotheses for the origins of the deposits proposed. Comparisons are made between the deposits, conditions of bauxitization in Australia discussed, and criteria to aid in further exploration for bauxite suggested. Suggestions for further studies are given. Appendix 1 describes a Russian classification of bauxites, and summarizes bauxite deposits in Russia; it is a precis of a lecture Dr Tenyakov presented to BMR.

It would of course be presumptuous to pretend to solve the problems from our limited personal knowledge of the deposits. We have produced more questions than we have answered. However, the overall view of the deposits allows many useful comparisons and analogies to be made and provides an alternative approach to those of the recent papers by Dr P.L.C. Grubb (1970, 1971a, 1971b). It is hoped the ideas presented here will stimulate further thought and study of the deposits and assist in exploration for new deposits.

Itinerary

The visitors' movements were as follows:

1.4.71	Thursday	-	Arrive Perth from USSR. Visit University of Western Australia, Geological Survey of Western Australia, CSIRO
2.4.71	Friday	-	Inspect Jarrahdale deposit.
3.4.71	Saturday	-	Travel Perth - Canberra.
4.4.71	Sunday	-	Inspect Moss Vale deposit.
5.4.71	Monday	-	Visit BMR.
6.4.71	Tuesday	-	Travel Canberra - Cairns
7.4.71	Wednesday	-	Cairns-Weipa. Inspect Weipa deposit.
8.4.71	Thursday	-	Inspect Weipa deposit. Weipa - Cairns.
9.4.71 10.4.71	Friday) Saturday)	-	Easter Friday. Free time Cairns.
11.4.71	Sunday	-	Travel Cairns - Mount Isa.
12.4.71	Monday	-	Visit Mount Isa Mines. Travel Mount Isa - Darwin.
13.4.71	Tuesday	-	Darwin - Cobourg Peninsula - Wessel Islands - Gove. Inspect Gove deposit. Return Darwin.
14.4.71	Wednesday	-	Darwin - Mitchell Plateau. Inspect Mitchell Plateau deposit. Return Darwin.
15.4.71	Thursday	-	Leave Darwin. Return to USSR.

Outline of work

Field work: As can be seen from the itinerary the visits to the individual deposits were necessarily brief, and generally amounted to only about half-a-day actually spent on each deposit, excepting Weipa, where two half-days were available. During this time the major exposures, chiefly quarries, were examined as completely as time permitted. It was still possible to make many useful observations during this time.

Laboratory: A small number of typical specimens were studied with the optical microscope, the scanning electron microscope, and the electron microprobe.

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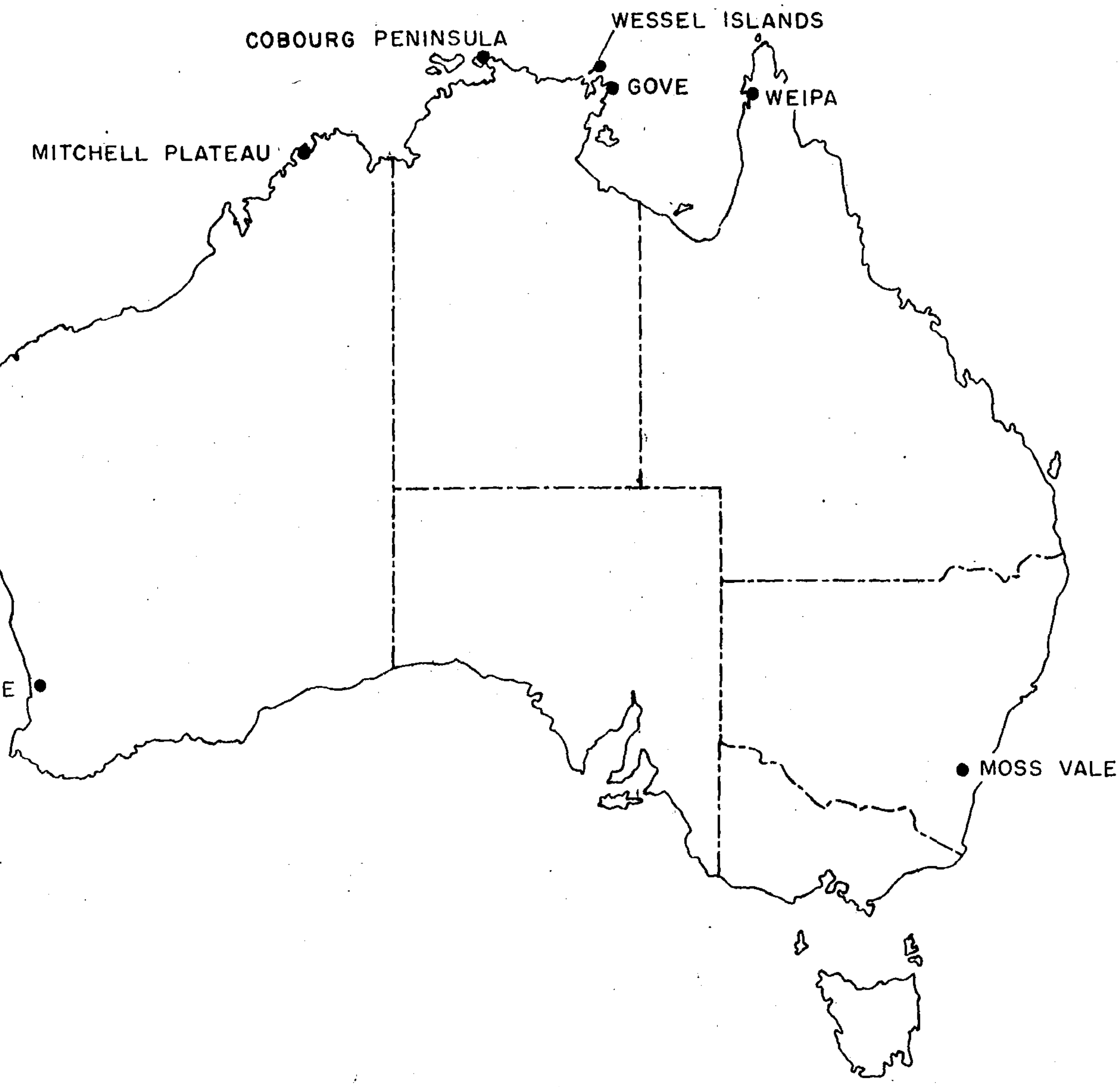

Fig. 1 Location of bauxite deposits visited

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(1) The optical microscope was simply used to study the fine textures of the rocks and to relate these to the field observations. No attempts were made to accurately identify the mineral components of the rocks; bauxite mineral identification requires very sophisticated techniques and the deposits concerned have been adequately studied in this way by previous workers. In common with experience of other workers on similar rocks it was found that polished sections revealed the textures better than thin sections.

(2) The intensity of electron emission from the specimen surface beneath the scanning electron microscope is proportional to the average atomic number of the sample. Thus iron-rich material produces a whiter photographic image than alumina, which appears dark grey (e.g. Plates 3, 4, and 5). Aluminium and silicon have similar atomic numbers so gibbsite cannot be distinguished from clay. This method, in combination with other methods, provided a convenient visual picture of the compositional variation across samples. For samples from Gove, which possessed reasonable compositional contrasts, the method revealed internal structures much more clearly than conventional polished sections under the optical microscope. Samples from Weipa and Mitchell Plateau (Plates 9, 11) were more homogeneous and textures were often clearer beneath the optical microscope owing to colour differences.

(3) The samples studied were much larger than those normally studied beneath the electron microprobe, and this posed practical problems. Firstly it was not possible to directly identify the position within a sample beneath the probe and secondly, because of the sample size, the time required to do a series of spot analyses, compared against suitable standards, was prohibitive for such a reconnaissance study, even if the positions of the spots could be accurately identified. It was decided therefore to carry out continuous scans across samples along previously marked lines with continuous printout of results on graphs. This provided a semi-quantitative picture of the composition variations, since no comparisons were made against standards, but was still useful. Scans had to be carried out manually, with subsequent loss of precision, because the extremely slow speed of the automatic scanning motor on the probe made its use too slow for the size of samples studied. Nevertheless, useful data on composition variations were obtained and various layers could be identified by characteristic 'signatures'. Studies were made of Al, Fe, Ti, and Si.

Terminology

Since first used by Buchanan (1807) the term laterite has taken on many different meanings, some purely descriptive and some with genetic implications. Many workers favour abandoning the term because it is too confusing, but the general trend appears to be towards the use of a purely descriptive definition, devoid of genetic implications. This approach will be used here, the term being used as defined by Alexander & Cady (1962), which is the preferred definition of Maignien (1966): '<u>laterite</u> is a highly weathered material rich in secondary oxides of iron, aluminium, or both. It is nearly void of bases and primary silicates, but it may contain large amounts of quartz and kaolinite. It is either hard or capable of hardening on exposure to wetting and drying.' The origin may be further qualified by use of terms such as 'detrital laterite', 'reworked laterite', 'in situ laterite' etc.

Recent literature (Maignien, 1966; De Carvalho, 1967) use the term <u>cuirasse</u> to distinguish the hard lithified lateritic crust, generally resulting from surface hardening of either detrital or in situ laterites.

Bauxite is defined here specifically as an alumina-rich laterite suitable for use as an ore of aluminium. It can also be qualified by adjectives such as detrital, in situ etc. Confusion is commonly introduced into the literature by bauxite geologists who use the term for all laterites whether of ore grade or not. Sub-ore grade material will be described here as aluminous laterite, ferruginous laterite etc.

ACKNOWLEDGMENTS

The assistance of the staff and managements of ALCOA, COMALCO, NABALCO, and AMAX (Australia) for their hospitality in allowing inspections of their deposits, and in providing the necessary facilities, is gratefully acknowledged. In particular we were conducted around the deposits by Mr G.F.U. Baker (ALCOA, Jarrahdale); Mr Bill Duchatel (COMALCO, Weipa); Messrs Richard Hind and John Beaumont (NABALCO, Gove); and Messrs Wayne Jackson and Tim Graham-Taylor (AMAX, Mitchell Plateau). Discussions and information were provided by staff members of CSIRO, Geological Survey of Western Australia, and Geology Department, University of Western Australia, in Perth. Dr P.L.C. Grubb, previously with CSIRO, and now at the Institute of Mining Research, University of Rhodesia, Salisbury, has corresponded on matters raised in his publications. Mr R.N. England of BMR assisted with the electron scanning microscope and electron microscope studies.

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REVIEW OF HYPOTHESES ON ORIGIN OF BAUXITE

During the latter half of the 19th century a variety of origins were proposed for bauxites but many of these, such as deposition from hot springs and hydrothermal alteration, quickly lost favour, so that by the turn of the century two main schools had developed; those who favoured a detrital origin and those who favoured an origin by weathering in situ. The detrital school developed largely from work in France, where recent work (e.g. Nicolas, 1968) shows that the deposits are in fact detrital. The in situ school developed mainly from work in India, where the emphasis, even in more modern times, has been on the in situ deposits (e.g. Fox, 1932; Chowdhury, Anandalwar, & Tyagi, 1964; Chowdhury, Venkatesh, & Paul, 1964; Chowdhury, Venkatesh, & Paul, 1968), although even here detrital laterites and bauxites were recognized at quite an early stage by Mallet (1883; quoted from Fox, 1932), who proposed a threefold classification of laterites:

1. Due to deposition
2. Alteration of rock in situ
3. Detrital or redeposited.

Fox (1932), although recognizing detrital bauxites in India, considers them to be of minor importance.

One of the more valuable pieces of work was by Lacroix (1913; quoted in Gordon, Tracey, & Ellis, 1958) who, in French Guinea, demonstrated the formation of bauxite by in situ weathering and then subsequent erosion, transportation, and redeposition of the material; Dr V.A. Tenyakov (pers. comm.) has studied deposits in Guinea and concurs with Lacroix's interpretation. Similar relations between in situ and detrital bauxites have been determined more recently in Arkansas (Fig. 2), where the gradual transition from fresh syenite to in situ bauxite, its erosion and deposition as detrital bauxites and, finally, beds of bauxite in a normal sedimentary sequence some distance from the original in situ bauxite, is described in some detail by Gordon et al. (1958). It is difficult to decide at just which stage an in situ bauxite should be considered as transported or detrital; the distinction can become rather academic.

In Russia both in situ and sedimentary bauxites are recognized (Dr V.A. Tenyakov, pers. comm.; Appendix 1), but it would appear that the emphasis is on the sedimentary types. Bushinsky (1964) points out, firstly, that many bauxite deposits in the world formerly considered to be in situ are of sedimentary or detrital origin, and secondly, that despite their widespread distribution the economic production from in situ bauxites throughout the world is comparatively small compared to sedimentary bauxites.

A rather parallel evolution of ideas has developed with regard to the formation of laterites as a whole. Most emphasis has been on in situ origin, mainly from the influence of the early work in India (Fox, 1932), and in Australia (Woolnough, 1927). But Mallet (1883) had recognized detrital laterites in India, and both Simpson (1912) and Woolnough (1927) described detrital laterites in Australia, although concentrating most of their discussions on the mechanisms of formation of in situ laterite. Modern workers tend to consider laterites as being formed by a variety of processes involving both in situ weathering and depositional processes (Maignien, 1966; de Carvalho, 1967).

It is now generally accepted that laterites can form in areas of moderate relief and on relatively steep slopes (e.g. Prider, 1966; Maignien, 1966), in opposition to the old concept that laterites only form on peneplains (Woolnough, 1927). In fact the modern view is that relief favours laterite formation by providing suitable drainage, particularly for bauxites; Maignien (1966) notes that laterites on relatively high relief areas tend to be more aluminous than those lower down. The old concept of bedrock leaching, upward movement of iron and alumina-rich solutions by capillary action, and evaporation at the surface, is also losing favour. Maignien (1966) points out that this process, although it does occur, is inadequate on quantitative grounds to form the laterites observed; he stresses the importance of downward and lateral movement of groundwater. Laterite components are deposited at the base of the soil profile and the kaolinite or pallid zone is not an essential factor in the formation of laterite but is instead an incidental accessory (Maignien, 1966; McFarlane, 1971).

Harden & Bateson (1963) describe an in situ bauxite in which a change in drainage conditions produced downward leaching of an earlier formed clay. Iron was reprecipitated at the base of the zone of second stage leaching (? top of water table), silica was lost from the system, and the alumina remained to form bauxite.

Finally, McFarlane (1971) proposed an interesting process by which lateritization, with sparsely scattered pisoliths, accompanied down-wasting and erosion of an area of moderate relief. As erosion proceeded soluble components and fine clays etc. were carried away while the pisoliths remained and were concentrated in a remanié deposit, undergoing some transport and redistribution in the process. The end product is a

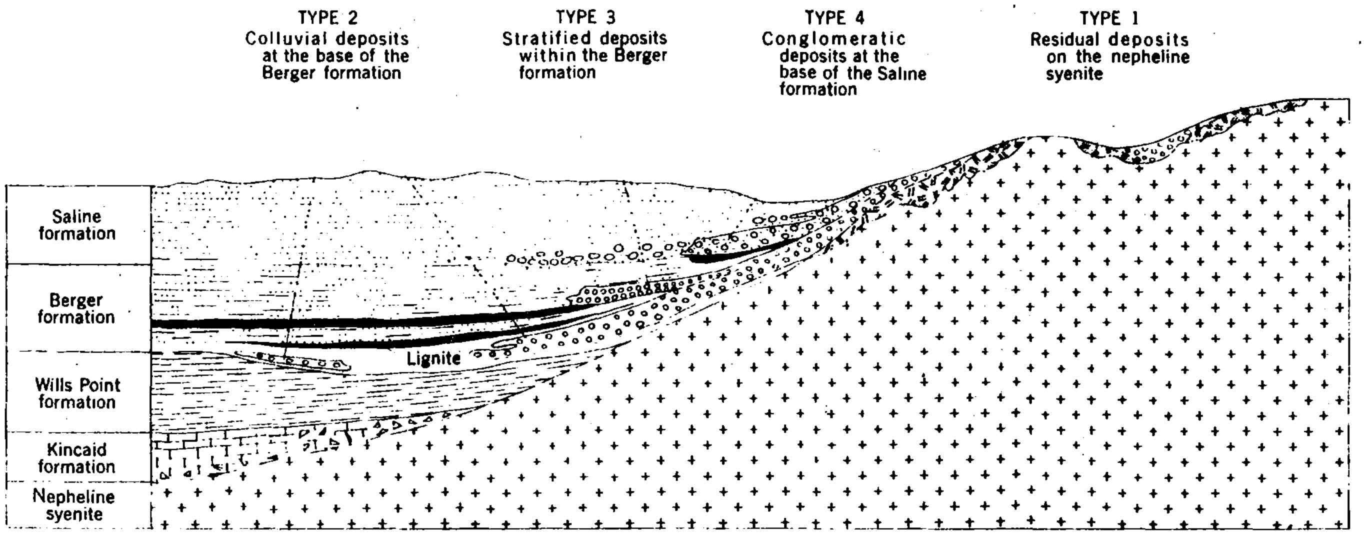

Fig. 2 Diagrammatic section of the principal types of deposits in the Arkansas bauxite region (after Gordon, Tracey, Ellis, 1958)

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relatively flat terrain covered by a layer of closely packed pisoliths; the peneplain, or plantion surface as preferred by McFarlane, is the end-product of the process, rather than the cause, and whether the laterite should be regarded as an in situ, residual deposit or a detrital deposit becomes, once again, rather academic.

For many years Australian literature was dominated by the peneplain concept of Woolnough (1927) and in situ origins of laterites. Prider (1966) drew attention to the considerable relief which can be present in laterite areas and Hays (1967) and Mulcahy (1967) have drawn attention to the complex geomorphological processes associated with the formation of laterites, producing many detrital as well as in situ laterites. The various BMR field parties which the author (KAP) has been associated with over the years have recorded widespread detrital laterites in northern Australia.

The history of bauxite investigations have been similar. Early workers invariably referred to the bauxites as in situ residual deposits (Owen, 1954; Gardner, 1957; Loughnan & Bayliss, 1961; Tomich, 1964; Dunn, 1965, Evans, 1965; Grubb, 1966). It is only quite recently that Grubb recognized both in situ and detrital bauxites amongst the Australian deposits. He considers that Weipa (Grubb, 1971a) and Boolarra-Mirboo (Grubb, 1971c) deposits are entirely in situ residual deposits; Gove (Grubb, 1970) and the Darling Ranges (Grubb, 1971b) deposits contain both in situ and detrital material; and the Mitchell Plateau deposit (Grubb, 1970) is now considered to be entirely reworked detrital material.

DESCRIPTIONS AND INTERPRETATIONS OF DEPOSITS

GOVE

Development

Brown (1908) made the first reference to bauxite in the Northern Territory when he described a siliceous pisolitic laterite from Cobourg Peninsula, near the western border of Arnhem Land. This report attracted the attention of H.G. Owen (1954) of BMR, who was carrying out an Australia-wide survey for bauxite. He visited Brown's deposits in June 1949, and at the same time requested members of the Northern Territory Coast Patrol Service to collect specimens of pisolitic material from other places along the Arnhem Land coast.

Before the end of 1949 Captain F.E. Wells and Seaman F.J. Waalkes, of the Patrol Service, had forwarded specimens of bauxite from Truant Island and Wessel Islands containing between 34.6 and 40.8 percent available Al_2O_3.

It was not until October 1951 that Owen was able to make a reconnaissance visit to the deposits with Captain Wells. During this reconnaissance they also visited the shores of Melville Harbour, but they only found siliceous and ferruginous laterite of granitic origin.

In 1952, as a result of this reconnaissance, the Australian Aluminium Production Commission tested the Wessel Islands deposits extensively (Puckey & Richardson, 1952) but while this work was proceeding Captain Wells, in February 1952, collected a specimen of pisolitic bauxite containing 52.6 percent Al_2O_3 from near Gove airstrip. Owen visited the deposit in August 1952 (Owen, 1952) and all attention was subsequently directed to Gove instead of Wessel Islands.

In 1955 the New Guinea Resources Prospecting Co. investigated the deposits at Gove (Gardner, 1957). The Commonwealth Aluminium Corporation (COMALCO) carried out a detailed survey of the area in 1958 and was granted Special Mineral Lease No. 1, which was terminated about 1964 (Dunn, 1965).

In 1961 the Gove Bauxite Corporation Ltd began a survey of areas exclusive of S.M.L. No. 1 and in 1963 were granted S.M.L.'s 2, 3, and 4. These were subsequently transferred to Gove Mining and Industrial Corporation Ltd, but work on the leases has since lapsed.

In 1964 NABALCO was formed and was granted S.M.L. No. 1 in 1965 (Australian Mining, 1971). Preparations for mining commenced after a feasibility study during 1966-67. During our visit in 1971, construction of a township, treatment plant, conveyer belt, ship loading facilities etc. were well advanced and mining had just begun.

The deposit is situated on the Gove Peninsula at the northeastern tip of Arnhem Land, 660 km east of Darwin (Fig. 1). Access is essentially by sea and air, although a dirt road has been constructed across Arnhem Land from Katherine.

Australian Mining (1971) quotes reserves of about 250 million tonnes of bauxite. Dunn (1965) quotes approximate average grades of:

Al_2O_3	SiO_2	Ignition loss	Fe_2O_3	TiO_2
48.7%	3.6%	26.3%	17.0%	3.4%

Figures given by NABALCO (Hind, pers. comm.) are of a similar magnitude.

Previous investigations

Most work to date has been concerned with the economic testing of the deposits and the results, apart from Gardner (1957) and Dunn (1965), are confidential. The only detailed published study specifically concerned with the origin of the deposits is by Grubb (1970).

Early workers, such as Gardner (1957) and Dunn (1965), have considered the deposit to be the product of in situ lateritization. However, Grubb (1970) concluded that only these parts of the deposit preserved on topographically high areas are in situ; much of the deposit is of sedimentary origin, resulting from physical and chemical reworking of the in situ material. Grubb has carried out detailed mineralogical studies and presented his results as a series of typical profiles through both in situ and detrital material.

Regional setting

Arnhem Land is occupied by parts of the Proterozoic McArthur and Arafura Basins overlying Lower Proterozoic basement rocks. All these rocks are themselves overlain by thin subhorizontal marine and terrestrial sediments, the Lower Cretaceous Mullaman Beds.

At Gove, Mullaman Beds consist of claystone and arkosic sandstone and lie unconformably on a topographically uneven basement of gneiss and granulite, the Lower Proterzoic Bradshaw Granite. The bauxite is derived from the Mullaman Beds and perhaps locally (Gardner, 1957) from Bradshaw Granite. Fossils found in drill holes have confirmed the Lower Cretaceous age of the Mullaman Beds (Dodson, 1967).

Age of the deposit

Grubb (1970) mentions a possible Proterozoic age for the sediments at Gove, following Gardner (1957), in preference to the Lower Cretaceous age assigned by Dunnet (1965), and thus concludes that some bauxitization may have occurred during Mesozoic as well as Tertiary times. However, as previously described, fossils confirm that the sediments at Gove are Lower Cretaceous.

Hays (1967) has described a complex series of land surfaces and periods of lateritization in the Northern Territory formed throughout the late Mesozoic and Cainozoic. Although he lacked detailed personal knowledge of Gove he considered that his Tennant Creek and Wave Hill surfaces were present in northern Arnhem Land. The Tennant Creek Surface was the surface on which the main in situ laterite profiles formed

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in the Northern Territory; it is pre-Miocene in age and Hays suggests an early or mid-Tertiary age for its formation in the north. The younger Wave Hill Surface is superimposed on the older surface by erosion. It is characterized by truncated laterite profiles and detrital laterites, and is considered to be Miocene-Pliocene because marine sediments of this age overlie it on the Barkly Tableland and East Kimberleys. Lloyd (1968) prefers Miocene as the more probable age of the sediments. The younger Koolpinyah Surface is younger than the bauxite at Gove.

Correlation of land surfaces over wide areas is difficult, but the history of Gove suggests an overlap of the effects of both the Tennant Creek and Wave Hill Surfaces, indicating a probable mid to late Tertiary age for the formation of the Gove Bauxite deposit.

Field observations

The deposit is a fossil bauxite preserved as an erosional remnant on top of a dissected plateau near the extremity of Gove Peninsula. The plateau surface is undulating and varies from 10 to 100 m above sea level (Somm, 1971). In places the plateau directly abuts the coast in scarps up to 50 m high and most of the deposit is found at elevations of about 30-50 m above M.S.L. (after Grubb, 1970). The permanent water table now lies between 30 and 50 m below the surface, although a secondary water table situated well above this does persist well into the dry season (after Grubb, 1970).

Observations made during our visit and described in this report were unfortunately confined mainly to one quarry at the site of initial mining operations, about 2.4 km east of the airstrip and at an elevation of about 45 m above M.S.L. This locality lies about half-way between Grubb's Profile C, one of his residual in situ profiles, and Profile D, a reworked profile. In elevation the locality is nearest to that of Profile C and lithologically seems to fit Profile C best, although direct comparison is difficult because of the different lithological terminology used by Grub. Grubb does, however, note a probable erosional break near the top of Profile C.

In the quarry the ore was about 4.5 m thick and consisted of three layers; from the bottom up, tubular bauxite, cemented pisolitic bauxite, and loose pisolitic bauxite (Plates 1 and 2). The tubular bauxite is underlain by a clayey-ferruginous conglomerate, which in turn sits on white clay. The loose pisolitic bauxite is overlain by some 30 cm of grey-brown soil containing scattered pisolites.

The thickness of the various layers ranges widely (Plate 1b) and locally individual layers (e.g. the cemented pisolitic bauxite) may be absent. Contacts between the layers are extremely sharp (Plates 1b, g; 2c, d, e, f).

The base of the ore is a chemical cutoff based on silica content (Hind, pers. comm.; Gardner, 1957). Dunn (1965) defines the ore as having a silica content less than 5 percent. NABALCO generally include the tubular bauxite within the ore-grade material although sometimes it is of sub-ore grade (Australian Mining, 1971; Somm, 1971; Hind, pers. comm.). Generally there is little difference in grade between the three ore-types - tubular, cemented pisolitic, and loose pisolitic. The average volume of ore types if 30 percent tubular, 50 percent cemented pisolitic, and 20 percent loose pisolitic (Hind, pers. comm.). In comparison earlier workers (Gardner, 1957; Dunn, 1965) have considered the tubular material as generally being of sub-ore grade, with only the upper part locally of ore-grade, and describe a marked change in silica content at the top of the tubular layer. In Grubb's (1970) profiles, although the lithological units we have recognized are difficult to identify, it would appear that the tubular bauxite is generally of sub-ore grade except, possibly, in Profile C, where the upper tubular zone may be of ore grade. Throughout the deposit the total thickness of ore ranges from 0-10 m and averages 3-4 m (Somm, 1971).

The <u>white clay</u> underlying the bauxite was not observed in the quarry but some very poorly preserved drill cuttings from this area were examined. Very good exposures in cliffs on the eastern coastline could not be visited but on the slope of Mount Saunders the clay zone could be seen to be simply the result of leaching of original argillaceous sediments - a normal pallid zone of a laterite profile. Mottling is scarce, there is only some pink staining of the clay along joints towards the top of the section. The change into the overlying laterite is very sharp - the clay appears to belong to a truncated profile.

The <u>clayey-ferruginous conglomerate</u> (Plate 1c) was only seen as poor exposure on the quarry floor and no direct contact with the overlying tubular bauxite was visible, although the change appeared to be quite sudden. The mine staff refer to the material as 'porous laterite' and elsewhere it has been described as 'pseudo-conglomerate' (Gardner, 1957; Australian Mining, 1971). The conglomerate consists of an open framework of rounded fragments of red-brown to black ferruginous material in an orange-brown matrix. Open channelways or tubes are common in the matrix and the fragments are always covered by a thin yellow skin of clay (Plate 1c). When broken the fragments are seen to consist of small white oolites in a ferruginous matrix. The fragments have every appearance of normal pebbles in a conglomerate.

The tubular bauxite (or vermicular bauxite, Hays, 1967) consists of an open framework of interconnected deep red-brown 'tubules' or 'vermicules', with the spaces between filled by yellow to orange-brown pisolitic bauxite (Plate 1d, e, f). Scattered small open channelways are also visible. The tubules and intervening spaces tend to be oriented vertically but can be quite irregular, and the pisolitic bauxite sometimes spreads out horizontally into 'lens-like' masses. The red-brown material contains rounded ferruginous fragments, or pisolites, about 2 mm diameter, scattered through the fine-grained dense red-brown matrix. The pisolites filling the 'tubules' are distinctly different from those in the red-brown material and similar to those of the overlying cemented pisolitic bauxite. They appear to fill pre-existing cavities from above. The pisolites range from 1-6 mm in diameter, contain well developed concentric outer shells, and a variety of types of core. The tubular bauxite is hard and massive and requires blasting during mining.

The cemented pisolitic bauxite consists of closely packed red-brown, well formed pisolites 1-8 mm in diameter cemented together at their points of contact by gibbsite (Plates 1g, h; 2a). There is little or no matrix material and considerable void space between the pisolites. When broken the rock tends to break across or through the pisolites. The pisolites universally have a distinctive thin yellow hard outer shell, presumably of gibbsite. The cores range from soft porous material to hard dense black iron-rich material. Most cores are composed of fine oolitic material; the number of concentric shells developed around the pisolites is not constant. The cemented pisolitic bauxite also requires blasting during mining.

The loose pisolitic bauxite (Plate 2b) is a completely uncemented rock composed of pisolites of similar size and appearance to those in the cemented pisolitic bauxite, in a loose, friable, red-brown matrix of fine bauxite fragments and quartz. When dug with a hammer or shovel the pisolites immediately separate. Scattered throughout the material are peculiar hollow nodules, 1.5-3.0 cm in diameter, with an outer shell of fine amorphous bauxite and scattered matrix fragments (similar structures occur at Weipa-Plate 8g). The hollow cores may be either empty or filled with pisolites identical to those in the host-rock, and the outer shell may be either complete or have a hole at one end. Similar nodules also occur in the cemented pisolitic bauxite (Plate 2a).

Gardner (1957), Dunn (1965), and Somm (1971) describe an irregular layer of nodules commonly found above the tubular bauxite but this feature was not observed by us, nor is it mentioned by Grubb (1970).

PLATE 1

(a) Typical quarry face - Gove Bauxite Deposit

(b) Quarry face - Gove Bauxite Deposit. Tubular bauxite in lower 1/3 with sharp contact to overlying cemented pisolitic bauxite. Upper ½ loose pisolitic bauxite. Note irregular, undulating contacts.

(c) Clayey ferruginous conglomerate - Gove Bauxite Deposit. Polished surface. Reg. No. 71/10/0004. Larger fragments about 1 cm diameter. Large cloudy white patches are air bubbles in plastic mounting medium.

(d) Tubular bauxite - Gove Bauxite Deposit. Polished surface. Reg. No. 71/10/0003. Specimen width about 7 cm. Cloudy white patches are air bubbles in plastic mounting medium.

(e) Outcrop typical tubular bauxite - Gove Bauxite Deposit.

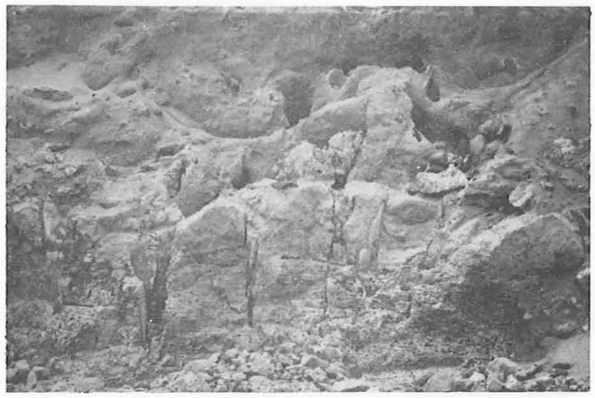
(f) Outcrop typical tubular bauxite - Gove Bauxite Deposit.

(g) Sharp contact between tubular bauxite below and cemented pisolitic bauxite above - Gove Bauxite Deposit.

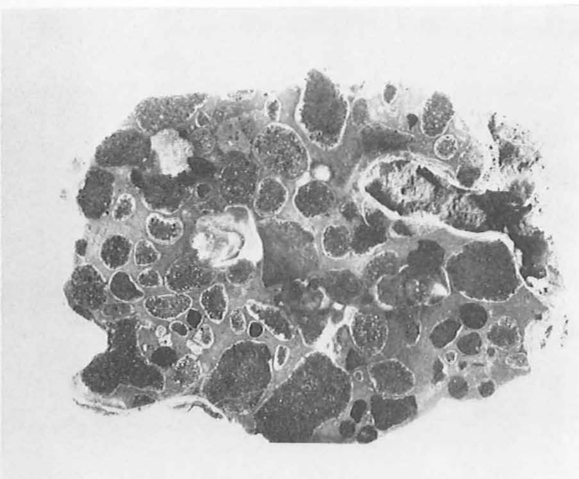
(h) Detrital fragment (top left of lens hood) in cemented pisolitic bauxite - Gove Bauxite Deposit.

PLATE 1

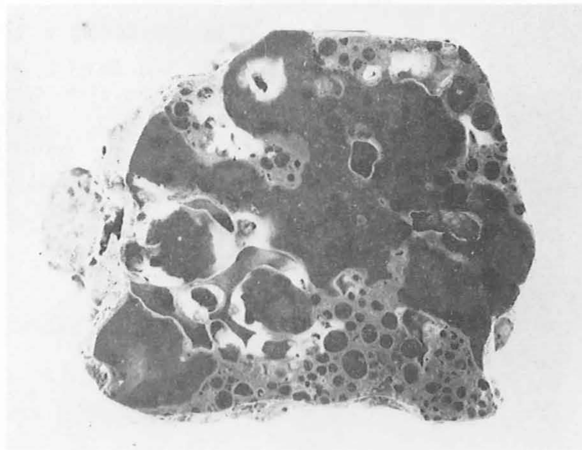
-a- (GA 5159)



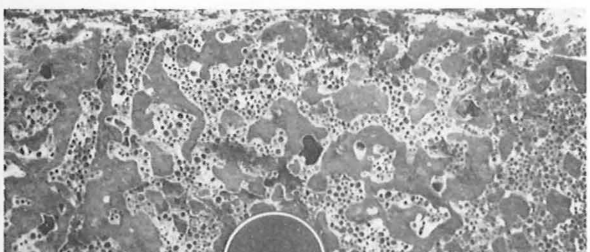
-b- (GA 5164)



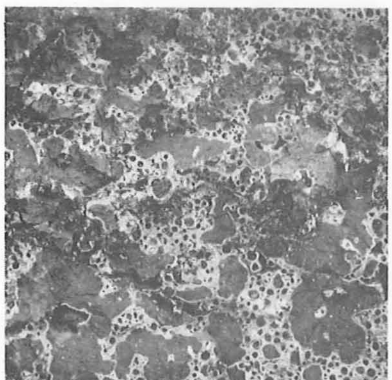
-c- (GA 5223)



-d- (GA 5222)



-e- (GA 5143)



-f- (GA 5140)

-g- (GA 5142)

-h- (GA 5150)

PLATE 2

(a) Pisolite filled nodule within cemented pisolitic bauxite - Gove Bauxite Deposit.

(b) Typical loose pisolitic bauxite - Gove Bauxite Deposit. Red-brown pisolites, 3-5 mm, and larger hollow nodules, in a sparse, friable earthy matrix.

(c) Sharp contact loose pisolitic bauxite overlying cemented pisolitic bauxite - Gove Bauxite Deposit. ?Channel-fill or old ?root solution shaft.

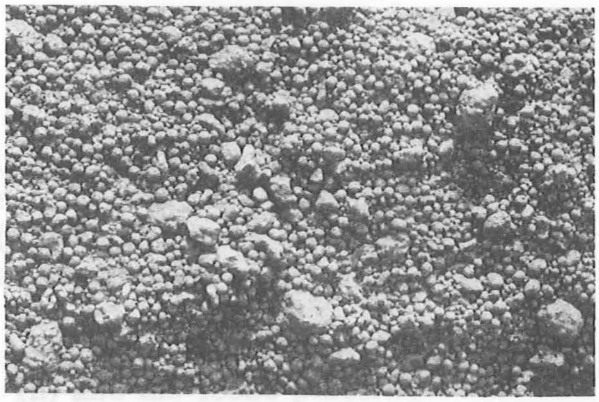
(d) Sharp contact loose pisolitic bauxite overlying cemented pisolitic bauxite - Gove Bauxite Deposit. ?Channel-fill. Larger gragments within loose pisolitic bauxite are of cemented pisolitic bauxite.

(e) Ancient root solution shaft in tubular bauxite filled with cemented pisolitic bauxite - Gove Bauxite Deposit. Recent shaft, containing tree root, to left.

(f) Ancient root solution shafts in tubular bauxite filled with loose pisolitic bauxite - Gove Bauxite Deposit.

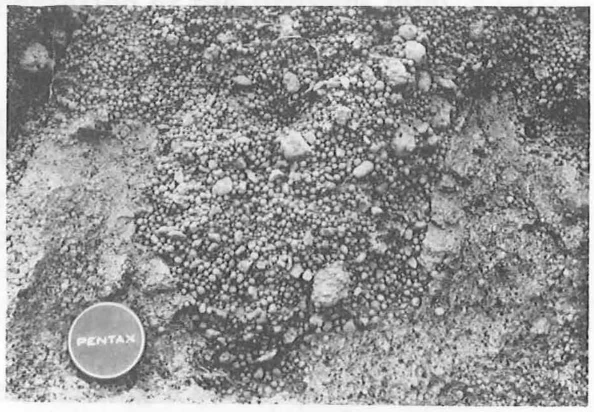
PLATE 2

-a- (GA 5156)



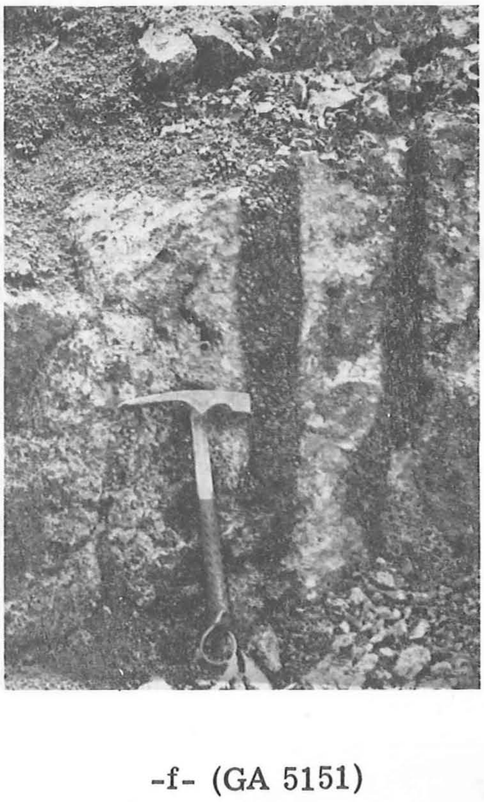
-b- (GA 5157)

-c- (GA 5145)



-d- (GA 5158)

-e- (GA 5149)



-f- (GA 5151)

Where well exposed the contacts between the tubular, cemented pisolitic, and loose pisolitic bauxites are very sharp but irregular, as one might expect with erosion surfaces (Plates 1b, g; 2c, d, f). Many hollows resemble channel-fills or similar structures.

The cemented pisolitic bauxite contains fragments of either tubular bauxite or broken nodules (Plate 1h) and the loose pisolitic bauxite contains fragments of tubular and cemented pisolitic bauxites.

The top of the loose pisolitic bauxite has a hard crust, up to 1 m thick, resulting from secondary cementation at the present land surface.

Throughout the deposit vertical hollow shafts up to 1 m across extend several metres downwards from the present surface and, in some cases, contain tree roots. They result from solution of bauxite by humic acids or similar agents related to the roots; identical examples are found at Weipa (Plate 6a). A thin hardened casing due to secondary cementation surrounds the shafts and they can take a number of forms:

(1) completely hollow shafts penetrating a number of layers, with or without associated tree roots, and extending down from the present surface.

(2) shafts penetrating cemented pisolitic and/or tubular bauxite and filled from above by loose pisolitic bauxite (Plate 2f).

(3) shafts penetrating tubular bauxite only and filled by cemented pisolitic bauxite (Plate 2e).

Published descriptions indicate a definite relation between topography and the distribution and thickness of ore. Isopachs of total ore thickness show that the ore is thin over high ground and thick in depressions (Somm, 1971). The upper layer of loose pisolites is removed by erosion from high ground (Australian Mining, 1971; Somm, 1971) and is thickest in depressions (Australian Mining, 1971).

Laboratory investigations

Grubb (1970) has carried out extensive mineralogical studies of the Gove ores. His results can be summarized as follows:

(1) The main ore mineral present is gibbsite (50-70%) with minor boehmite ($<$ 10%), locally showing an increase at the top of the profile.

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(2) Kaolinite is generally $<$ 10 percent within the ore, with an absolute maximum of 20 percent, and increases to 70 percent below the ore.

(3) Goethite plus hematite is fairly uniform at about 15 percent (locally up to 30%) and shows a zero to two-fold increase below the ore.

(4) Quartz is very minor and uniform throughout the reworked profiles but is confined to the upper part of the in situ profiles.

Our studies have been oriented mainly towards interpretation of the fine textures of the rocks, including a semi-quantitative analysis of chemical variations within these textures.

The first and most obvious conclusion to be derived from the electron microprobe studies is that the major oxides, iron and aluminium are, as one would expect, exactly complementary to each other; alumina peaks always correspond with iron troughs and vice versa (Fig. 3c). This observation applies to all rocks from all areas. Silica and titanium, which are present in quite small amounts, are much more random.

Secondly, within one area, such as Gove, the colour of material in thin or polished section is a rough guide to relative Al/Fe contents, but not Si or Ti. Thus dark brown material is richer in iron than red-brown or orange-brown material, which is alumina-rich, while very high alumina tends towards yellow. These colours cannot be correlated between different deposits however - the colour variations at Gove reflect very much greater compositional variations than they do at Weipa.

The fragments in the clayey-ferruginous conglomerate (Plate 1c) have a variety of compositions but the yellow clay-rich skin is universal. The most common fragments are dark red-brown in colour and composed of white clay-rich oolites, 0.1-0.5 mm diameter, in a dark red-brown, slightly more ferruginous matrix (Plate 3g, h). Some fragments have a micro-brecciated internal texture (Plate 3i). The oolitic material has a characteristic widely fluctuating composition profile on the microprobe. The matrix of the rock is a distinctive orange-brown colour and very massive with some faint oolites; compositionally it is moderately rich in alumina and clay-poor. Other fragments in the rock have widely differing compositions (Plate 3k, l), some being almost pure hematite while others, with a distinct orange colour, are alumina-rich and poor in iron and silica. The yellow clay-rich skins are distinct on both the microprobe and the electron scanning microscope (Plate 3).

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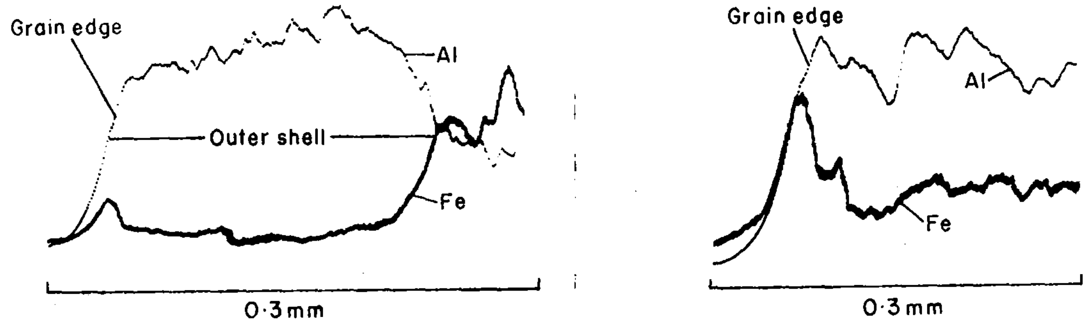
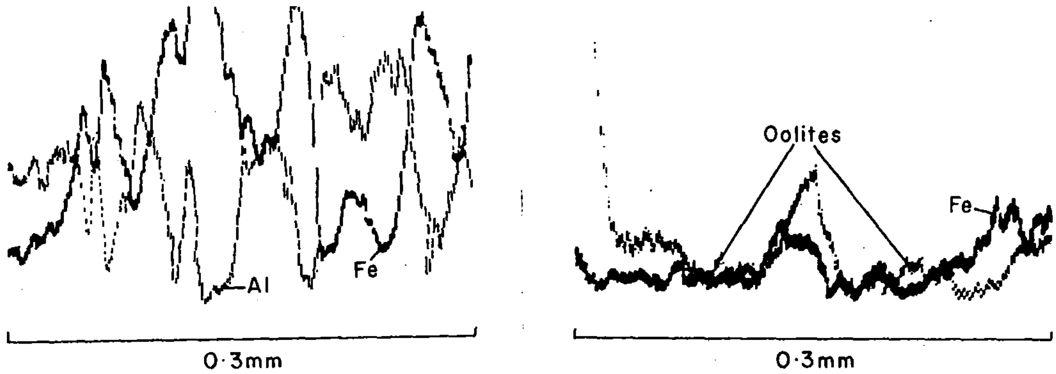


(a) (b)

(a), (b) - Loose pisolitic bauxite - Gove. Outer gibbsite shells of pisolites. Note thin outer Fe skin, Al rich outer shell. Fe scale in (b) more magnified than (a).



(c) (d)

(c), (d) - Loose pisolitic bauxite - Weipa.

(c) - Highly altered pisolite core. Note complementary relationship between Fe and Al.

(d) - Oolitic core of pisolite. Note silica deficient oolites compared to matrix between.

Figure 3. Examples of electron microprobe oscilloscope images of parts of bauxite pisolites. Vertical scale registers counts/sec. at various convenient magnifications. Variations are semi-quantitative and not converted to absolute element concentrations.

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PLATE 3

Scanning electron photomicrographs - tubular bauxite. Reg. No. 71/10/0003 (a) to (f); clayey ferruginous conglomerate Reg. No. 71/10/0004 (g) to (l) - Gove Bauxite Deposit.

(a), (b) oolitic iron-rich cores and aluminous outer shell and veinlets, of pisolites within red-brown matrix.

(c) pisolite within yellow matrix. Massive iron-rich fragmentary core, salmon aluminous shell, then slightly more aluminous yellow matrix.

(d) pisolite within yellow matrix. Rounded, complex core surrounded by salmon, grading to yellow, aluminous shell.

(e) contact zone yellow (left) and red-brown (right) matrix. Yellow massive and more aluminous. Red-brown oolitic texture; veinlet of yellow. Locally gradational contact.

(f) contact zone yellow (top) and red-brown (bottom) material. Red-brown has slightly more ferruginous oolitic 'pisolites' (left) enclosed in oolitic matrix (right).

(g), (h) oolitic texture in pebbles. Oolites clay-rich in ferruginous groundmass. Clay shell visible around pebble (g).

(i) microbreccia fabric in pebble.

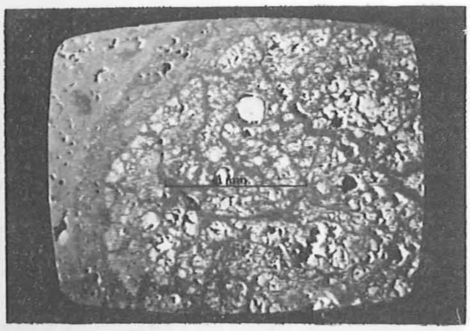
(j) small yellow clay rich pebble in iron-alumina matrix.

(k) hematite pebble (bottom) and alumina rich pebble (top) in iron-alumina matrix. Narrow clay shells around pebbles.

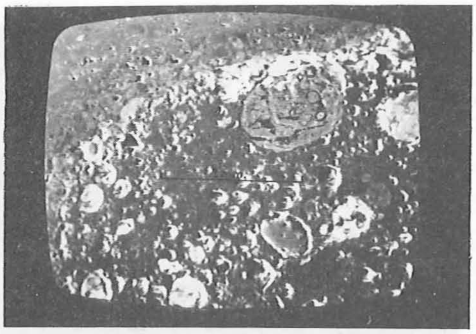
(l) oolitic hematite pebble (lower left) and clayey oolitic pebbles in locally iron-rich matrix. Narrow clay shells around pebbles.

<u>NOTE</u>: The scale has been inadvertently omitted from some photomicrographs on plates 4 and 5; all are at the same scale.

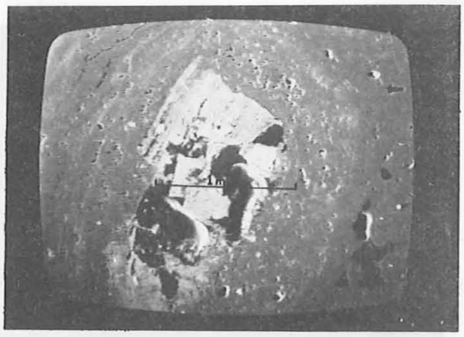
PLATE 3



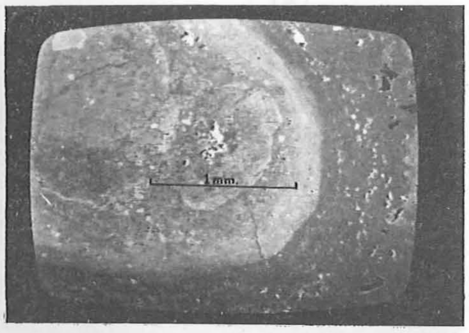
(a)



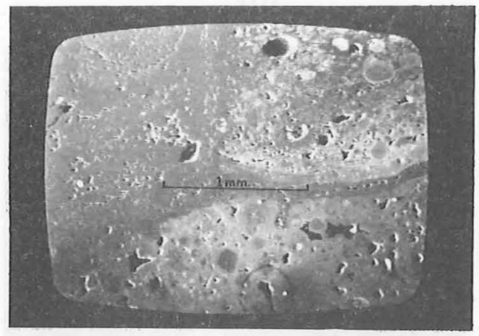
(b)



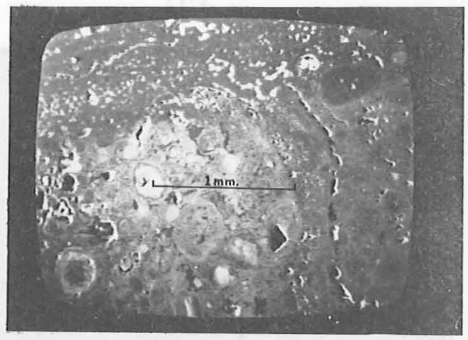
(c)



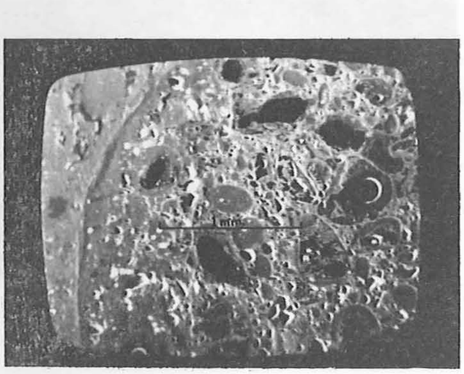
(d)



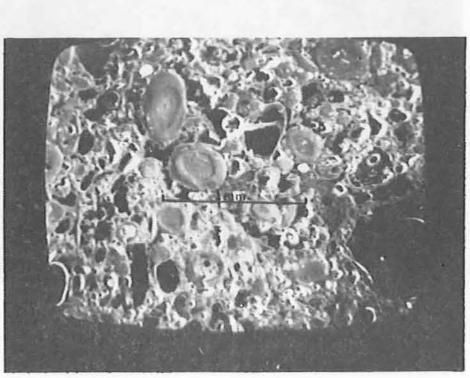
(e)



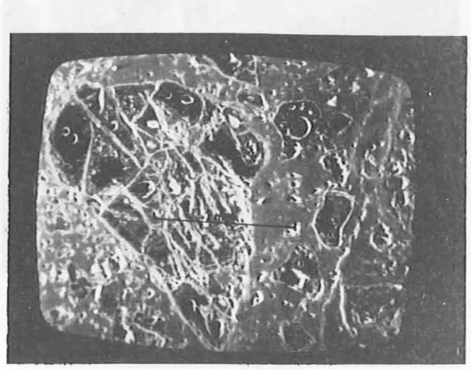
(f)



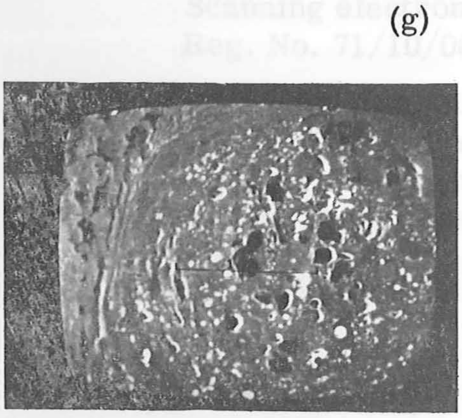
(g)



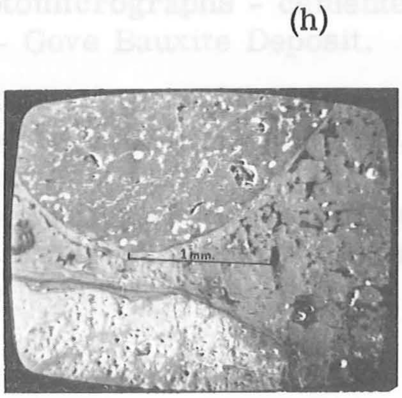
(h)



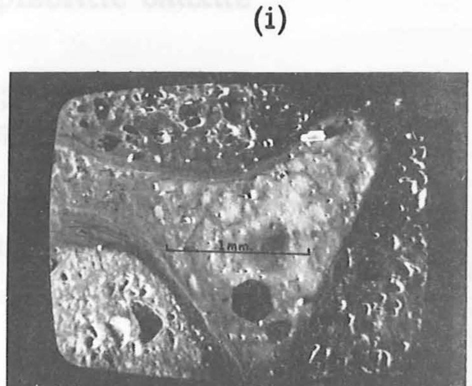
(i)



(j)

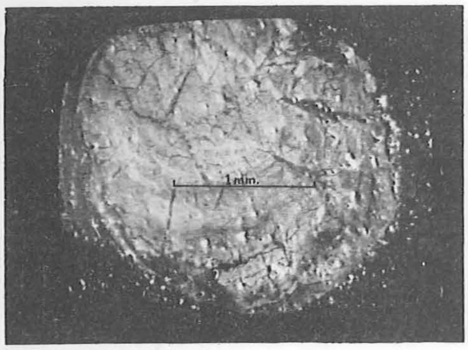


(k)

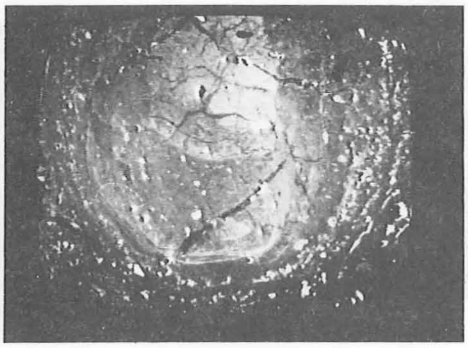


(l)

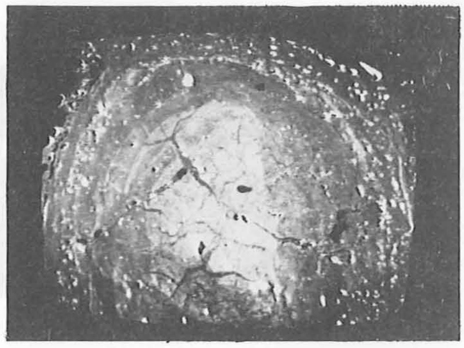
PLATE 4



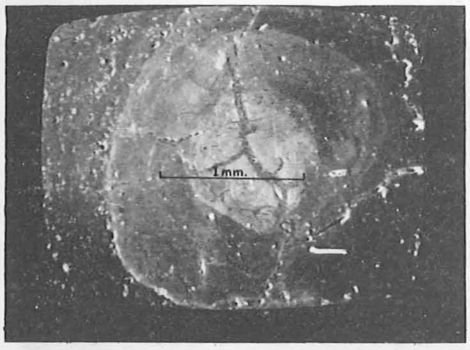
(a)



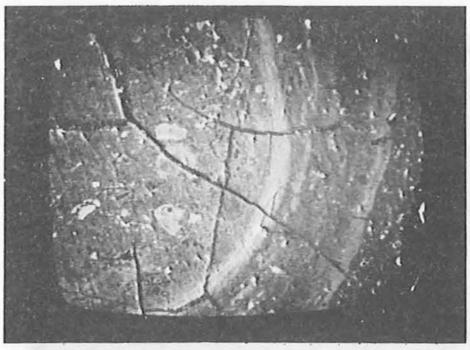
(b)



(c)

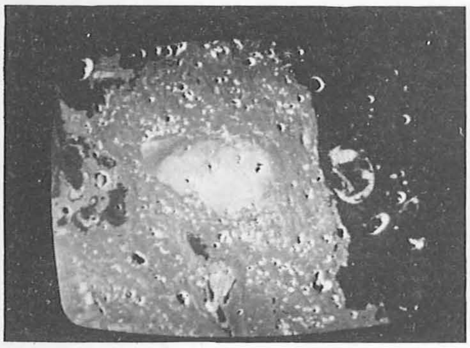


(d)

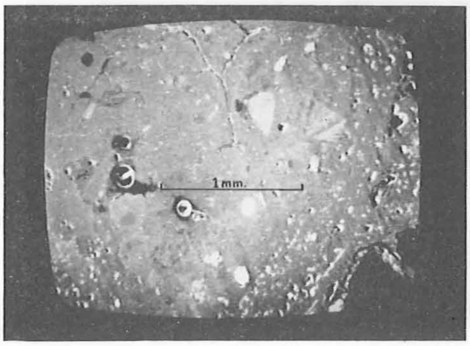


(e)

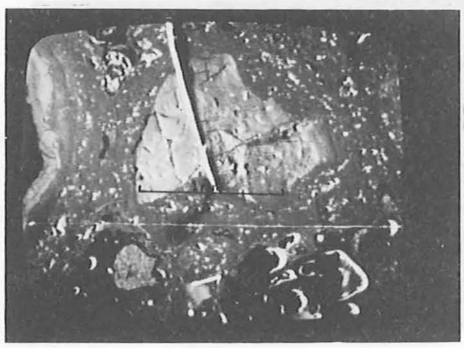
(f)



(g)



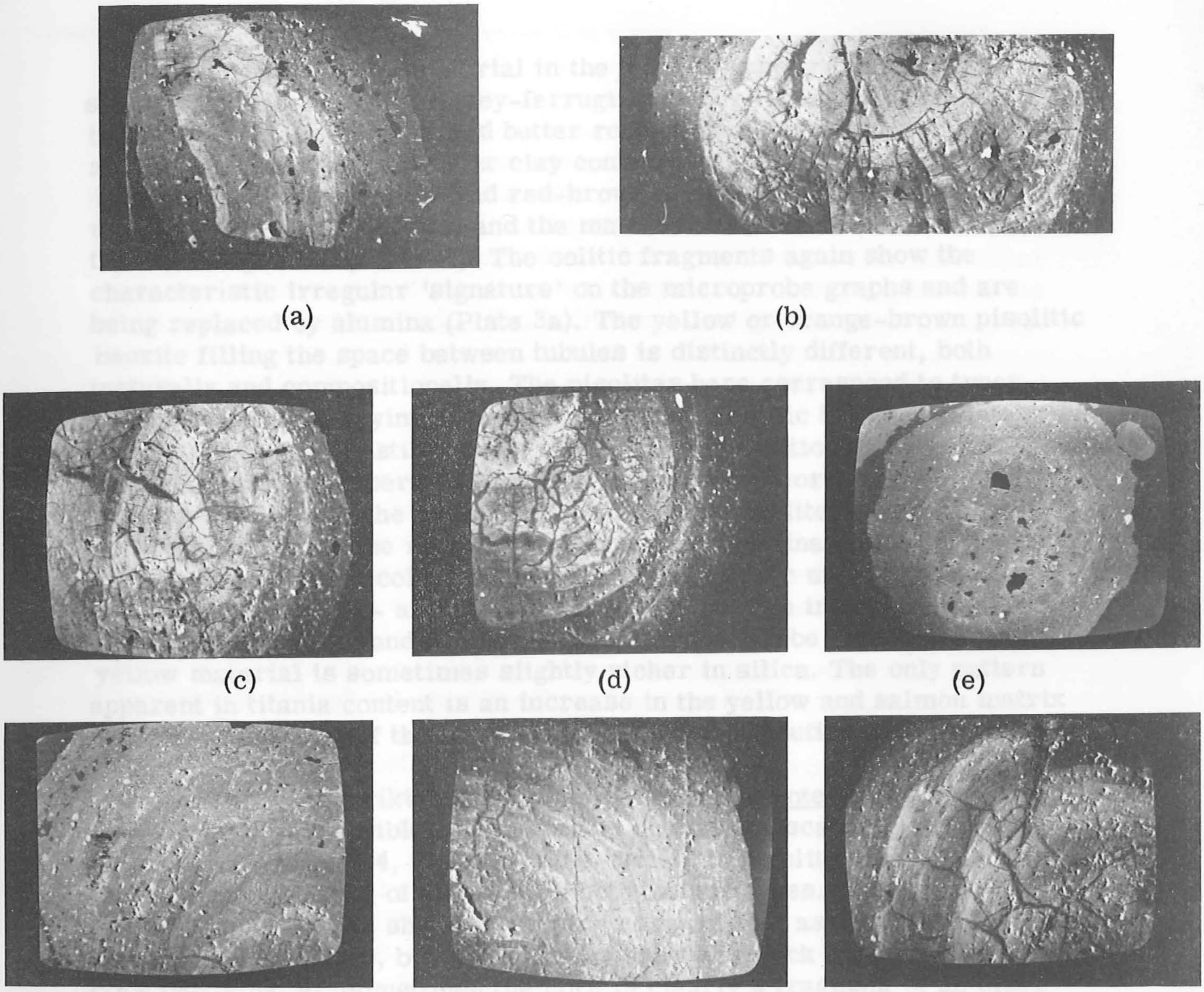
(h)



(i)

Scanning electron photomicrographs - cemented pisolitic bauxite Reg. No. 71/10/0002 - Gove Bauxite Deposit.

Note compound pisolite structures (a), (b) and (c); simple structure (d); oolitic core (e); portions of three pisolites, in cement, with markedly different compositions (f).
(g), (h) and (j) are small fragments within cement. Note general similarities with pisolites of Plate 5 and similarity of cement to outer shells of pisolites of Plate 5.



Scanning electron photomicrographs - loose pisolitic bauxite pisolites Reg. No. 71/10/0001 - Gove Bauxite Deposit.

Note similarity of outer shell of all specimens. Simple fragment of older pisolite in core of (a). Fragmentary cores, complex shells, and fractured, veined cores - (b), (c), (d). Oolitic texture in core of (e). Simple concentric shells of uniform composition - (f), (g). Alternating aluminous and ferruginous shells (h).

The red-brown material in the tubular bauxite (Plate 1d) is similar to the underlying clayey-ferruginous conglomerate except that the fragments are smaller and better rounded and the microprobe shows a marked decrease in silica or clay content, with corresponding increase in alumina. The fragments and red-brown matrix both show oolitic microtexture (Plate 3a, b, f) and the matrix is overall more aluminous than the fragments (Plate 3f). The oolitic fragments again show the characteristic irregular 'signature' on the microprobe graphs and are being replaced by alumina (Plate 3a). The yellow or orange-brown pisolitic bauxite filling the space between tubules is distinctly different, both texturally and compositionally. The pisolites here correspond to types observed in the overlying cemented and loose pisolitic bauxites (Plate 3c, d). They have a distinct core, of various compositions and textures, surrounded by a number of concentric shells. Many cores are distinct angular fragments. The outermost shells of the pisolites are invariably bright yellow while the rest of the matrix has very fine colloform banding of yellow and salmon coloured material. These latter materials have similar composition - alumina-rich and very poor in iron relative to the red-brown tubules - and relatively smooth microprobe signatures; the yellow material is sometimes slightly richer in silica. The only pattern apparent in titania content is an increase in the yellow and salmon matrix relative to the rest of the rock; otherwise its distribution is quite irregular.

The most striking features of both the cemented pisolitic and loose pisolitic bauxites, visible under both the optical and scanning electron microscopes (Plates 4, 5) are: (1) the variety of pisolite types present and (2) the similarity of pisolites in both bauxite types. Most show a number of concentric shells of varying composition, as in classic pisolites (e.g. Plates 4e; 5f, h), but some simply show one thick shell around a central core (Plate 5a, e). Sometimes the core is clearly a fragment of an older pisolite (Plate 5a), others are rounded fragments of oolitic bauxite (Plate 4e, 5e); the majority are of the latter type or fine ferruginous fragments of indeterminate source (Plates 4a, b, c, d; 5b, c, d, h). The cores are mostly more ferruginous than the outer shells but they can be alumina rich. While many pisolites show a simple regular growth of concentric shells others have complex histories of growth of layers, breaking of grains, erosion, more growth, and so on (Plates 4a, b, c; 5b, c, d). The cores and inner shells are commonly fractured and the cracks filled with alumina rich material. The cement of the cemented pisolitic bauxite is yellow or white, with scattered small angular ferruginous fragments (Plate 4g, h, j) and has a uniform composition - rich in alumina and poor in iron; probably gibbsite - similar to the salmon and yellow matrix of the tubular bauxite infilling. The outermost shell of the pisolites in the loose pisolitic bauxite is similar in appearance and composition to the cement of the cemented pisolitic bauxite, except for a very slight addition of silica, and the presence of a thin brown outer skin, only a few microns thick, which shows a marked iron and silica peak on the microprobe (Fig. 3a, b). This feature is apparently a micro-weathering effect due to exposure of the pisolites to the loose porous matrix, a sort of micro-unconformity, and similar iron skins can be recognized on some of the inner shells. Apart from these outer shells silica is very low throughout the pisolites. Titania shows no regular pattern. Peaks can be related to visible grains of anatase or rutile but otherwise the titania content is either low and uniform right across the pisolite, or it peaks in sympathy with iron in the cores, apparently substituting for iron in the molecular lattice.

Interpretation

There seems little doubt that the bauxite we observed is detrital. The different layers are beds deposited in different sedimentary environments. The features such as the truncated pallid zone, the irregular, sharp erosion contacts between layers, the macro-texture of the clayey-ferruginous conglomerate, and the detrital fragments of lower layers in upper layers, all indicate erosion and deposition.

The recent root solution shafts (Plate 6a) are clearly related to the land surface so the truncated shafts (Plates 1b, 2e, 2f), filled by overlying material, show that the tubular bauxite was exposed at the surface before being covered by cemented pisolitic bauxite (plate 2e), and the cemented pisolitic bauxite was in turn exposed before being covered by loose pisolitic bauxite (Plate 2f).

The textures of the pisolites under the microscope are consistent with a sedimentary origin and correspond well with the terrigenous and authigenic pisolites or oolites of Belyaev (1970). Angular fragmentary cores dervied from older pisolites, complex histories of fracturing and shell growth exhibited by individual pisolites, shrinkage cracks filled by the material of later shells, and so on, are all consistent with a sedimentary origin. The variety in the types of core, in both composition and texture, indicate derivation from a variety of sources. The marked difference between the compositions of the pisolite cores and outer shells or cements are the result of precipitation in different physicochemical environments. These internal structures must be used with care; Jones (1965) has pointed out that, although they are classically considered to indicate a sedimentary origin they can develop by movement within a soil profile, and Mac Geehan (1972) explains shrinkage cracks, distinct outer shells, and so on, by different episodes of bauxitization at Aurukun, near Weipa.

Many of these internal textures are typical of the colluvial (Type 2) and stratified deposits (Type 3) at Arkansas (Gordon et al., 1958) although similar features are also found in their 'birds-eye' ore at the very top of the residual deposits (Type 1). The boundaries between their Type 1 and overlying Type 2 deposits are commonly gradational and difficult to define so it is possible that the 'birds-eye' ore could include a considerable reworked component. The bauxite types most like those at Gove are closely packed, loosely cemented pisolites from Type 2 (Fig. 17, Gordon et al., 1958) and Type 3 (Fig. 24c, Gordon et al., 1958) deposits; these are identical with the cemented pisolitic bauxite at Gove. Vermicular bauxite (Fig. 15, Gordon et al., 1958), similar to the tubular bauxite at Gove, is found at the top of the 'birds-eye' ore.

The topography of the Gove area, with elevation differences of up to 100 m across the deposit, is consistent with the concept of erosion of bauxite from high areas and its redeposition on low areas. The ore is now thickest in depressions while the upper layers have been eroded from high ground (Australian Mining, 1971; Somm, 1971). This contrasts with what would be expected from a purely residual deposit where the thickest and richest bauxite should be developed on high ground where drainage and leaching is greatest. The problem then becomes whether any in situ residual bauxite is still preserved at Gove, as postulated by Grubb (1970), or whether it is now all reworked. Since we have not seen Grubb's residuals profiles we cannot be conclusive, but the apparent similarity between the section we observed and, at least Grubb's Profile C suggests that the residual bauxite may be more restricted in extent than indicated by Grubb. Grubb (pers. comm.) has indicated that he recognizes the profile types mainly on field criteria such as unconformities and a relatively 'polymict' association of pisolite sizes in the detrital profiles. Unconformities or erosional discontinuities are obviously convincing evidence for detrital bauxite, but their apparent absence does not prove the bauxite is in situ. They could be easily overlooked in poor or limited outcrops available to Grubb, since mining had not commenced during his work.

Descriptions by NABALCO geologists (Australian Mining, 1971; Somm, 1971) imply that the same types of bauxite are found throughout the deposit, except where the upper layers have been removed by erosion, although Somm (pers. comm.) has mentioned unusually thick sections, found mainly in depressions and therefore probably detrital, composed entirely of loose pisolitic bauxite. The lithological profiles described by Grubb (1970) do not indicate any marked differences between the residual and reworked bauxites we observed, although from his descriptions, there is more cementation of the ore nearer the coast. It seems strange that bauxites of such different origins, residual and detrital, should look so superficially similar unless all the main textural features of the pisolites etc. had been formed in the residual bauxites and then not substantially modified by the very limited later mechanical reworking; this will be found to be inconsistent with our later environmental interpretations.

Vertical mineralogical variations in Grubb's residual profile A show some significant differences from the detrital profiles, and are essentially identical with those at Weipa (Grubb, 1971a) and, even more noticeably, to those of Aurukun (MacGeehan, 1972); Grubb's (1970) Profile C is intermediate between the extremes. The residual profiles show marked increases in quartz and boehmite at the top and uniform heavy minerals, particularly anatase, throughout. Reworked profiles show only slight increase in boehmite at the top, no quartz enrichment, wide variations in heavy minerals across unconformities, and more iron. Quartz and boehmite have been attributed to leaching in a non-saturated environment (MacGeehan, 1972) while a genetic relationship between unconformities and heavy minerals is to be expected. It does not follow however that an absence of heavy mineral variations means that unconformities are absent.

Summarizing, it is not possible to comment conclusively on the presence of residual profiles, without direct personal observation, beyond saying that Grubb's (1970) hypothesis is consistent with the topographic distribution of his profile types. Detailed study by Grubb has revealed differences between the two types of profiles but it is surprising that more major lithological differences are not readily apparent. It does seem probable that the residual profiles, if present at all, are less extensive than postulated by Grubb (1970).

Possible depositional environments of detrital bauxites

Clayey-ferruginous-conglomerate. The fabric of this rock is clearly that of a sediment. The irregular shapes and moderate rounding of fragments of relatively soft material suggest a very short distance of transport; it was probably largely a colluvial deposit near the base of a slope. Consistent with the sedimentary origin is the variety of compositions of the fragments, indicating different sources. The abundance of very fine matrix suggests transport of the fragments within a thick colloidal slurry. Under conditions of total water saturation clay skins developed around the fragments. With subsequent draining and evaporation of water from the sediment mass any remaining silica in solution was preferentially carried away and alumina precipitated to leave the present matrix. The oolitic internal fabric of the fragments, which are probably pieces of in situ lateritized or bauxitized bedrock, is significant. A corollary is that the first product of in situ weathering is a fine-grained oolitic clay-rich laterite or bauxite. There are no fragments of pisolitic rock.

Tubular bauxite. Dr Tenyakov (pers. comm.) has observed recent tubular bauxite in Guinea. It forms around the edges of swamps and lakes in the zone of reed growth, close to a source area of residual bauxite. Both mechanical and chemical transport of aluminous material occurs as evidenced by the proportion of fine-grained fragments and gel-like cement. Tubular bauxite is always red because of the well aerated oxidizing environment. As the lake shore becomes exposed the roots of swamp plants decompose leaving hollow tubes and the detrital fragments become cemented together by chemically precipitated bauxite (as proposed for the clayey-ferruginous-conglomerate). Plants may produce humic acid and so aid the precipitation of bauxite.

McFarlane (1971) notes the occurrence of vermiform laterite in areas of stable oscillating water table adjacent to swamps. The veriform laterite is considered to be a mature form developed by alteration of pisolitic laterite. She does not believe that the tubes are formed by plant penetration.

From our observations the reddish material of the tubular bauxite is similar to the clayey-ferruginous-conglomerate; only the fragment size is smaller. It could form the upper zone of the clayey-ferruginous-conglomerate, altered in the manner described by McFarlane (1971) (we could not observe the contact clearly). Our interpretation of the depositional environment of the conglomerate is similar to Dr Tenyakov's description of tubular bauxite. We cannot decide conclusively between the alternative origins of the tubes, but favour the root hypothesis because the process can be seen in younger bauxites. The tubes are much larger and more continuous than those figured by McFarlane and grade morphologically into those being formed by roots today. They clearly formed rather quickly on the surface of the conglomerate before being covered by the cemented pisolitic bauxite layer, the latter material having then partly infiltrated and filled up the tubules.

Cemented pisolitic bauxite. Dr Tenyakov (pers. comm.) considers that in general cemented pisolitic bauxite forms on gentle hill slopes, downslope from outcropping residual bauxite or laterite. Mechanical and chemical erosion produces thick slurries of mechanically transported fragments suspended in aluminous colloids which slowly move down slope over a period of many years during intense tropical downpours. The fragmental material is of diverse origins - pieces of bedrock, residual bauxite fragments, clay flakes, quartz grains, fragmented pisolites etc.; the proportions of the various types of material would depend on such factors as type of bedrock, angle of slope, intensity of erosion etc. Alumina-rich colloidal suspensions percolate through the deposit and precipitate concentric shells around the nucleii to form pisolites. The spaces between pisolites are then filled with further aluminous material to form a cemented pisolitic bauxite. This process is also essentially that of the colluvial (Type 2) deposits at Arkansas (Gordon et al., 1958).

The observed features of this ore are consistent with this process - the multiple source of nuclear fragments, complex histories of pisolite growth, variations in pisolite compositions reflecting variable physicochemical states of percolating solutions, and so on. The open framework of cemented pisolites is consistent with rapidly percolating solutions throughout periodically saturated and dessicated colluvium; deposition from colloidal suspension at the base of lake or lagoon would be expected to give rise to a solid, massive rock.

Loose pisolitic bauxite. Dr Tenyakov (pers. comm.) interprets the loose pisolitic bauxite as a mechanically eroded and transported deposit derived directly from reworking of the cemented pisolitic bauxite. Once again the features observed are consistent with this hypothesis. The obvious similarity of the pisolites in the two ores suggests that one is derived from the other; however, one cannot ignore the possibility that some of the pisolites were a product of erosion of residual pisolitic bauxite. The closely packed pisolites and absence of interstitial matrix conforms with normal mechanical transport and sorting. The absence of any cement precludes aluminous gels as a transporting medium. The very thin outer silica and iron rich pisolite skin, deposited about the outer yellow gibbsite shell remaining from the cemented pisolites, could easily be deposited from transporting water with fairly normal groundwater composition. The increased thickness of loose pisolitic bauxite in topographic depressions accords well with the proposed origin.

MARCHINBAR ISLAND, WESSEL ISLANDS

The deposits on Marchinbar Island are described by Owen (1954) and their regional geological setting by Plumb (1965).

Their discovery by Captain Wells and Seaman Waalkes, and subsequent testing by the Australian Aluminium Production Commission in 1952, has been described in this report. Testing defined seven economic deposits. Owen (1954) gives the following figures: proved ore totals 8 980 000 tonnes containing between 48.0 and 53.3 percent of Al_2O_3;

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available alumina ranges between 43.5 and 47.8 percent and total silica is between 4.1 and 8.8 percent. In addition there is a further 800 000 tonnes of indicated ore containing 47.7 percent Al_2O_3, 42.8 percent available Al_2O_3 and 6.8 percent of SiO_2. The average depth of bauxite in the various deposits ranges between 1.35 m and 2.4 m; the maximum thickness of pisolitic bauxite is 4.95 m. The main bauxite mineral is gibbsite.

During regional mapping of Arnhem Land in 1962, the deposits were visited briefly, but not by the author (K.A.P.), and their regional geological setting was determined. During the visit to Gove in 1971 an aerial reconnaissance was made of Marchinbar Island.

The bedrock of the Wessel Islands is sedimentary rock of the Adelaidean Wessel Group. Marchinbar Island consists of a strike ridge of quartz sandstone, the Marchinbar Sandstone, dipping uniformly to the northwest at about 3°, and underlain in cliffs at the eastern side of the island by shales and minor sandstones of the Raiwalla Shale.

On Elcho, Drysdale, and other islands to the southwest, the Marchinbar Sandstone is conformably overlain by further shale and sandstone of the Elcho Island Formation.

Owen (1954) considered that the bauxite was derived from sericite-quartz siltstone interbeds in the Precambrian sequence. The 1962 mapping showed that the bauxite always overlay Marchinbar Sandstone, never Raiwalla Shale directly. This was considered unusual as the Marchinbar Sandstone does not have significant shale or siltstone interbeds, so it was inferred that the source rock was the overlying Elcho Island Formation. Laterite profiles developed on Elcho Island Formation farther to the southwest are described by Plumb (1965). Owen (1954) illustrates a cliff section from the east coast of Marchinbar Island which, as interpreted by the 1962 mapping, shows 6 m of Marchinbar Sandstone between the overlying laterite and the underlying Raiwalla Shale. The Marchinbar Sandstone is normally 240 m thick. Our 1971 aerial reconnaissance confirmed a full thickness of Marchinbar Sandstone dipping uniformly across the island at about 3° and confirmed the stratigraphic interpretation of the east coast cliff sections. The bauxite is clearly subhorizontal (as Owen described) and rests unconformably on various beds of the Marchinbar Sandstone, right across the island. It cannot be derived from Elcho Island Formation in situ.

Owen (1954) describes the bauxite as pisolitic, and commonly overlying a tubular bauxite, which in places is ore grade. The tubular bauxite is confined to the eastern side of the island, lenses out westwards, and the westerly deposits are all pisolitic. He illustrates specimens which are identical to the tubular and cemented pisolitic bauxites we observed at Gove.

Therefore it is logical to interpret the bauxite as being detrital, providing a ready explanation for its unconformable attitude on top of an unsuitable source rock-type. The lensing-out of the tubular bauxite may indicate an easterly source direction. The source rock could be Raiwalla Shale, which may have cropped out to the east before erosion and submergence by the sea. A more likely source is Lower Cretaceous sediments to the east, since removed by erosion. On the mainland, lateritized Lower Cretaceous sediments overlie almost all of the Raiwalla Shale outcrop because of its susceptibility to pre-Mesozoic erosion. Almost all laterites in North Australia have formed on Cretaceous rocks and they have provided the source for bauxites at Gove, Weipa, and Cobourg Peninsula.

Laterite and bauxite sections containing pisolitic layers overlying with sharp contacts tubular layers, described by Plumb (1965), on Elcho and Nyagamiringora Islands, and studied by the author (K.A.P.), can now be reliably interpreted as detrital. On Elcho Island, loose pisolitic bauxite overlies tubular bauxite which sits directly on unaltered Marchinbar Sandstone. On Nyugamiringora Island the laterite is ferruginous and the tubular zone lies, with sharp contact on a truncated mottled and pallid zone developed in Elcho Island Formation. On the western side of Elcho Island a complete ferruginous in situ profile is preserved on Elcho Island Formation.

MITCHELL PLATEAU

Development

Although some interest had been shown in the Kimberleys for many years by companies such as Reynolds Metals and BHP Ltd, it was not until May 1965 that Mr Ken Malcolm of AMAX discovered pisolitic bauxite, subsequently shown to be uneconomic, on the Couchman Range in the northern part of the Ashton 1:250 000 Sheet area; a few weeks later, as exploration expanded, he discovered the deposits on the Mitchell Plateau. It is interesting that in early 1965, W.J. Perry of BMR following photo-interpretation of the Montague Sound Sheet area, recognized the thick laterite profile and, in an unpublished report to the party, recommended that the BMR's Kimberley Plateau field party specifically examine the Mitchell Plateau area for bauxite during the 1965 field season. Ken Malcolm had independently recognized the potential of the area from aerial photographs and was prompted into action by the knowledge of the pending BMR field program. He took out an authority to prospect and arrived in the area two weeks before the BMR party, and immediately discovered the Couchman Range deposit.

AMAX mounted an extensive program of testing and feasibility studies extending over several years. The deposits appeared to be economically exploitable and negotiations proceeded for some time to arrange a suitable consortium to mine the deposit. Mining was recently suspended for an extended period.

Australian Mining, in 1969, quoted inferred reserves of greater than 350 million tonnes of ore which would be reduced through beneficiation processes to more than 230 million tonnes. During our visit Jackson (pers. comm.) quoted proven reserves of 118 million tonnes of beneficiated bauxite and considerably more indicated reserves.*

Average grades were:

Total Al_2O_3	Available Al_2O_3	Total SiO_2
51.8%	46.8%	2.8%

Average thickness of ore was quoted as 12 feet (3.6 m); maximum thickness of 30 feet (9 m); economic cutoff 8 feet (2.4 m) thickness and 30 percent available Al_2O_3.

Previous investigations

The results of the extensive testing of the deposits are confidential to the company. Sofoulis (1966) produced a brief description of the deposits, based on surface investigations in 1965, immediately after the deposits were discovered. Grubb (1970) carried out detailed mineralogical studies of the deposits and concluded that physical reworking of the bauxite was extensive.

*At the 1973 Aus.I.M.M. Conference in Perth, G.F. Joklik, W.D. Jackson, and J.A. Zani described in detail the Kimberley bauxites. In addition to Mitchell Plateau they gave further indicated reserves of 980 million tonnes averaging 36 percent total alumina from Cape Bougainville, to the east of Mitchell Plateau. We understand that the Aus.I.M.M. propose to publish this paper in the new 'Geology of Australian Ore Deposits' volume.

Regional setting

The Mitchell Plateau is a dissected plateau on the southern shore of Admiralty Gulf, on the northwestern coast of the Kimberley Region, north Western Australia. The plateau has an elevation of about 300 m, and is bounded in the northeast by steep scarps dropping straight down to sea level.

The bedrock is flat-lying Proterozoic basalt of the Carson Volcanics, part of the Kimberley Group of the Kimberley Basin. The basalt is preserved in the core of a broad syncline, the Admiralty Gulf Syncline, with the bauxite lying almost along the axis of the syncline. The basalt has been eroded from the flanks of the syncline to expose the underlying massive, jointed King Leopold Sandstone forming the bedrock of the steeply dissected Prince Regent Plateau.

Age of the deposit

The only positive control to the age of the Mitchell Plateau bauxite is that it overlies basalt of Carpentarian age (ca. 1800 m.y.). One is tempted to relate the bauxite to the period of lateritization prevalent across Australia during the Tertiary, although palaeogeographic reconstructions of the Bonaparte Gulf Basin indicate the Kimberley Plateau has been land throughout the Phanerozoic. Erosional remnants of laterite and bauxite can be traced, at a similar elevation and topographic position to the Mitchell Plateau, right across the Kimberleys to the Tertiary laterites of the Sturt Plateau east of Halls Creek, a part of Hays' (1967) Tennant Creek Surface, and it is attractive to relate them all to a similar period of evolution. The laterites are also extensively reworked (Hays' Wave Hill Surface of post-Miocene age).

The Kimberley Region has undergone late or post-Tertiary uplift - marine Miocene is at an elevation of 250 m in the East Kimberley (Lloyd, 1968). The bauxite is a reasonably hard rock, particularly the surface 'ferruginous hardcap', and is now preserved as erosional remnants on mesa cappings. It apparently antedates this late uplift. From the leaching, reworking, lithification and jointing Prof. Shcheglov remarked that the deposit 'looks older' than those at Gove and Weipa. On the other hand it could simply be a function of its mode of origin; the young uplift could promote the extreme leaching, jointing, dessication etc.

Summing up - the Mitchell Plateau bauxite is younger than 1800 m.y. old and circumstantial evidence suggests a similar age to Gove, mid to late Tertiary.

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Field observations

The bauxite is preserved as erosional remnants capping a series of mesas whose individual areas range up to several square kilometres. Elevations of the mesas range from about 250 to 340 m, decreasing gradually northwards towards the sea. The same surface, capped by low grade bauxite, is preserved on various offshore islands at elevations as low as 30 m. The mainland plateau remnants have relief of about 60-150 m above the main drainage lines, while near the coast the plateau falls off sharply, by way of steep scarps, right down to sea-level.

The bauxite was examined in two prospecting pits, each about 9 m deep (Plate 6b, d). The immediate impression is the difference in appearance of the ore from that at Gove and Weipa - it is massive, hard, and pale and contains an initially bewildering variety of rock types. The base of the bauxite has a sharp contact (Plate 6c) but above the base (Plate 6d) contacts between rock types are obscured by extensive alteration and fracturing due to leaching; relations between rock types could not be determined from the rapid examination available to us. Grubb (1970) shows considerable variation between the different profiles he studied.

The bauxite is immediately underlain, with an extremely sharp contact, by a mottled clay-rich ferruginous conglomerate or breccia (Plate 6c). This material is referred to as 'clay' by company personnel and the sharp contact at its top corresponds to the economic cut-off of the bauxite. The conglomerate or breccia is poorly sorted with both angular and rounded ironstone fragments and scattered large (15 cm) rounded fragments of white pisolitic bauxite. There is an abundant clay matrix, altered and stained to varying degrees by iron.

Mr W.D. Jackson (pers. comm.) noted that the conglomerate overlies, with very sharp contact, massive white and varicoloured clay, which in turn passes down into fresh basalt.

The bauxite layer itself has a wide variety of rock types including massive white bauxite, pisolitic bauxite, conglomerates and breccias up to 5 cm grainsize. The massive white breccia, perhaps the most striking rock type, appeared to be a fine colloidal precipitate, but examination of a polished surface proved it to be a microbreccia (Plate 6f). The other rocks (Plate 7a-e) are clearly sedimentary and bear a striking resemblance to sedimentary bauxites from Var, in France, figured by Nicholas (1968), and to the colluvial and conglomerate deposits of Arkansas (Gordon et al., 1958). The immediately obvious difference from the Gove and Weipa ore is the dense, massive nature of the ore; pore space between fragments is commonly completely filled with cement. All the ore will have to be blasted during mining.

Relations between the rock types are commonly difficult to see owing to the amount of fractured, altered, and leached material present (Plate 6d). However, both sharp and gradational contacts can be seen. Channel-fill structures were observed. The richest ore is the massive white bauxite at the base of the ore layer. Iron content increases quite markedly up section, the ore grading through leached, porous material into a ferruginized 'ironstone hardcap' at the surface. All the internal structures of the bauxite below are preserved in the hardcap (Plate 7e), the 'hardcap' being a simple replacement, particularly of breccia fragments, by iron. Initial alteration in the basal ore is visible as zones and veinlets of yellow-green staining.

Very little soil overlies the 'hardcap' compared with the upper soil development at Gove and Weipa.

<u>Laboratory investigations</u>

The essential mineralogical features of the Mitchell Plateau as determined by Grubb (1970) are:

(1) the main mineral is gibbsite (80-85%). Boehmite (2-10%) increases towards the top of the section.

(2) Kaolinite is generally $<$ 5 percent but locally can be up to 20 percent.

(3) Hematite plus goethite is generally $<$ 15 percent, increasing to about 25 percent in the 'ironstone hardcap'.

(4) Quartz is very minor and confined to either the top of the section or the zone below the ore.

(5) Heavy minerals fluctuate widely throughout the vertical sections.

Thin and polished sections, and the scanning electron microscope, confirm the essentially fragmentary nature of the rocks at fine scale (Plate 9). The apparently massive white bauxite is made up entirely of densely cemented, closely packed, small subangular fragments (Plate 9i, j). Some fragments still have a relict basalt texture, a feature figured by Grubb (1970). Pisolites are found in clearly detrital rocks - mostly they are associated with more massive fragments in a fine conglomerate (Plate 7a; 9a, c, d, e, f), but even in the richly pisolitic rocks (Plate 7b) the matrix between the pisolites is a microbreccia similar to that shown in Plate 9l. Pisolites show abundant desiccation cracks, fragmentary pisolites are common, and fragmented pisolites commonly form cores of later pisolites.

The most striking feature of the rocks is the compositional homogeneity of the white bauxite, readily apparent in Plate 9i, j. Sometimes small ferruginous fragments form the cores of some pisolites (Plate 9d, e, f, g) but even these show replacement by gibbsite (9f). The rest of the white bauxite, from electron microprobe study, is almost pure gibbsite and scattered boehmite fragments, identified by higher Al_2O_3 content on the microprobe; there is almost no iron, silica, or titanium. Iron and titanium show relative concentration within the yellow-green alteration veins and zones (9h, 1), with titanium showing quite wide fluctuations on the microprobe related to the alteration veinlets.

The 'ironstone hardcap' (Plate 10) shows simple replacement of fragments by iron. There is a clear tendency for selective replacement of the fragments and pisolites, rather than the matrix, and relict internal textures are still preserved (Plate 10b, e). Selective replacement of various shells has accentuated the complex structures of some pisolites and oolitic texture appears to have grown in some shells during replacement (10f). The matrix of the 'hardcap' has been completely transformed into an oolitic texture (10c, f).

Interpretation

We concur fully with Grubb (1970) that - 'reworking of the residual bauxite......was so extensive that no undisputably residual bauxite now remains'*. There is abundant evidence that the bauxite

*Joklik, Jackson, & Zani (1973, Aus.I.M.M. Conference) describe numerous primary features of the Carson Volcanics preserved in the overlying bauxites, and conclude that the bauxite is a residual in situ deposit. Analogues of nearly all features observable in the bauxite can be found in basalt exposures. Areal zoning of the deposits, interpreted by Grubb as channelling, can be related to bed-rock structure. Many of these features were not elucidated until after Grubb made his observations, and depend largely on exposures not seen by him. Observations by Grubb and the authors were confined to a small area of local breccia development which Joklik et al. correlate with adjacent volcanic breccia bedrock. We consider that most fabrics we observed do not resemble volcanic breccia, and other features are not consistent with in situ weathering. Perhaps Mitchell Plateau is another example of both in situ and detrital bauxite preserved in the same deposit. The dense nature of the bauxite still indicates conditions peculiar to Mitchell Plateau, related either to the basalt source-rock or geomorphological history.

represents an accumulation of transported detritus. This has been a multicycle process, with superimposed alteration and leaching. It is impossible to interpret fully the complex history of the rocks from the short visit made by us.

The concentration of the bauxite along the axis of the Admiralty Gulf Syncline could be consistent with accumulation of reworked bauxite because on the broad scale the topography in the area reflects the regional structure. All the volcanics have been stripped from the higher synclinal flanks to expose the underlying resistant King Leopold Sandstone. This stripping could have occurred before bauxitization, so that the presence of bauxite in the syncline is purely related to preservation of volcanics, while, on the other hand, at least some of the stripping may have accompanied bauxitization, providing the source of bauxite for deposition. Mapping of bauxite types by Grubb (1970) shows a striking relationship to the synclinal axis, indicating at least a local control.

The lithification of the deposits and their similarity to the water-laid deposits at Var suggest deposition in water such as lakes or swamps rather than a slope wash. The dense cement is a direct colloidal precipitate. Grubb has similarly compared the lithification to various water-laid deposits around the world.

The rapid changes and confusing pattern of rock types in the bauxite indicate either multiple reworking of the deposit, a very dynamic environment of deposition with sudden changes in environment, or, most probably, a combination of both. Superimposed on these processes is extensive leaching and reprecipitation of iron and silica in situ, exemplified by the present 'ironstone hardcap' which is clearly related to the present land surface - the 'hardcap' occurs at the surface with veining, leaching, fracturing, and iron-staining progressively dying out downwards into the highest grade, dense, massive ore at the base. This 'hardcap' formation could be related to accentuated drainage after the latest uplift of the area to its present high relief. This uplift is considered to be relatively recent because of the youthful topography of the area. Increased drainage would normally favour bauxitization, but the dense nature of the richest ore, low in the profile, precludes large-scale removal of material from it; it has probably not been subjected to leaching of iron. Downward movement of iron solutions, as proposed by Maignien (1966), is more consistent with the observed downward penetration of secondary iron rich veins from the surface.

PLATE 6

(a) Tree roots in large solution shaft within loose pisolitic bauxite - Andoom Bauxite Deposit - Weipa. Diameter of shaft about 0.5 m. Thin hardened crust surrounding shaft.

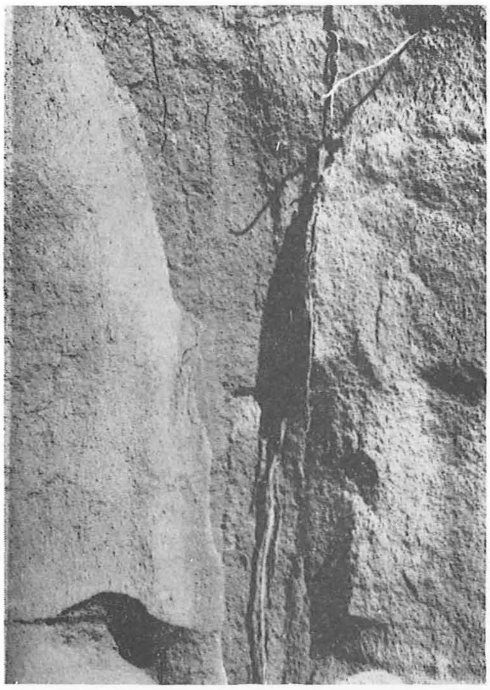
(b) Costeen - Mitchell Plateau Bauxite Deposit. Ore 6 m thick. Massive white bauxite grades up into "ironstone hardcap".

(c) Sharp contact between massive white bauxite, above, and clayey ferruginous conglomerate, below - Mitchell Plateau Bauxite Deposit. Crude stratification within conglomerate.

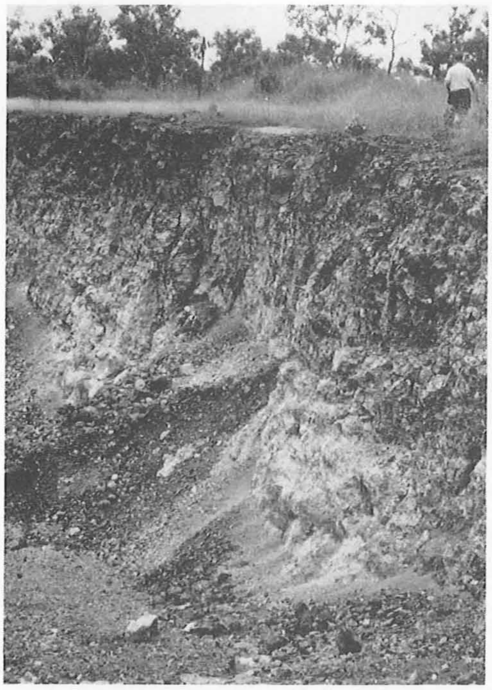
(d) Massive white bauxite grading upwards into "ironstone hardcap" - Mitchell Plateau Bauxite Deposit. Note hard massive nature of bauxite and degree of fracturing and jointing.

(e) Polished surface clayey ferruginous conglomerate - Mitchell Plateau Bauxite Deposit. Width of specimen 6 cm. Clayey and ferruginous fragments in clayey matrix. Note apparent stratification. Reg. No. 71/10/0012.

(f) Polished surface massive white bauxite - Mitchell Plateau Bauxite Deposit. Width of specimen 5 cm. Reg. No. 71/10/0015. Note fine fragmentary texture and overall uniform composition.

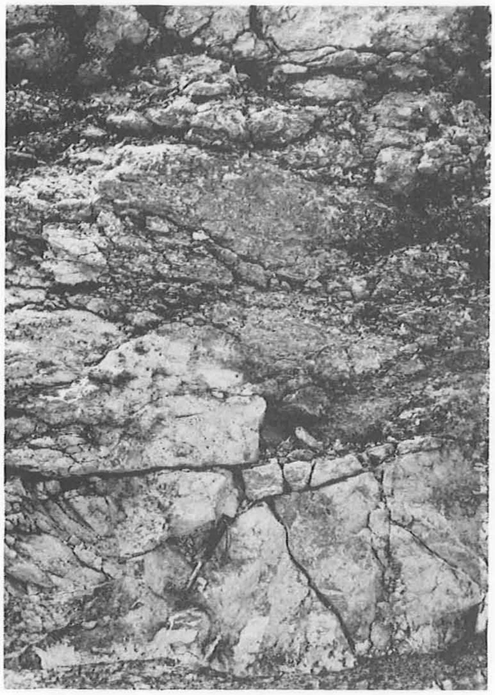


-a- (GA 5137)

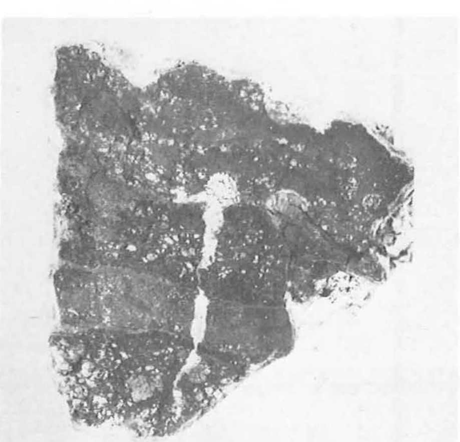


-b- (GA 5160)

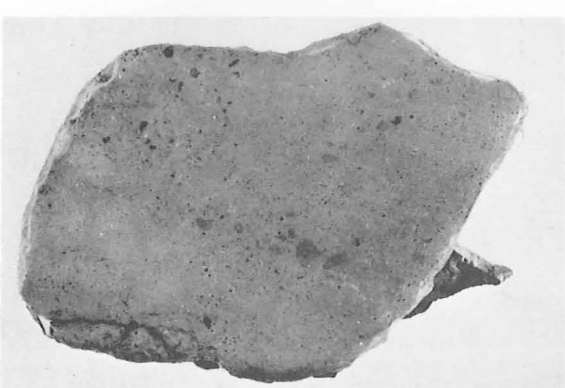
-c- (GA 5153)



-d- (GA 5141)



-e- (GA 5218)



-f- (GA 5225)

PLATE 7

(a) Polished surface fine bauxite conglomerate - Mitchell Plateau Bauxite Deposit. Width of specimen 8 cms. Reg. No. 71/10/0015. Brown bauxite fragments and white pisolites in massive white gibbsite cement.

(b) Massive white pisolitic bauxite conglomerate - Mitchell Plateau Bauxite Deposit. Width of specimen 8 cm. Reg. No. 71/10/0014. Brown and white pisolites in fine granular matrix and gibbsite cement.

(c) Outcrop of bauxite conglomerate - Mitchell Plateau Bauxite Deposit.

(d) Outcrop of bauxite conglomerate - Mitchell Plateau Bauxite Deposit. Note scattered pisolites amongst larger fragments.

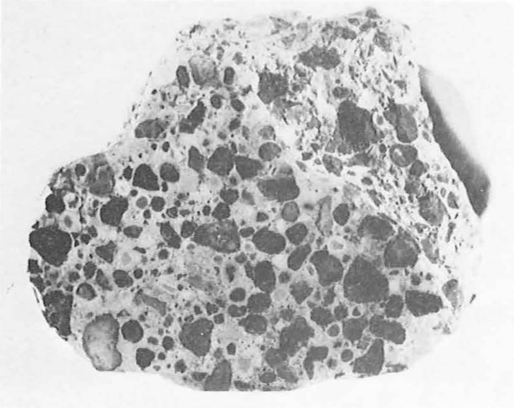
(e) Polished surface ferruginous caprock - Mitchell Plateau Bauxite Deposit. Width of specimen 8 cm. Reg. No. 71/10/0017. Rock stained red-brown. Fragments hematitic. Note textural similarity to photo (a).

(f) Weipa shoreline from Andoom area. Note flat, low-lying topography.

(g) Quarry face - Weipa Bauxite Deposit - Face consists entirely of loose pisolitic bauxite. Floor is nodular ironstone.

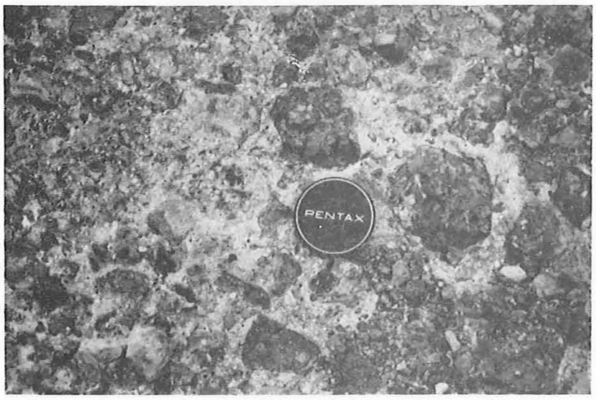
(h) Surface hardened crust (immediately below hammer) at top of loose pisolitic bauxite - Andoom area - Weipa Bauxite Deposit. Crust overlain by soil with scattered pisolites.

PLATE 7

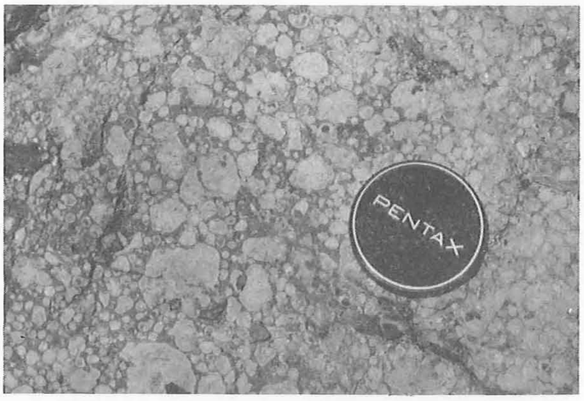


-a- (GA 5219)

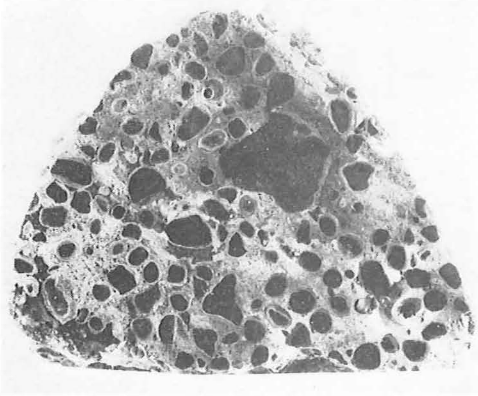
-b- (GA 5220)



-c- (GA 5147)



-d- (GA 5154)



-e- (GA 5221)

-f- (GA 5152)

-g- (GA 5135)

-h- (GA 5165)

PLATE 8

(a) Local sharp contact between loose pisolitic bauxite overlying (?)nodular ironstone - Weipa Bauxite Deposit. Ironstone generally loose and friable; locally cemented as in centre of photo.

(b) Cemented nodular ironstone (near centre (a)) - Weipa Bauxite Deposit. Note horizontally aligned tubular structure with infilling of loose pisolites.

(c) Polished surface cemented nodular ironstone - Weipa Bauxite Deposit. Width of specimen 8 cm. Reg. No. 71/10/0010. Irregular fragments ferruginous bauxite and claystone. Some oolitic texture.

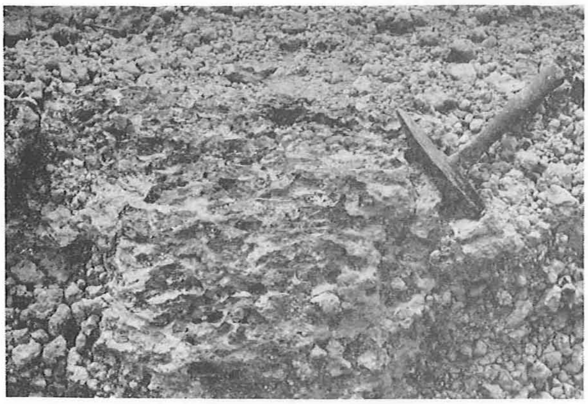
(d) Root solution shaft passing through both loose pisolitic bauxite (dark top of photo) and loose nodular ironstone - Weipa Bauxite Deposit. Ironstone generally uncemented. Note discontinuous horizontal dark band below hand which has not been converted to nodular ironstone.

(e) Horizontal stratification in nodular ironstone - Weipa Bauxite Deposit. Top of nodular ironstone just above head level. Note pinch out to right at top of white layer.

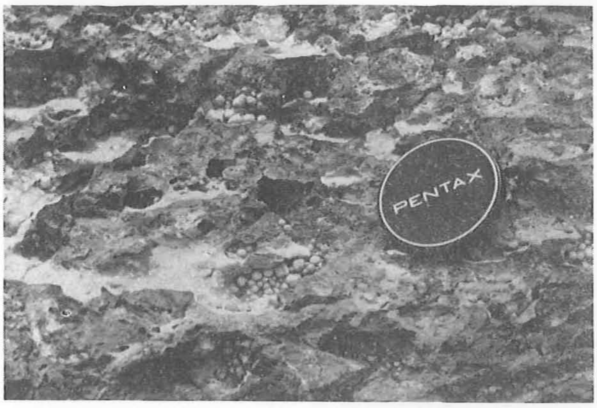
(f) Loose pisolitic bauxite - Weipa Bauxite Deposit. Orange-brown pisolites, 3-8 mm and large hollow nodules in reasonably abundant, loose, friable, earthy matrix.

(g) Hollow, pisolite filled nodule - Weipa Bauxite Deposit. Shell consists of cemented matrix material.

(h) Polished surface cemented pisolitic bauxite - Weipa Bauxite Deposit. Width of specimen 6 cm. Reg. No. 71/10/0008. Note oolitic cores top and lower right. Large numbers of shells on larger pisolites. Variety of smaller pisolites.

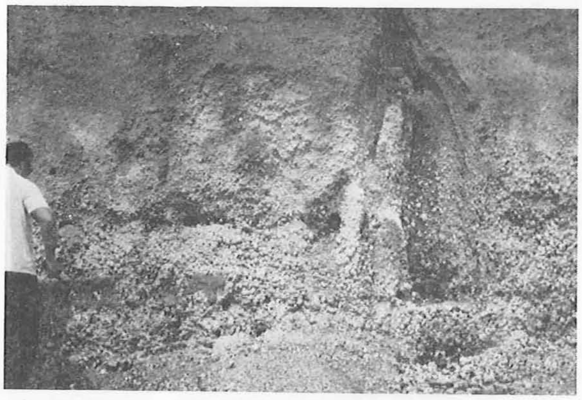


-a- (GA 5146)



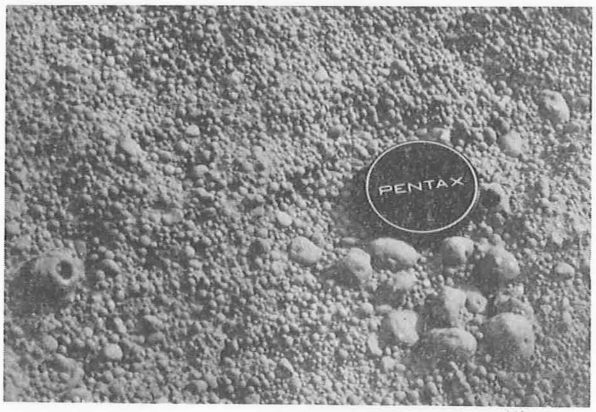
-b- (GA5163)

-c- (GA 5226)

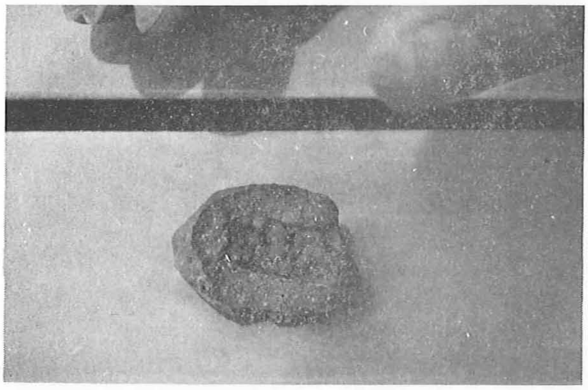


-d- (GA 5139)

-e- (GA 5162)



-f- (GA 5138)



-g- (GA 5136)

-h- (GA 5224)

PLATE 9

Scanning electron photomicrographs - white bauxite - Mitchell Plateau Bauxite Deposit.

Note overall compositional unity of most samples - contrast in these photos increased relative to Plates 3-5 to accentuate textures.

(a), (b), (c) -pisolites in white pisolitic bauxite Reg. No. 71/10/0014 - (b) and fine bauxite conglomerate Reg. No. 71/10/0015 - (a), (c).

(d), (e), (f), (g) - ferruginous fragments, sometimes with thin outer alumina shells, within fine bauxite conglomerate Reg. No. 71/10/0015 - (d), (e), (f) and massive white bauxite Reg. No. 71/10/0016A - (g).

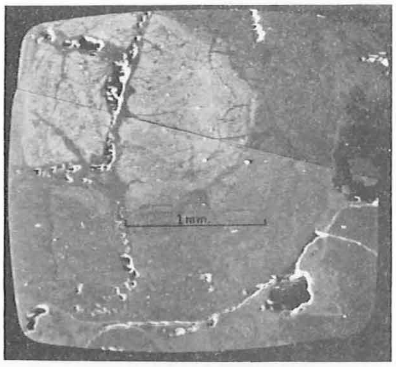
(h) ferruginous oolitic fragment within outer alumina shell - fine bauxite conglomerate Reg. No. 71/10/0015.

(i), (j) - microbreccia fabric - massive white bauxite Reg. No. 71/10/0016A.

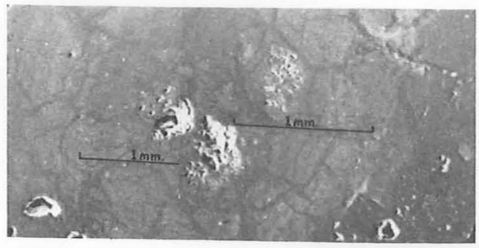
(k), (l) - yellow alteration veins (light colour) is massive white bauxite Reg. No. 71/10/0016B. Microbreccia fabric preserved. Dark unaltered areas (?)boehmite.

(m) (?)Boehmite fragment in yellow alteration vein - massive white bauxite Reg. No. 71/10/0016B.

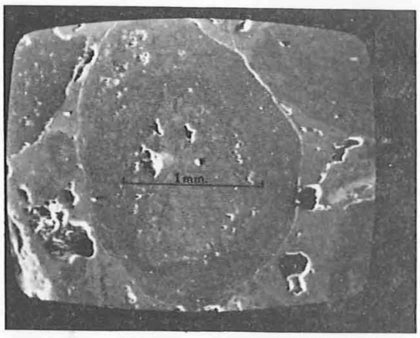
PLATE 9



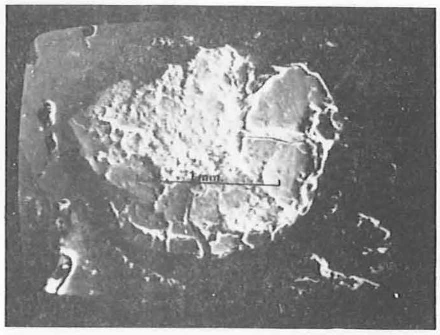
(a)



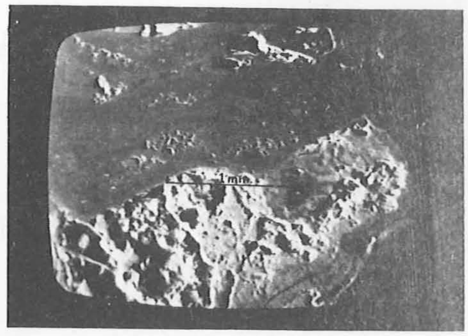
(b)



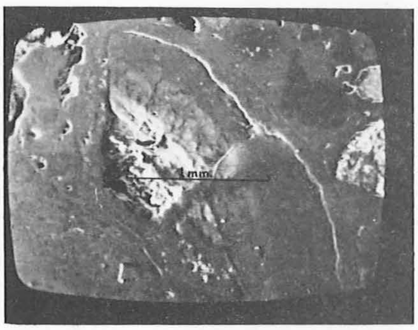
(c)



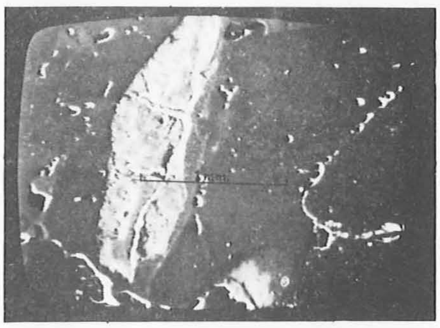
(d)



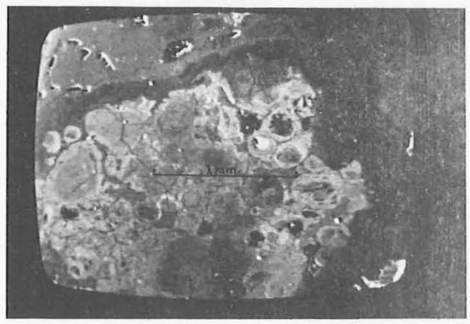
(e)



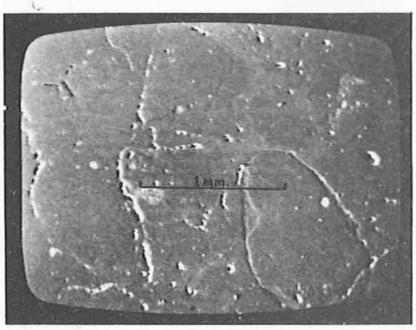
(f)



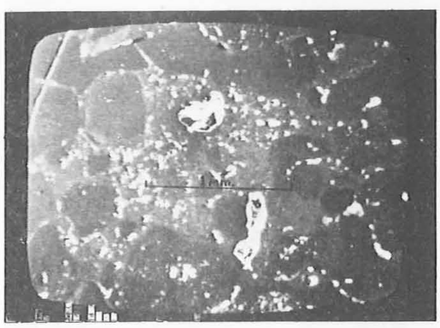
(g)



(h)

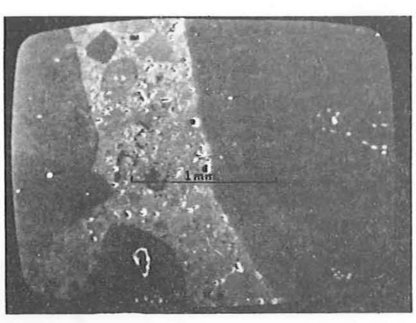


(i)

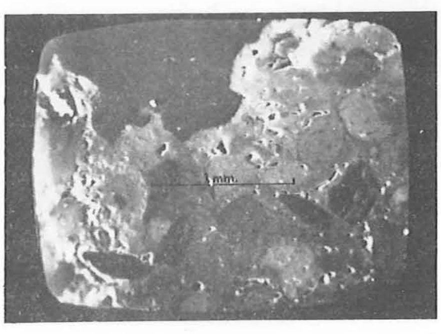


(j)

(m)



(k)



(l)

PLATE 10

Scanning electron photomicrographs - "ironstone hardcap" Reg. No. 71/10/0017 - Mitchell Plateau Bauxite Deposit.

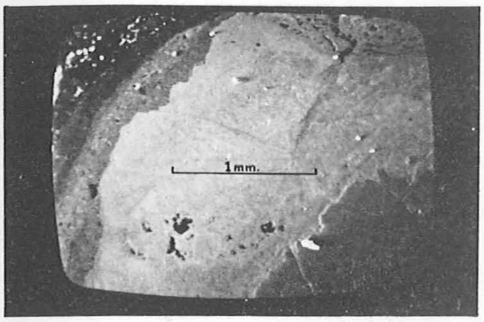
(a), (b), (c) - portions of large complex fragment undergoing selective replacement by hematite. Hematite-light; alumina-dark, (a) - northwest sector; (b) - centre sector; (c) - northeast sector. Other aluminous shells (a) and (c); relict oolitic texture in core (b).

(d) hematite fragment in contact with oolitic alumino7s matrix.

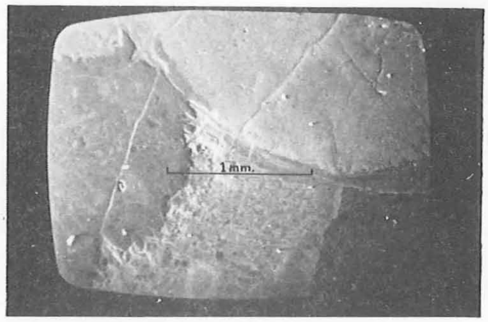
(e) gradational replacement of relict oolitic material by hematite in core of fragment.

(f) complex arrangement of shells in large pisolite undergoing selective replacement by iron. Note oolitic texture in some shells and oolitic, aluminous matrix.

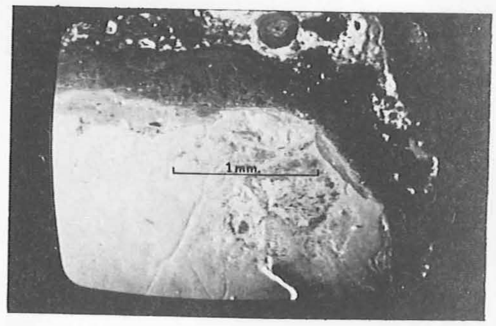
PLATE 10



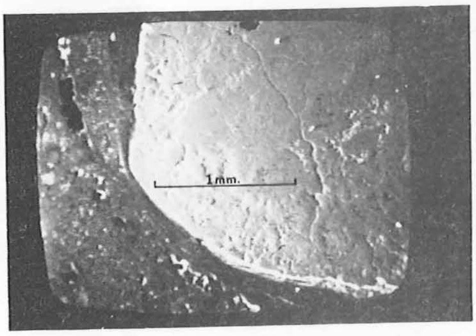
(a)



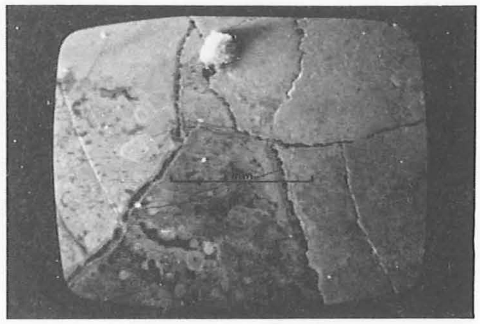
(b)



(c)



(d)



(e)

(f)

PLATE 11

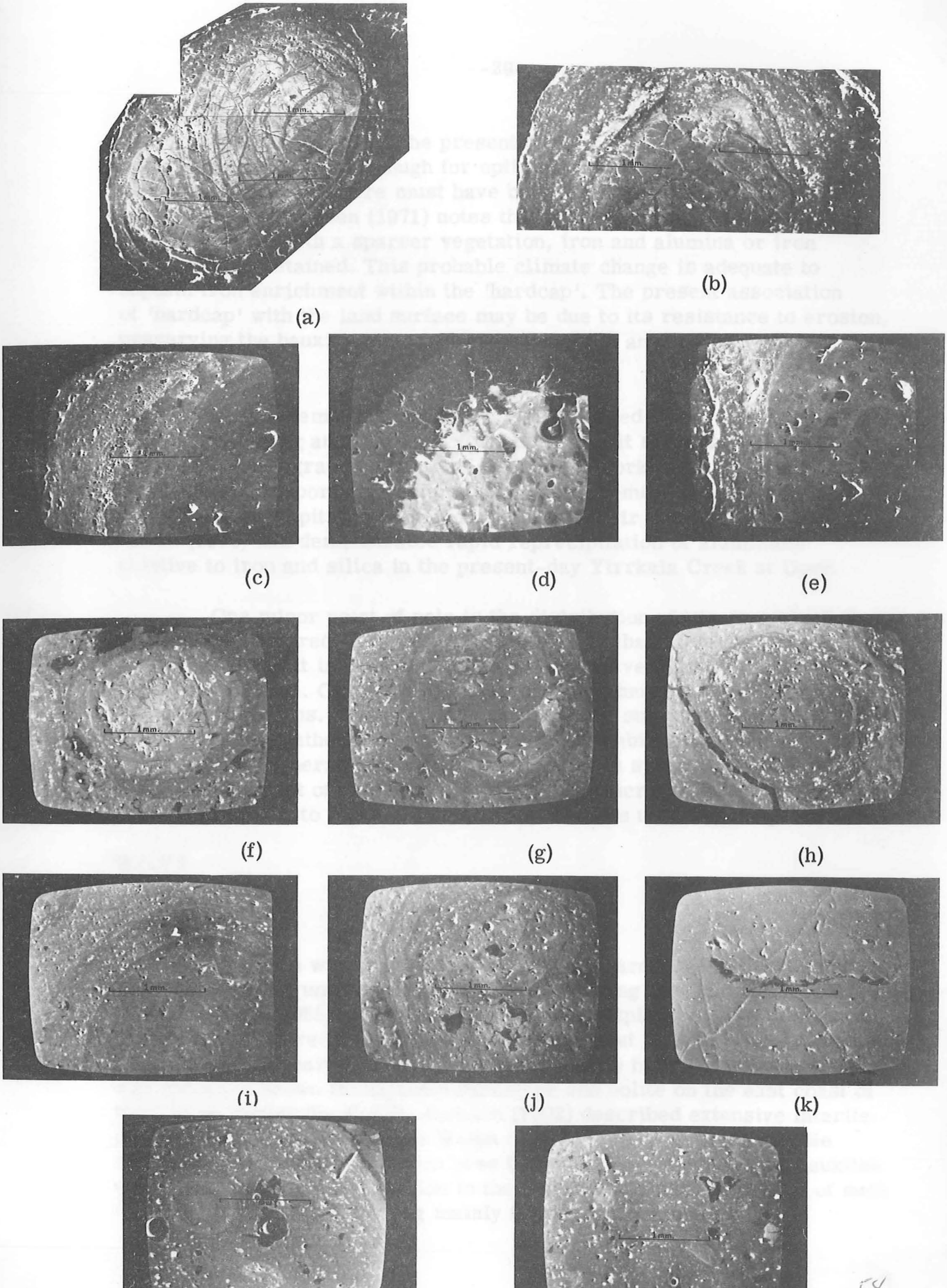
Scanning electron photomicrographs - loose pisolitic bauxite Reg. No. 71/10/0006 (a) to (e) and cemented pisolitic bauxite Reg. No. 71/10/0008 (f) to (m) - Weipa Bauxite Deposit.

(a), (b) - complex concentric shelled pisolites. Note overall compositional uniformity, particularly (b). Compare outer shells to Plate 3.

(c), (d), (e) - oolitic texture in pisolite cores. Aluminous cores (c), (e); ferruginous core (d).

(f) to (m) - pisolites within cement. Note overall compositional uniformity of rock and variety of pisolite structures - concentric shells but opposite composition gradient (f), (i); complex cores (g), (j); uniform composition (k); oolitic cores (l), (m).

PLATE 11



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m)

It is unlikely that the present climate is wet enough or the vegetation cover dense enough for optimum conditions of bauxitization at Mitchell Plateau; there must have been a climate change since bauxitization. Petersen (1971) notes that under oxidizing conditions, to be expected beneath a sparser vegetation, iron and alumina or iron alone may be retained. This probable climate change is adequate to explain iron enrichment within the 'hardcap'. The present association of 'hardcap' with the land surface may be due to its resistance to erosion, preserving the bauxite as erosional remnants in an area of dynamic topography.

If, as seems likely, the ore is not related to the latest phase of in situ weathering and 'hardcap' formation then it must have been progressively upgraded during the multiple reworking of the deposit. An aqueous transporting medium could easily remove excess iron and silica while precipitating alumina because of their relative solubilities; Grubb (1970) has demonstrated rapid reprecipitation of aluminium relative to iron and silica in the present-day Yirrkala Creek at Gove.

One minor point of note is the distribution of titanium which is generally considered to be even more insoluble than aluminium. At Mitchell Plateau it is enriched within secondary veinlets suggesting mobility with iron. Grubb (1970) notes that it is more insoluble under reducing conditions. Two explanations therefore suggest themselves. Firstly, its sympathetic relation to iron and its ability to substitute for ferric ions in mineral lattices allows mobility in sympathy with iron. Secondly, an onset of oxidizing conditions may increase its solubility sufficiently for it to move into secondary veinlets until reprecipitated.

WEIPA

Development

Attention was first drawn to the Weipa area by Matthew Flinders when he noted the unusual red cliffs while charting the Gulf of Carpentaria in 1802. Evans (1965) records that many early explorers drew attention to the pisolitic texture of the Cape York laterites but failed to recognize them as bauxites. The earliest reference was probably by R.L. Jack in 1880, who recorded brown ferruginous sandstone and oolite on the east coast of Cape York Peninsula. C.F.V. Jackson (1902) described extensive laterite extending along the coast from Weipa to Vrilya Point in the north. He described them as pisolitic iron ores but noted the association of bauxites with laterites and drew attention to the possible economic potential of such deposits, apparently referring mainly to iron but presumably, by implication, to bauxite as well. Owen (1954) drew attention to Jackson's report and recorded a partial analysis of an alumina rich specimen from Pera Head; he confirmed Jackson's opinion on the bauxite potential of the area but was unable to visit the area personally.

The economic potential of the area was finally recognized by H.J. Evans of C.R.A. who discovered economic grade bauxite and determined the general extent of the deposits while carrying out a geological reconnaissance of Cape York Peninsula in June 1955 as part of an assessment of the region's oil potential. A program of detailed assessment by the Commonwealth Aluminium Corporation (COMALCO) followed, leading to the start of full scale mining in January 1963 (Evans, 1965). Adjoining leases are currently being investigated by ALCAN to the northeast of Weipa and Tipperary Land and Exploration Corporation at Aurukun, to the south.

Evans (1971) describes laterite residuals covering an area of at least 1300 km^2 of which 500 to 800 km^2 contain economic grade bauxite; these figures apparently apply only to the COMALCO leases. Proved reserves are 500 million tonnes with an additional 1500 million tonnes indicated. The proved reserves have only been drilled out within a 24 km radius of Weipa (Evans, 1965). Accurate figures are not available for the adjoining ALCAN and Tipperary leases, but they are believed to exceed 1000 million tonnes of indicated ore. The reserves in the area are thus immense and almost certainly constitute the largest deposit in the world.

Added to these immense reserves are exceptionally easy mining conditions. There is generally less than 1 m of overburden, the ore is generally friable and can usually be mined directly by mechanical shovel without blasting or breaking up. Beneficiation to produce shipping grade ore simply consists of washing to remove fines, and the deposits are on the coast immediately adjacent to shipping facilities.

Mining to date is confined to the immediate area around Weipa where the average composition of the ore, as quoted to us by the company, is:

Al_2O_3 (total)	SiO_2 (total)	Fe_2O_3	TiO_2	Ignition Loss
53-57%	10%	8%	2%	20-25%

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Much of the silica is in the uncombined form and thus easily removed. Locally there are small patches of very high grade cemented ore which is used for the manufacture of artificial corundum. Grade of this ore was quoted as:

Al_2O_3 (total)	SiO_2 (total)	Fe_2O_3	TiO_2 + ignition loss
$>$60%	3.5%	5%	20%

A railway has now been constructed across Mission River to Andoom where mining of a higher grade ore (less SiO_2) is due to commence very shortly. Average grade is:

Al_2O_3 (total)	SiO_2 (total)	Fe_2O_3
ca. 50%	5%	15%

The ore averages 2.4 m in thickness (Evans, 1971) but ranges from about 1 - 9.0 m (Evans, 1965) and the thickest ore occurs in the Andoom area.

Weipa is accessible by land, sea, and air. Ore is currently being shipped directly to COMALCO alumina plants at Gladstone, Queensland and Bell Bay, Tasmania, or direct to alumina plants in Japan.

Previous investigations

Baker (1958) and Edwards (1957, 1958) showed by means of heavy mineral studies that the Weipa bauxites were derived from the underlying arkosic parent rock. Loughnan & Bayliss (1961) determined the overall mineral compositions of the bauxite and underlying rocks in relation to depth in the profiles, one of the most significant results being the identification of boehmite increasing in quantity towards the top of the profile. They concluded that the bauxite was formed by intensive in situ leaching of silica from kaolinitic sandstones and demonstrated that in a suitably 'aggressive' environment a parent material containing 90 percent silica and as little as 3 percent alumina may give rise to bauxite relatively deficient in silica. The pisolitic bauxite was described as forming within a 'zone of concretion' while the underlying iron-rich material was supposed to form by concentration of iron, derived from upward migration from the underlying parent rock, within a 'zone of fluctuating water table'. The parent rock lies below the permanent water table. From a number of assumptions they estimated the time necessary for formation of the bauxite profile at Weipa as 50 million years, placing the commencement of bauxitization at early to middle Tertiary.

Evans (1965) described the overall geology and history of exploration and development of the deposits. He considered that the bauxite formed by prolonged in situ weathering of Tertiary sediments on an exceptionally stable peneplain, at or just above sea level. The pisolitic bauxite was thought to have developed by concretionary growth within the very limited zone of annual rise and fall of the water table while the iron rich material, which has nodular and tubular zones, formed within the relatively static zone of the water table. The tectonic stability of the peneplain favoured the concretionary growth of the abundant pisolites within a matrix of earthy type bauxite. After completion of the process, rapid lowering of the water table, perhaps by uplift of the bauxite, promoted rapid leaching of the uncemented bauxite resulting in a complete removal of the soft matrix, leaving the pisolites as a residual and giving rise to the present loose porous texture. From groundwater studies, Evans (op. cit.) showed that a miniature process of lateritization is still in progress.

Grubb (1971a) carried out further detailed mineralogical studies at Weipa and concluded that the land surface at Weipa was in a much less dynamic state than at Gove, with a lower leaching rate and a lack of extensive physical reworking. The peculiar features of the Weipa bauxite, its uniformity, extent and quantity, are all a function of the tectonic stability of the area, with suitable drainage provided by subterranean aquifers.

MacGeehan (1972) in an excellent field and laboratory study of the Aurukun deposits, again concluded that the bauxite formed by in situ weathering, but described two stages of bauxitization. In the first stage gibbsitic pisolites formed in the zone of wet-season saturation of a fluctuating water table. Heavy leaching within this zone produced depletion of silica and residual enrichment in anatase, gibbsite, and boehmite. The permanent dry-season water table was located in the zone of iron enrichment at the base of the nodular ironstone horizon. Later uplift of the peneplain lowered the water table and impressed a new set of Eh, pH controls on the bauxite. Secondary enrichment in boehmite occurred in the upper oxidized levels to produce boehmite sheaths, while gibbsite sheaths grew in the lower levels within the new zone of wet-season saturation. He considers the second stage of development is continuing today.

Regional setting

The Weipa bauxite deposits are situated on the western coast of Cape York Peninsula overlying flat-lying to shallowly dipping sediments of the Mesozoic-Quaternary Carpentaria Basin. The bauxite immediately

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overlies unfossiliferous poorly lithified clay, sandy clay, and sand of the Upper Cretaceous or Lower Tertiary Bulimba Formation. These beds dip gently westwards at angles no greater than 4° and there is absolute correlation between the bauxite and Bulimba Formation - BMR regional mapping shows that the bauxite extends to the east almost exactly to the limit of preservation of the Bulimba Formation; farther east they are stripped to expose Lower Cretaceous beds. Regionally the Bulimba Formation has very abundant coarse quartz sand and granules in a clay matrix and occasional thick clay beds; in the Foundation Bore below Weipa clay predominates.

The Carpentaria Basin sediments rise gradually eastwards until Precambrian basement of the Coen Inlier is exposed in the central range of Cape York, 100+ km to the east. Weipa appears to be situated within a very shallow northwest-trending syncline or downwarp and 100 km to the south the northwest-trending Gilbert-Mitchell Trough contains a considerable post-Bulimba Formation sedimentary section. Thus Weipa is situated within a shallow depression on a Cainozoic upwarp or still-stand. Contouring by a BMR regional field party shows a gradual westerly dip in both present topography and levels of old stratigraphic horizons with a break in slope, and more gentle gradient, near the coast. The bauxite is confined to this flat area with the easterly limit corresponding closely to the break in slope.

A striking feature of Weipa is its low-lying flat topography (Plate 7f). The bauxite is preserved on the tops of low mesas into which later streams have been incised, while extensive salt and mud flats border the estuaries. These mesas extend up to 50 km inland and contain numerous small circular swamps on them. Evans (1965) notes that the mesas rise in elevation to the east at an average gradient of 1.5 m per km to a maximum elevation of about 30 m at the eastward limits.

Evans (1965) shows levels of water table at Weipa ranging from 2.2 m below ground surface in March to 8 m below surface in October. The shallow water table is emphasized by semi-permanent and permanent lakes and swamps scattered around the surface; most of these contained water during our visit in April. There is no bauxite, only clay, present beneath these swamps.

Age of the deposit

The Bulimba Formation is unfossiliferous, but overlies fossiliferous Lower Cretaceous rocks with a probable slight disconformity. The formation is Upper Cretaceous or Lower Tertiary. The bauxite is therefore probably largely Tertiary although it may have begun to form in the late Cretaceous. Bauxitization may have continued throughout much of the Tertiary but intensive bauxitization has now ceased.

Field observations

The immediately striking features of the deposits at Weipa, which probably collectively make the deposits unique, are:

(1) the vast extent of bauxite

(2) the monotonous lithological uniformity of the bauxite

(3) the loose pisolitic texture of the bauxite.

These properties indicate an exceptional combination of geological conditions during the bauxite's formation.

Our study was confined to one quarry of pisolitic bauxite south of Weipa township, one quarry in nodular ironstone (locality H) used for road gravel, one prospecting trench in pisolitic bauxite at Andoom, and drill cuttings from the 28 m deep Foundation Bore.

Three main layers can be recognized in the area; from the bottom up - kaolinitic clay; nodular ironstone; loose pisolitic bauxite. Evans (1965) recognizes two sub-zones within the loose pisolitic bauxite; MacGeehan (1972) recognizes three; and Evans in places recognizes a cellular or tubular clay zone beneath the nodular ironstone.

No outcrops of kaolinitic clay were seen but drill cuttings from the Foundation Bore were examined - the sequence below 6 m consists of interbedded white clay, sandy clay, and clayey sandstone. The sandstone is permeable and provides an excellent aquifer which supplys the township and plant with water; 80 l/s (65 000 gals/hr) are being pumped at Weipa with 12.5 l/s (10 000 gals/hr) produced from one bore. It was noted, however, that the aquifer is absent below Andoom (Duchatel, pers. comm.). Below 24 m the white clay passes gradually down into fresh grey and grey-green claystone. The clay thus represents a normal pallid zone of a laterite profile. Where clay, rather than sand, is present immediately below the nodular ironstone, Evans (1965) describes a cellular or tabular zone consisting of 'ferruginous kaolinized clays and sandy clays with a porous cellular structure. Vertical tubes lined with iron and aluminium hydroxides are common and the whole zone is mottled with purple-red to brown patches. Ferruginous concretions and some sporadic pisolites also occur.' J. Smart (pers. comm.) describes, from the few outcrops he observed, a gradational contact between the white clay and nodular ironstone with mottling of the upper zone of the clay owing to patchy iron staining, the iron appearing to have moved downwards along joints. Within the drill cuttings we observed there was a gradual downward increase in clay associated with the ironstone between 3 and 6 m.

The overlying nodular ironstone was seen in a quarry (Locality H) used for road metal (Plate 8 a-e). The ironstone here is about 1.5 m thick; Evans (1965) notes that throughout Weipa it ranges from about 0.9 - 1.5 m in thickness. The top of the ironstone marks the base of the ore, the ironstone containing considerably more silica than the pisolitic bauxite above. The ironstone consists of closely packed rounded to irregularly shaped highly weathered and ferruginized bedrock fragments coated with clay or gibbsite shells, and scattered patches of pisolites within hollows. Generally the nodules are not cemented (Plate 8a, d), but locally patches of dense cemented tubular ironstone occur (Plate 8a, b). The internal structure of the nodules (Plate 8c) ranges from ironstained claystone, through fine oolitic claystone, to almost massive hematite. The iron appears to be of secondary origin, infiltrated through fine fractures. Stages in development seem to be separation of small (1 mm) clay patches separated by iron-filled fractures, then development of these clay patches into spherical oolites. The contact between the ironstone and overlying bauxite is sudden, but generally gradational (Plate 8d, e), but locally, where the cemented tubular material occurs, the contact is very sharp (Plate 8a). A well defined horizontal stratification resembling bedding can be seen within the ironstone, including pinch-outs (Plate 8e), although no compositional differences could be detected between layers. Locally (Plate 8d), dark brown discontinuous layers, in which coarse nodules are not developed, occur parallel to the stratification.

The ore layer consists of orange-brown to red-brown uniform loose or friable pisolitic bauxite, ranging in thickness from 1 - 9 m (Plate 7g). The spherical pisolites are generally about 2-8 mm in diameter, but range from 1-25 mm, and are enclosed in a sparse reddish-brown friable sandy clay matrix (Figure 8f). Although the pisolites make up by far the greater part of the rock there is more matrix present than in the loose pisolitic bauxite at Gove - the pisolites tend to be either separated by the matrix or only barely touching. The large pisolites scattered through the bauxite (Plate 8f) are compound structures composed of hollow shells of cemented matrix material, the interior being either empty or containing groups of smaller pisolites (Plate 8g). The top of the bauxite is a slightly irregular surface (Plate 7g) with a hardcap of cemented pisolites up to 1 m thick, and overlain in turn by a soil overburden with scattered pisolites (Plate 7h). Locally where this hardcap is particularly thick complex shells have grown about the larger pisolites, forming very high grade bauxite, used in corundum manufacture. Vertical hollow solution shafts, 5-50 cm wide, extending downwards from the soil layer, are well developed in many places and are clearly related to solution around tree roots (Plate 6a). The shafts are surrounded by thin 'hardcap' shells of cemented bauxite and can penetrate right through the nodular ironstone (Plate 8d).

The internal structure of the pisolites is of three types (1) oolitic bauxite, (2) highly altered bedrock, (3) complexly developed concentric shells around a small nucleus. On closer study of polished surfaces, many cores thought to be sandy claystone showed the white 'quartz' grains to be small oolites. Oolitic cores tend to be porous, soft, and earthy. The concentric shelled pisolites are smaller, denser, and harder, and possess a vitreous lustre. Occasionally large (25-50 mm) fragments of bauxitized bedrock form cores to pisolites.

The sandy clay matrix is composed largely of small white oolites, as in pisolite cores, together with finely crushed bauxite fragments, clay, and quartz grains. Fragments of broken pisolites are common in places. This matrix, particularly the oolites, is cemented together to form the shells of the large compound pisolites, around which is deposited a secondary shell, 1 mm thick, of fine red-brown material, apparently composed of boehmite-Fe_2O_3 admixture (after MacGeehan, 1972).

Our rapid study did not reveal any significant vertical variations in the bauxite layer but Evans (1965) recognizes two subzones. The upper zone is rich in boehmite, has a 'hardcap' at the top, and contains compound pisolites up to 50 mm. The lower zone has pisolites decreasing in size with depth, apparently more matrix, few if any compound pisolites, and silica and boehmite decreasing with depth.

MacGeehan (1972), on the other hand, recognizes three zones at Aurukun. The upper Boehmite Zone contains uniformly sized pisolites well spaced in sandy clay matrix. Both concentric banded and earthy cellular (?oolitic) pisolites occur, quartz inclusions are common, hard pisolites predominate, and partly altered bedrock fragments are found at the top of the zone. The Concretionary Boehmite Zone below may be up to 5.5 m thick, has pale red external sheaths of boehmite-Fe_2O_3 admixture enclosing gibbsitic pisolites, or occasionally boehmitic pisolites at the top, fragments of altered parent rock, and compound pisolites. The gibbsitic pisolites are closely packed, with little matrix, and concentric-banded pisolites are most common. The upper Gibbsite Zone has densely packed, uniformly sized, mostly concentric-banded pisolites. Earthy cellular (?oolitic) pisolites gradually become predominant towards the base, clay matrix reappears between pisolites, and compound pisolites develop again at the base by growth of gibbsitic membranes. We cannot, in retrospect, positively relate our observations to this zonation.

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Laboratory investigations

Studies by Loughnan & Bayliss (1961), Grubb (1971a), and MacGeehan (1972) all give similar results for the ore layer. The most abundant mineral is gibbsite (ca. 75%). Hematite/goethite, kaolinite, and titania generally show very uniform contents through the vertical profile. Boehmite increases gradually and markedly towards the top of the profile, reaching a maximum of about 20 percent. Quartz sometimes increases slightly at the top of the profile. Below the ore kaolinite and quartz both increase markedly and gibbsite/boehmite disappear completely. Hematite/goethite generally shows a marked peak (up to 30%) in the nodular ironstone, decreasing strikingly both up and down section from there; in the kaolinite zone it decreases to zero. Heavy minerals (Grubb, 1971a) show little systematic variation although there is a tendency towards a proportionate increase in total heavy minerals within the bauxite and Grubb notes a greater proportion of coarse grains within the bauxite. The heavy mineral types are consistent with derivation of the bauxite from the underlying sands and clays.

The grab samples we studied cannot be positively positioned within the ideal profile of MacGeehan but probably come from the upper Gibbsite Zone or Concretionary Boehmite Zone. The first impression of thin sections is that the pisolites are the same as those found in the loose pisolitic bauxite at Gove. The concentric shelled pisolites generally have a more ferruginous core than the outer shells of the pisolite and more often than not the core is itself a fragment of an older broken pisolite. They show similar complex histories of shell growth to those at Gove (Plate 11a, b). The oolitic cored pisolites have much simpler histories; they generally only have the main outer shell around a rounded core of oolitic bauxite. The oolites themselves tend to be white within a red-brown matrix. All pisolites, of both types, aresurrounded by an identical continuous yellow coloured shell about 0.5 mm in thickness, presumably composed of gibbsite. This is then generally covered by a thinner outer red-brown skin, apparently the boehmite/Fe_2O_3 admixture of MacGeehan (1972). Gibbsite-filled synaeresis cracks are common within the cores of the concentric shelled pisolites but do not extend into the outer gibbsitic and boehmitic shells. Syneresis cracks do not occur within the oolitic cored pisolites.

A major difference from the pisolites at Gove, however, is the compositional uniformity of the Weipa pisolites. Colour differences between the shells at Weipa are only a little less marked than at Gove, but the electron scanning microscope shows very uniform compositions throughout the Weipa pisolites (Plate 11), particularly in the high-grade cemented pisolitic bauxite. The electron microprobe supports these results. Within the oolitic pisolites alumina, iron, titania, and silica are roughly uniform right across the pisolites, with alumina very much in excess of iron. The concentric-shelled pisolites mostly have a slightly more ferruginous core, the core is deficient in silica, and titania is again uniform throughout. The silica content tends to be higher than at Gove and Mitchell Plateau, which is consistent with the assays. In the concentric shelled pisolites, it is concentrated in the outer shells, but in the oolitic pisolites it tends to be uniform throughout; on the finer scale, within the cores, the small oolites have less silica than their matrix (Fig. 3d).

Interpretation

The vast size and lithological uniformity and the loose pisolitic nature of the Weipa bauxite poses considerable problems in interpreting the origin of the bauxite. Most deposits in the world show considerable lateral variations and ore-grade material is patchy (Figs 2, 4, 5).

All published descriptions of Weipa to date conclude that the deposit is of in situ residual origin, an essential feature of the theories being prolonged weathering of the underlying claystone on an exceptionally stable peneplain. Evans (1965) describes a quartz pebble zone at Pera Head, which can be traced up-dip from the clay, through the nodular ironstone, into the bauxite, as evidence for in situ origin. Heavy minerals in the bauxite, bauxite coated bedrock fragments in the nodular ironstone, and relict arkose texture in pisolites indicate derivation from the underlying claystone. Grubb (1971a) considers that bauxitization at Weipa was dominated by static geomorphological and tectonic conditions. Low-lying and gently undulating topography, with a low seaward dip, provided optimum drainage conditions and protected the deposit from planation or physical reconstitution, although he notes some truncation of profiles on the flanks of the synclinal warp at Pera Head and Andoom. Grubb relates the relatively high boehmite content to the less dynamic land surface, which implies a lower leaching rate and more accentuated accumulation of boehmite within the surface horizons. Subterranean drainage through aquifers is postulated, but it is stressed that a completely free drainage system is not enough; partial reprecipitation of sesquioxides (especially aluminium) is essential to produce pisolites and can only be brought about by a slightly fluctuating water table, a feature described by all authors (Evans, 1965; Grubb, 1971a, MacGeehan, 1972) except Loughnan & Bayliss (1961), who considered the zone of fluctuating water table to lie in the zone of iron enrichment, below the bauxite, which they describe as a zone of concretion.

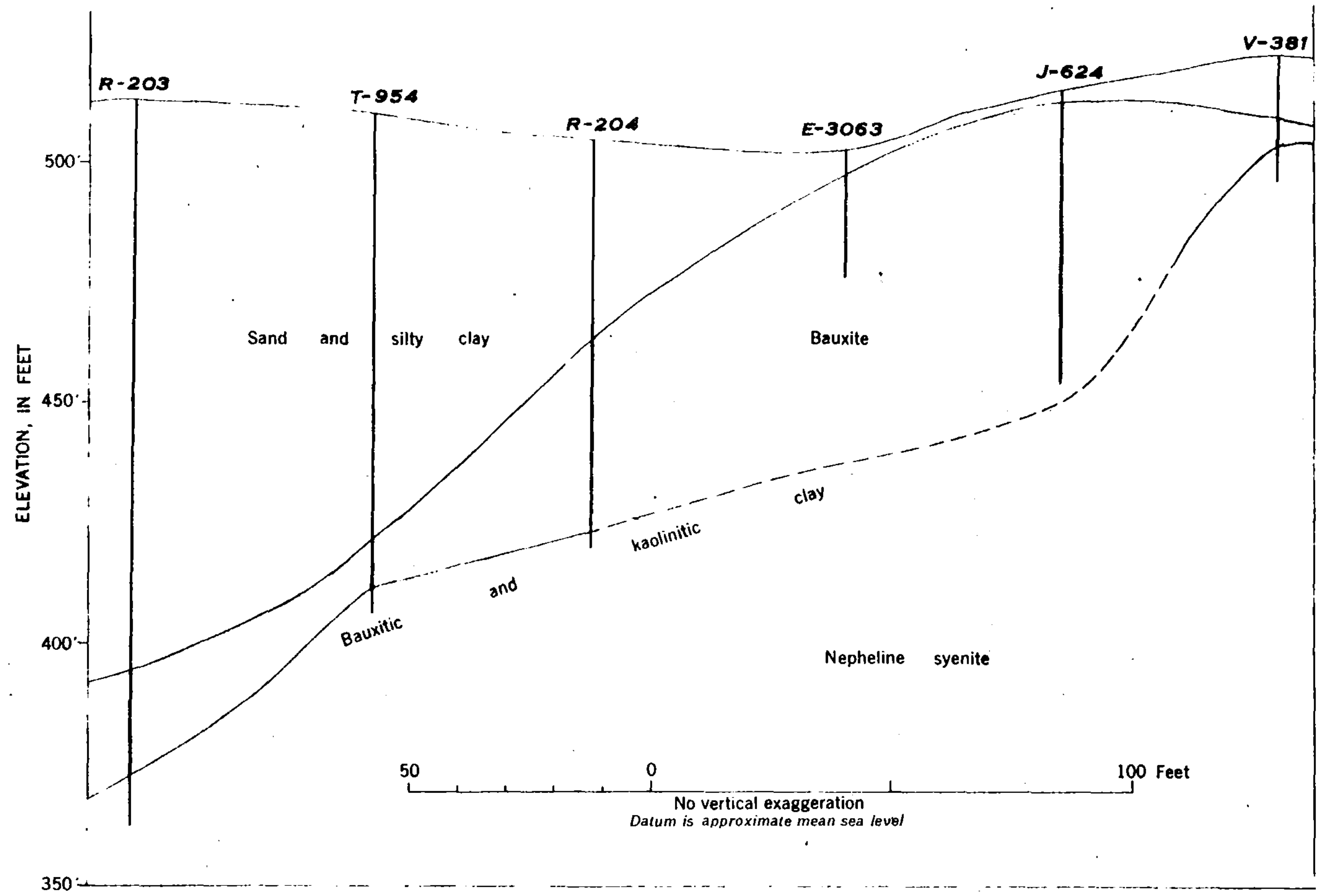
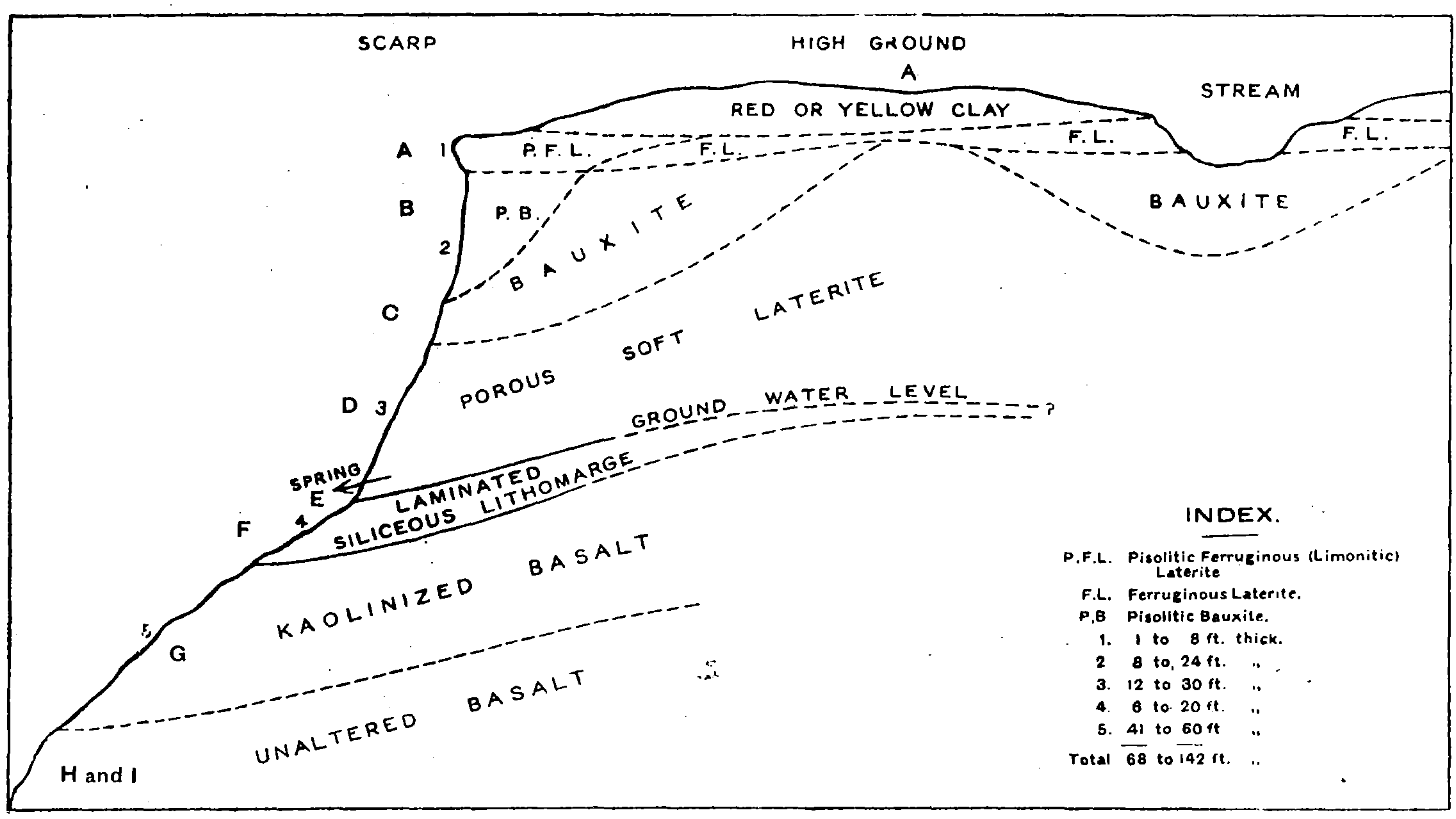


Fig. 4 Cross section showing the steep slope of the bauxite surface in a part of the section 26 mine, Arkansas bauxite region (after Gordon, Tracey, Ellis, 1958)



C. S. Fox.]

Fig. 5 Diagrammatic section of part of a typical Indian laterite plateau with bauxite (after Fox, 1932) 69

Evans' pebble band certainly indicates a residual in situ origin, locally at least. Grubb's and MacGeehan's mineralogical profiles show gradual, progressive vertical variations which are consistent with a residual origin, but cannot, on their own, be conclusive. The paramount problem to these hypotheses is the degree of geomorphological stability postulated; Evans for example postulates prolonged weathering of a peneplain at or just above sea level. Although not stated explicitly in his paper we infer, perhaps incorrectly, that he means that the relative positions of the land surface and sea level have remained approximately constant throughout the major period of bauxite formation and during this time the water table fluctuated seasonally up and down through approximately the same interval of rock which eventually became the pisolitic bauxite - the present day seasonal fluctuation is about 4.5 m (Evans, 1965), a figure of similar order to the ore thickness, but the present upper seasonal level is 2-3 m below the top of the ore. Evans postulates a late fall in water table level as responsible for the loose matrix and boehmite enrichment.

The bauxite is a fossil bauxite (MacGeehan, 1972). The present-day climate is not suitable for bauxitization according to the criteria of most authors; Grubb (1970) and Dr Tenyakov (pers. comm.), for example, both stress very high rainfall, high temperatures, rapid drainage, and dense vegetation. This is not the case today, but relict patches of dense jungle vegetation observed at Andoom indicate a denser vegetation in the past. Grubb (1970) emphasizes that a water table which fluctuates only slightly is necessary for bauxitization. A highly seasonal climate with large fluctuations in water table, the condition existing at Weipa today, will cause supersaturation in iron and kaolinite growth - a ferruginous laterite. Evans (1971) describes recent clay precipitation through the bauxite matrix while our microprobe studies showed iron and silica enrichment in the outermost pisolite shells - observations in agreement with Grubb's (1970) thesis and indicating, together with the vegetation, a different climate during bauxitization. Water table fluctuations will have been quite different, probably much less than the present day, and insufficient to build up the thickness of bauxite as envisaged by Evans (1965).

Although there are no positive data on the time necessary to form a deposit such as Weipa the exceptional uniformity of the deposit suggests great maturity, that is, a very long, steady process which eventually achieves an advanced state of equilibrium - compare the variations in most other deposits around the world (Figs 2, 4, 5) and Gove and Jarrahdale in Australia. There have been substantial eustatic changes in sea level during the Quaternary; the Tertiary was probably similar. Even without tectonic movements the deposits at Weipa will have had quite different elevations relative to sea level in the past; the present sea level may bear no relation to its position at the time of formation of the bauxite.

Grubb (1970) describes a steadily falling water table and optimum drainage as critical to the removal of dissolved silica from bauxite while maintaining (Grubb, 1971a) that geomorphic stability at Weipa provides optimum drainage; these statements are incompatible, but a steadily falling water table could be consistent with the argument just presented concerning very limited seasonal fluctuations in the water table.

Simple mass, volume, and density considerations show that the volume of bauxite now remaining must be much less than that of its parent rock. Even if the Weipa bauxite is less dense than the parent clay there would be some loss of Al_2O_3 during leaching, plus the considerable detrital quartz component. A considerable volume reduction during the bauxitization process seems inescapable, and there must have been a physical and chemical downwasting of the surface which should be accompanied by an absolute fall in water table.

In Grubb's and MacGeehan's profiles titanium only shows gradual changes up the section but there is significant enrichment (2X - 3X) in the bauxite relative to clay, consistent with downwasting. Heavy minerals lack the very sharp discordances which are associated with the unconformities at Gove but there are rather erratic vertical variations which could reflect different beds in the parent rock (Grubb, 1971a) or could also form during downwasting. There is again an enrichment (2X to 3X) in total heavy minerals relative to the clay and Grubb notes a concentration of coarser grained heavy minerals in the bauxite. This could well be caused by sorting on reworking during mechanical downwasting of the bauxite.

The present sea level is of no significance to earlier bauxitization. Its only significance is that it provides a base level to the present-day water table.

Adequate drainage is essential to bauxitization and topographic relief is generally proposed to provide it (Prider, 1966; Maignien, 1966; Grubb, 1970; McFarlane, 1971; Dr Tenyakov, pers. comm.). Cross sections of bauxite deposits (Figs 2, 4, 5) support this. At Weipa, subterranean drainage is envisaged (Grubb, 1971a), largely because of the aquifer beneath Weipa. This aquifer is local to Weipa, however; it is absent beneath Aurukun (Doutch, pers. comm.), and Andoom (Duchatel, pers. comm.) where the bauxite is both thicker and higher grade (less SiO_2). Certainly the poorly lithified parent rock would be permeable initially, but this would be reduced by progressive silicification in the clay zone. It would appear that some other additional factor is essential for adequate drainage at Weipa.

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Thus, although many field observations suggest an in situ residual origin for the bauxites at Weipa the published hypotheses are not completely adequate in their present form.

During our brief field visit Dr Tenyakov (pers. comm.) expressed the tentative opinion that the Weipa bauxite has been transported. He specifically did not exclude later in situ chemical activity (bauxitization) and upgrading of the previously transported pisolitic bauxite.

The principal evidence within the bauxite for transport was the presence of subrounded fragments of highly altered bedrock (significantly found in the cemented pisolitic bauxite, high in the profile, as noted by MacGeehan (1972)), the common occurrence of primary bauxite (which we have shown in the laboratory to be oolitic bauxite) as cores to many of the pisolites, and the presence of broken pisolite fragments.

The nodular ironstone was considered by Dr Tenyakov to be a conglomerate, the closely packed nodules being transported fragments. Their limited rounding indicates limited transport. The stratification shown in Plate 8e was considered to be bedding within the conglomerate and the sharp upper contact noted in Plate 8a was considered to indicate a sharp bedding contact.

Dr Tenyakov considers that in a typical residual bauxite profile the ferruginous zone should overlie the bauxite, which then overlies the clay, if present; the profile at Weipa is therefore reversed. To achieve this he postulates development of a normal in situ laterite profile. During subsequent mechanical erosion the ferruginous cap is eroded first and subsequently deposited at the bottom of the resulting sedimentary layer. The underlying bauxite or clay layers are then exposed to chemical and mechanical erosion, transported, and deposited as a pisolitic sedimentary bauxite overlying the ferruginous bed.

During subsequent discussions Dr Tenyakov indicated that generally, in his experience, in situ growth of pisolites is not common and only occurs under rather special, near surface conditions. He considers that they usually form as a result of combined chemical and mechanical transport of material.

Subsequent analysis and work by us raises many questions about these ideas.

Firstly, the literature abounds with references to in situ growth of pisolites, both in solid rocks (e.g. Gordon et al., 1958; McFarlane, 1971) and 'buckshot gravels' in soils. Secondly, there are many references to ferruginous zones underlying bauxite in residual profiles (e.g. Harden & Bateson, 1963) or ferruginous zones both above and below bauxite (e.g. Fig. 5, this report; Chowdhury, Anandalwar, & Tyagi, 1964; Chowdhury, Venkatesh, & Paul, 1964, 1968) as well as ferruginous zones overlying the bauxite as at Mitchell Plateau and Jarrahdale. There is no typical sequence in a laterite or bauxite profile, a point readily apparent from the variety of profiles described by Magnien (1966).

The closely packed, interlocking fragments within the ironstone (e.g. bottom corners of Plate 8a) do not resemble those in a water-laid conglomerate. Internally the fragments are secondarily ferruginized clay; the material formed in a zone of iron precipitation. We did not see the lower contact of the ironstone which Smart (pers. comm.) has since described as gradational, with downward percolation of iron along joints into the clay below. The upper contact is also gradational in detail (Plate 8d, e); rarely, such as shown in Plate 8a, is the contact sharp.

The nodular ironstone is not a conglomerate. It is a zone of in situ secondary iron enrichment. The stratification observed is probably a relic from the parent rock, although it could possibly be related to old water table levels. At the time of its formation the ironstone would be at the top of the permanent water table; it would be water-saturated. The recent water table fall and climate change would desiccate it, cracking it into irregular, subangular fragments, whose sharp edges would be quickly removed by in situ chemical solution and abrasion. Changing physiochemical conditions with changing climate and falling water table would allow deposition of the outer gibbsite skins.

Harden & Bateson's (1963) concept of residual bauxite formation at the surface by downward leaching of iron and silica from clay, and iron enrichment to produce nodular ironstone at the top of the water table, is applicable to Weipa. Their graph of chemical variations through their profile is very similar to that at Weipa by Evans (1965) and by the present authors from data by Loughnan & Bayliss (1961).

The pisolitic bauxite at Weipa appears, at first, similar to that at Gove. However, the matrix at Weipa is more abundant and composed of small loose oolites. At Gove it is finely fragmented bauxite.

In the pisolitic bauxite at Weipa no stratification or bedding was seen. Detrital fragments of identifiable underlying layers such as the ironstone, or truncated root solution shafts do not occur. The solution shafts can only be related to the present day land surface. The large rock fragments we saw were highly bauxitized oolitic material.

The pisolite types observed are similar to those at Gove - concentric shelled and oolitic cored pisolites. The more uniform compositions at Weipa suggest either late leaching of excess iron from preexisting pisolites or, more likely, uniform physico-chemical conditions during their growth. The ubiquitous outer gibbsite shells, at least in our sample, and shown to be widespread by MacGeehan (1972), indicate definite slight late changes in physico-chemical conditions to produce precipitation of first gibbsite and, later, the boehmite/Fe_2O_3 aggregates.

The internal structures of the concentric shelled pisolites, with cores of older broken pisolites, complex growth histories etc., are classically considered to indicate sedimentary pisolites, although Jones (1965) has described such structures from movement of residual pisolites in a soil profile. We will consider, for the present, that they are consistent with a detrital origin. The syneresis cracks due to desiccation before deposition of the outer gibbsite shells could be consistent with exposure to air, erosion, and transport; this is significant in comparison to the lack of cracks in the oolite cored pisolites.

Illustrations in the literature of pisolites which have inequivocally grown in situ, either in rock (Gordon et al., 1958) or soil (Brewer, 1964), show that the matrix or saprolite of the host and the interior of the pisolite have the same texture and composition. The pisolite is simply a zone of local cementation or concretion, with or without precipitation of a thin outer rind. This is precisely the case in the oolitic cored pisolites at Weipa. The matrix, or saprolite, is made up mainly of small loose oolites and the pisolites, apart from their outer shells, are composed of fine oolitic bauxite. It is consistent with in situ growth of these pisolites.

Thus we have, in the same deposit, relatively large soft (oolitic) pisolites apparently of in situ origin, and smaller dense hard (concentric shelled) pisolites of apparent detrital origin and a source apparently different from their enclosing saprolite. There are scattered broken pisolites (?transported) and large fragments, possibly transported, of oolitic bauxitized bedrock. MacGeehan (1972) describes occasional bedrock fragments which are only partly altered and a quartz rich matrix right at the top of the profile; these latter features are consistent with transport to their present site from elsewhere.

McFarlane (1971) describes two types of pisolitic laterite - spaced pisolitic laterite and packed pisolitic laterite. The spaced pisolites are scattered through an abundant saprolite and have grown in situ within a soil profile. Both soft and hard pisolites occur. The packed pisolites have

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little matrix between them, have a distinct outer cutan, and small hard pisolites predominate. They are considered to be a remanié derived by mechanical downwasting of a spaced pisolitic laterite. She considers a peneplain over a laterite to be the result of lateritization, not the cause. She describes a process whereby an area of moderate relief is downwasted with accompanying lateritization. Spaced pisolitic laterite forms within the soil profile, which is then mechanically reworked as downwasting proceeds to leave a remanié of packed pisolitic laterite. The pisolites in the packed pisolitic laterite undergo a limited degree of both vertical and horizontal transport; McFarlane considers that they are, strictly speaking, detrital. The end result is an upper layer of packed detrital pisolitic laterite grading downwards into a spaced in situ pisolitic laterite, which in turn grades down into weathered rock.

This is precisely the profile described by MacGeehan (1972). The lower part of the bauxite contains mainly oolitic cored (in situ) pisolites separated by matrix. These grade upwards into more closely packed pisolites, with little matrix, dominated by small hard concentric shelled (detrital) pisolites. A slight anomaly is provided by an increase in matrix content and large oolitic cored pisolites in the very upper boehmite zone, with increased quartz in the matrix and partly altered bedrock fragments; these may be related to the overlying Recent soil or overburden layer or, could even be a distinct sedimentary layer. The lateral continuity of this layer is not known.

We have already described evidence, based on chemical volume considerations, for downwasting to produce the Weipa bauxite and McFarlane's concept provides the necessary drainage and approximates closer to the topography generally considered necessary for bauxitization. Grubb (1971a) has postulated some truncation of profiles at Pera Head and Andoom.

Therefore, there seem to be two possible origins for the bauxite at Weipa - (1) a detrital bauxite derived from transport from a distant source, (2) a remanié derived by 'in situ' downwasting, local scarp retreat and local transport of an in situ residual bauxite.

It is simple to imagine a widespread uniform sedimentary bauxite; other uniform sediments - sand, silt, etc. - are common in geology. If bauxite had developed on the higher slopes to the east, but only in situ ferruginization and clay had occurred in the lower saturated environment to the west, the bauxite could be later stripped by erosion and deposited on the lower flats, followed by subsequent in situ leaching and modification. Analogy with Gove shows that the original bauxite would be pisolitic and transport would be mainly mechanical. This could readily explain the connection between bauxite and the observed regional break in slope.

Why though is the bauxite only deposited on top of Bulimba Formation? Dr Tenyakov stresses that for detrital bauxites he only envisages local transport, 5 km at the most. The process proposed here would require transport from areas beyond the present limit of bauxite, that is, 30 km away. The soft pisolites could not stand transport of this magnitude and incorporation of rock fragments from other sources would be expected.

Proposed origin: Initially, moderately lithified clays, sandy clays, and sands were exposed in an area of moderate relief with a tropical climate - high, partly seasonal rainfall and dense vegetation cover. The vegetation cover protected the area from extreme mechanical erosion so that under the effect of a hot, wet climate chemical weathering and leaching was favoured. Permeable sediments promoted downward leaching above the water table and reducing conditions under the dense vegetation cover favoured retention of alumina and removal of iron and silica. In the lower zone of small seasonal water table fluctuation, straight leaching prevailed, producing a residium of loose alumina-rich soil made up largely of fine oolites; reprecipitation of alumina in the upper zone of water table fluctuation during seasonal water table fall led to growth of oolite-cored pisolites within the loose saprolite. The iron being carried downwards in solution was reprecipitated at the top of the zone of permanent saturation, a boundary layer between zones of differing physico-chemical conditions, while the silica was either reprecipitated lower down in the zone of permanent saturation or removed from the system.

Under the intense weathering conditions prevailing, the land surface was slowly eroded, both chemically and mechanically, accompanied by a gradual absolute lowering of water table level. Both the zone of leaching and iron enrichment followed the water table down. The upper levels of the profile underwent erosion and physical reworking; the fine matrix and softer pisolites were removed from the system while the harder pisolites were redeposited as a remanié, undergoing complex fracturing and regrowth in the process. As the relief was reduced by downwasting and scarp retreat, the rate of leaching and bauxitization decreased with the reduced drainage. Climate changes also contributed to the end of the process. The result was one of extreme maturity and equilibrium with the present low-lying peneplain of almost no relief and the water table and erosion base level controlled by sea level (we consider that the major present-day drainage was most probably incised into the preexisting bauxite surface owing to a fall in sea level, subsequent sea level rise has in turn flooded it in the main estuaries). The bauxite deposit is a fossil bauxite and intensive bauxitization has now ceased (Evans (1965) shows it still continuing to a small degree). Decline in vegetation cover has produced an oxidizing environment in the soil profile.

The ubiquitous yellow gibbsite cutans around pisolites may reflect ancient changes in the water table owing to climate or sea level changes, but their universal development can be more easily explained as the last shells deposited, at the very top of the zone of seasonal water table fluctuation, during the progressive downward retreat of the water table accompanying downwasting and the latest climate changes. The zone of gibbsite precipitation has now moved right down to the nodular ironstone although the ironstone is still stable in the present climate. MacGeehan (1972) postulates uplift to deposit the outermost pisolite skin of boehmite/Fe_2O_3 admixture in an oxidizing environment above water level; this can also be explained by the change to the present-day highly seasonal and drier climate and decline in vegetation cover. These changes have also caused precipitation of kaolinite within the matrix and in the outermost pisolite skins and the formation of the very thin ferruginous hardcap (Plate 7h).

This mechanism provides a simple explanation for the features of the bauxite deposit as parts of a single progressive one-way process. The critical factor is the operation of an exceptionally closely controlled set of climatic and geomorphic conditions over a long period; this applies to any origin postulated - in situ weathering, sedimentary, or in situ weathering and downwasting.

The parent rock was favourable over a wide area for bauxitization. Relief was just sufficient to produce optimum drainage without excessive erosion. The situation on a stable high in the Carpentaria Basin allowed a long period of weathering while the situation within a low, on this high, allowed any material which was eroded to be redeposited locally. Downwasting and redeposition of detritus, bauxitization, and fall in water table were able to proceed together, at mutually satisfactory rates to build up a thickness of bauxite without losing reworked material from the system.

This combination of factors was apparently unique to the flanks of the young Carpentaria Basin; areas elsewhere in north Australia seem to have had more dynamic geomorphic histories.

JARRAHDALE

Development

The presence of alumina-rich laterite in the Darling Ranges has been known for many years; Owen (1954) notes analyses with 44.6 percent total Al_2O_3 by Simpson (1902) and up to 50.68 percent total Al_2O_3 by Matheson (1942). Owen (1954) records only sporadic exploration and sampling.

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In 1957 Western Mining Corporation Ltd began prospecting the known deposits and were joined in 1958 by Broken Hill South Ltd and North Broken Hill Ltd to form Western Aluminium No Liability. After the economic feasability of the deposits had been established the Aluminium Company of America (ALCOA) joined Western Aluminium to form ALCOA of Australia Pty Ltd in 1961 and commercial mining at Jarrahdale began in 1963.

Indicated reserves at Jarrahdale are about 500 million tonnes of ore ranging from 30 - 45 percent total Al_2O_3. Recoverable Al_2O_3 is about 30 percent. A feature of the Jarrahdale deposits is their very high silica content but this is all present as free quartz and does not hinder treatment. Analyses by Grubb (1971b) show from 5 - 20 percent SiO_2 and almost no kaolinite, while total goethite/hematite ranges from 20 - 50 percent.

Many other companies are prospecting throughout the Darling Ranges and the additional total indicated reserves for the remainder of the region total some 1000 million tonnes.

Previous investigations

Although there have been frequent early reference to laterites and bauxites on the Darling Ranges those most relevent to this report have been made in the last decade. Tomich (1964) described the general geological features of the Darling Range bauxites. He regarded them all as in situ residual deposits and related the occurrence of bauxite to present day rainfall isohyets. Prider (1966), in reviewing the laterites of Western Australia, described several examples of bedrock features preserved in overlying laterites and considered that all the laterites of the Darlings Ranges were of in situ residual origin. He assigned a Pliocene age, after the epeirogenic uplift of the Western Australian Shield, to the lateritization. Mulcahy (1967) recognized a belt of detrital laterites in southwestern Australia confined almost entirely to the Darling Ranges, within which only small residuals of in situ laterite have been preserved; he suggests a Pleistocene age for the younger laterites and reworking, and these are antedated by an older laterite.

Grubb (1966) carried out detailed mineralogical studies on two in situ residual profiles at Jarrahdale and considered that bauxitization took place at the same time as the slow epeirogenic uplift (?Miocene) in the region. In a later study (Grubb, 1971b) he found many sections of reworked bauxite and concluded that the Jarrahdale deposits contained both in situ and detrital bauxites. Significant amounts of corundum were recorded for the first time and from heavy mineral characteristics and the high detrital quartz content he concluded that a significant part of the bauxite has been derived from sedimentary rocks, presumed to be Cretaceous, rather than the underlying granite-gneiss complex. Baker (1971, 1972) noted considerable control of bauxite distribution by bedrock types and concluded that the bauxite was an in situ residual deposit. Both Grubb and Baker assigned a Tertiary age to the deposits.

Regional setting

The deposits occur on the slopes of the Darling Scarp, to the east of the Darling Fault. The bedrock east of the fault, and beneath the bauxites, consists of Archaean granites, gneisses, migmatites and metasediments of the Yilgarn Block. West of the fault is the thick Permian to Recent sedimentary succession ($>$10 000 m) of the Perth Basin. The Perth Basin is now a low-lying area, much of which is covered by alluvium. The thickest sediments were deposited during the Permian - Cretaceous but more than 300 m of marine Tertiary are known.

The Darling Scarp is the hinge of a late Tertiary uplift which affected all of the interior to the east. The uplift is considered to postdate the Eocene Plantagenet Beds of the Norseman area to the east, and a Miocene age is commonly mentioned. The Plantagenet Beds, and other Eocene units in Western Australia, are lateritized (Prider, 1966) so a late Tertiary age is likely for the Darling Range bauxites.

Tomich (1964) describes laterite over a vertical range between 60 m above sea level, at the foot of the Darling Scarp, to 560 m near the top of the Darling Range. Bauxite is only found between 180-540 m and does not occur higher than 45 m below the range summits. Baker (1971) restricts the bauxite to elevations between 240-480 m.

Field observations

Only one of the present authors (V.A.G.) visited Jarrahdale.

G.F.U. Baker (pers. comm.) described the orebodies as discontinuous lenses generally occurring on the slopes of the partly dissected Darling Ranges. The bauxite lenses thin both towards the plateau surface and on reaching the valley floor, and are surrounded by ferruginous laterite. The orebodies average about 4.2 m thick and have a very sharp base where they overlie partially kaolinized bedrock. The bedrock is granite, gneiss, migmatites, and metasediments, intruded by dolerite dykes. The bauxite consists mainly of gibbsite with variable amounts of iron oxides and quartz. The ore is both pisolitic and fragmental. Baker (1972) referred to lateritized laminated shale fragments within the bauxite.

Published descriptions (Tomich 1964; Grubb 1966, 1971b) describe an almost universal, generally ferruginous, pisolitic hardcap up to 1 m thick overlying loose coarser grained pisolitic and nodular bauxite. Grubb (1971b) recognizes both in situ and reworked profiles. The in situ profiles have a fine pisolitic hardcap overlying a coarser loose pisolitic and nodular zone, increasing in grainsize downwards, and in turn overlying sandy clays and clayey sand. Free quartz is a significant component (up to 20% in the ore), but decreases rapidly up section, and numerous pockets of fine sand are scattered through the ore. Goethite is the iron mineral through most of the profile, but in the hardcap, where there is iron enrichment, the goethite is replaced by hematite and maghemite. Corundum also appears in the hardcap, associated with the hematite. Within the reworked profiles, which occur at lower elevations, the upper fine layers are missing, much of the ore takes on a brecciated appearance, and there is a general iron enrichment throughout the section. Hematite appears in the hardcap, but not to the same extent as in the in situ profiles, and quartz contents are lower. No corundum has been found. The heavy minerals in the gneissic granite bedrock consist of fine unabraded zircon and rutile. The bauxite profiles, however, contain coarser, well abraded, rutile, zircon, ilmenite, tourmaline, leucoxene, monazite, zoisite, and magnetite. Baker (1971, 1972) describes chemical and physical variations within the bauxite which reflects the structure and distributions of the immediately underlying bedrock.

Interpretation

Dr Tenyakov (pers. comm.) commented that the fragmental nature of the bauxite, its occurrence as isolated lenses on the fairly steep valley slopes, and its position overlying a quartz-rich bedrock with a sharp discontinuity, all suggested that the bauxite had been locally transported. He considered that the bauxitized laminated shale recently discovered by Baker could be the major source of the bauxite; the local weathered dolerite dykes are also a rich source of alumina. Dr Tenyakov considers that bauxites form from basic or intermediate igneous rocks or from aluminous sedimentary rocks, but never from granites because of the excessive amounts of free quartz. He suggested that, at this locality, the period of bauxitization had preceded the period of widespread ferruginization.

Baker (1971) considers the bauxite to be an in situ residual deposit while Grubb (1971b) considers both in situ and detrital material to be present. Baker (1971) considers that the ore is derived directly from the underlying granite, gneiss, metasediment bedrock while Grubb (1971b) considers, from the heavy mineral evidence, that the source rock had a significant clastic component, although the granite gneiss was still, nevertheless, a major source of alumina. He suggests that bauxitization was confined to a coarse feldspathic or arkosic sedimentary mantle directly overlying the granite gneiss basement. He suggests the existence of Cretaceous fluviatile sediments prior to uplift of the Darling Scarp. Grubb considers that the greater part of the bauxitization evidently took place between the late Cretaceous and Miocene, with prolonged, spasmodic uplift of the block providing ideal conditions for leaching. He notes, however, significant post-Miocene physical reworking of the deposits. He considers that during dehydration of goethite to hematite to form the hardcap in residual profiles Al is released from the goethite lattice to form corundum; equivalent zones in the reworked profiles contain diaspore because of their more hydrous environment.

We agree with Grubb's interpretation that both in situ residual and reworked profiles are present at Jarrahdale, without being able to comment on the relative proportion of each. From our regional geological considerations it would appear that the age of bauxitization can be restricted to post-Eocene, and the overall sequence of events is probably that described by Mulcahy (1967).

The late stage surface ferruginization to form a hardcap, as observed in the other deposits, Mitchell Plateau and to a much less degree Gove and Weipa, is significant and could, once again, reflect a post-bauxitization climate change. The more intense development at Jarrahdale and Mitchell Plateau can apparently be directly related to the greater topographic relief there; at Jarrahdale there are even more variations due to local topography. The high content of free quartz at Jarrahdale requires explanation; normally under optimum conditions of bauxitization silica is removed. Both Gove and Weipa had significant amounts of free quartz in the source rocks from which they were derived although Jarrahdale could have had more. Bauzitixitization may have been more rapid and less complete at Jarrahdale - the Al_2O_3 content is lower and relatively coarse-grained free quartz would be more resistant to chemical attack.

MOSS VALE DISTRICT

Three localities were briefly visited in this district - Wingello (about 1.5 km south from Wingello railway station); Sutton Forest (only one hill-top outcrop nearest the Hume Highway was visited); and one quarry in the Ellesmore Group of deposits. Small amounts have been produced at times for various purposes - flux in steel furnaces, road surfacing, and manufacture of aluminium chemicals. The deposits are described by Owen (1954). Only one of us (V.A.G.) visited the deposit and no subsequent work has been carried out.

The bedrock to the deposits is flat-lying mid-Tertiary basalt and some early Tertiary lacustrine sediments. The area has the generally subdued rolling topography typical of the Southern Tablelands with total relief of about 180 m. The laterite and volcanics are preserved as erosional remnants on hilltops. It is considered that lateritization commenced soon after volcanism; a Miocene age is commonly suggested. The reserves are small and the material rather ferruginous. The content of the bauxite given by Owen falls in the range of:

Al_2O_3	Fe_2O_3	SiO_2
27-42%	40-25%	2-7%

The general sequence seen at Wingello had a reddish-brown surface soil about 20 cm thick containing rare scattered pisolites overlying a zone of loose pisolites with a sharp contact parallel to the present surface. The second layer of variable thickness (0.5-3.0 m thick) overlies fine grained tubular bauxite with an irregular but clearly defined boundary. The tubular bauxite is at least 1 m thick.

Only the uppermost 5 m of the Sutton Forest deposit could be inspected. It consisted of a partly cemented pisolitic bauxite with rare scattered pieces and blocks of tubular bauxite and fine-grained bauxite containing some indistinct pisolite outlines. Some pisolites in this deposit contained small fragments of bauxitized (?)basalt.

The material in the Ellesmore quarry is also pisolitic. Among the cores of large pisolites or fragments were found bauxitized basalt or intermediate igneous rock and possibly shale or bedded claystone.

Dr Tenyakov (pers. comm.) suggested that local transportation and reworking of bauxite sequences during the Tertiary was the best explanation for the above observations. The variety of fragments and similarity to the other deposits such as Gove is consistent with such an interpretation.

DISCUSSION

COMPARISON BETWEEN DEPOSITS

Age

The deposits are all fossil bauxites; present-day climates in Australia are not suitable for bauxitization. The period of main bauxitization in all cases appears to be middle to late Tertiary, although the evidence for the Mitchell Plateau bauxite is circumstantial and not conclusive. All deposits have suffered post-Tertiary modification due to changes in climate and topography. Weipa may have commenced forming earlier and/or continued later than the other deposits. It is possible that all the deposits formed during a single Australia-wide period of bauxitization, but it is more likely that the process started and finished at different times in different areas.

The absolute limits to major bauxitization in the individual deposits are:-

GOVE: Post Lower Cretaceous; Pre-Quaternary. Probably middle to late Tertiary and no younger than Miocene.

MITCHELL PLATEAU: Post 1800 m.y. Probably similar age to Gove.

WEIPA: Post Upper Cretaceous or Lower Tertiary. Possibly throughout Tertiary. Probably finished during Quaternary.

JARRAHDALE: Post Eocene; Pre-Quaternary. (?) Miocene commonly suggested.

MOSS VALE: Post Mid-Tertiary. (?)Miocene commonly suggested.

Parent rocks

Dr Tenyakov (pers. comm.) considers that bauxites form from basic or intermediate igneous rocks or from aluminous sedimentary rocks but never from granites. Granites contain excessive free quartz; combined silica in silicate minerals is apparently much more readily dissolved and leached during weathering.

These preferred parent rocks apply quite well in Australia, as follows:

Cretaceous argillaceous sediments: Gove, Weipa, (?)Marchinbar Island, Cobourg Peninsula.

Basalts: Mitchell Plateau, Moss Vale, Couchman Range.

Probable Cretaceous arkose and Precambrian granite gneiss: Jarrahdale.

The ore deposit which does possess a considerable granite component in its parent rock, Jarrahdale, has the highest silica content (as free quartz).

The Cretaceous Bulimba Formation at Weipa and Mullaman Beds at Gove both contain considerable detrital quartz. It is curious that the bauxites are so silica deficient compared to Jarrahdale, although Weipa bauxite still is relatively high (10% SiO_2). Perhaps they are more mature and the silica is more effectively leached. These Cretaceous rocks are characterized by rapid facies changes. The Works Department bore at Gove shows thick clay immediately beneath the bauxite (Grubb, 1970) and the Foundation Bore cuttings we examined at Weipa showed very clayey beds beneath the bauxite. Both deposits may have developed above local clay-rich facies of their respective formations and this could be a critical factor in the specific localization of the bauxite.

Quite apart from their suitable content of clay there is a simple reason for the association between bauxites and Cretaceous rocks in North Australia - at the time of lateritization Cretaceous rocks formed a widespread blanket over most of the older rocks; commonly the only other rocks exposed were ridges of resistant rocks unsuitable for deep weathering. There is a ubiquitous association between exposures of Cretaceous rocks and deep laterite profiles.

Origins of the deposits

Past descriptions of Australian bauxite deposits have ascribed residual in situ origins to them. The stimulus of Dr Tenyakov's visit and Grubb's papers (1970, 1971a, 1971b) have brought an awareness of the importance of physical and chemical reworking in producing the deposits as we see them today. This fits well with the abundant observations of detrital ferruginous laterites by BMR field parties in northern Australia over the last two decades. It is indeed difficult to find full in situ laterite profiles preserved; many are truncated. We now have a full spectrum of bauxite deposits from those which are of essentially residual origin (Weipa), through those with relics of in situ bauxite amongst abundant detrital bauxite (Gove, Jarrahdale), to intensively reworked deposits in which no in situ material remains (Mitchell Plateau). These results concur with the findings of Bushinsky (1964) that most of the world's alumina is produced from sedimentary bauxites.

Weipa is the result of an extremely unusual combination of factors, perhaps unique to its position on the flank of the young, stable Carpentaria Basin; these factors are:

(1) a suitable, permeable, clay-rich parent rock,

(2) structural position within the basin - a stable high allowing a long period of weathering, but within a shallow depression on this high, preventing excessive erosion,

(3) sufficient relief for optimum drainage without excessive erosion,

(4) an ideal balance between rates of bauxitization, downwasting and deposition, and fall in water table level,

(5) a long, steady history leading to an advanced stage of equilibrium over a wide area.

Grubb (1970, 1971b) shows that the remnant residual profiles at Gove and Jarrahdale develop similar characteristics to the Weipa profiles, but have not reached the same stage of maturity, a result of their more dynamic geomorphology.

Dr Tenyakov (pers. comm.) stressed that the distance of transport involved in sedimentary bauxite is quite small, generally less than 5 km; this is certainly consistant with observations in Australia, namely the proximity of the residual and detrital bauxites at Gove and Jarrahdale and the form of the transported fragments. There will be overlap of the amounts of transport involved at Gove, for example, and the amounts of transport which could be involved in downwasting at Weipa; this accounts for the similarity in many of the features observed. McFarlane (1971) notes that her packed pisolites should really be considered to be detrital because they are now in a different position from that of their initial formation. The distinction between residual and detrital bauxite may be somewhat arbitrary and academic.

A feature common to all deposits is the internal fabric of primary transported fragments - fine-grained oolites. The oolites are generally white, enriched in alumina and deficient in iron and clay, and less than 0.5 mm (mostly less than 0.25 mm) in diameter. Concentric shell development in the oolites is poorly developed, generally no more than one or two shells, and commonly absent. This texture is the typical first product of in situ bauxitization. Iron and silica is leached out and alumina rapidly reprecipitates under the influence of some type of ionic or molecular attraction into fine concretions. Development of large pisolites requires a different process.

The variations between the various detrital bauxites can be simply related to the differing geomorphic histories of the deposits, different modes of transport, and differing environments of deposition. The individual deposits have been discussed and will be simply summarized here:

(1) Deposits in water. Lakes, swamps, etc. Combination of mechanical and chemical transport and deposition. Dense matrix, variable fabric - breccia, conglomerate, pisolitic framework; dense colloidal, oolitic, fragmentary matrix.

Examples: Gove - clayey-ferruginous conglomerate, tubular bauxite.

Mitchell Plateau - all deposits.

Jarrahdale - (?)lithified breccias.

(2) Slope-wash material. Chemical deposition dominant. Slurry of fine bauxite fragments in colloidal gel. Precipitation from percolating seasonal solutions builds up deposits of cemented pisolitic bauxite.

Example: Gove, (?)Jarrahdale (may be a secondary hardcap).

(3) Mechanical erosion of pisolitic bauxite. Redeposited as loose pisolitic bauxite with no precipitation of cement. Source rock may be either pisolitic residual bauxite or cemented pisolitic bauxite.

Example: Gove - loose pisolitic bauxite.

Dr Tenyakov (Appendix 1) mentions that freshwater continental deposits of bauxite are generally red while lagoonal-marine deposits are grey-green. Freshwater continental deposits are consistent with Gove and Jarrahdale. Mitchell Plateau (white) could be either. The deposits are very close to their source. Truncation of root hollows at Gove indicates surface exposure and tree growth on various beds. It could be expected that marine deposits would be interbedded with other sediments as well.

All the deposits described show late-stage surface features of varying degree - hardcap formation, ferruginization and silicification, boehmite and hematite development - which can be ascribed to climatic changes since bauxitization. They reflect a drier, more seasonal climate ('monsoonal').

CONTROLS FOR BAUXITIZATION

There is overall agreement between most authors on the conditions necessary for the formation of residual bauxite. The combined viewpoints of Gordon et al., (1958), Grubb (1963, 1970, 1971a) and Dr Tenyakov (pers. comm.) can be grouped into the following features:

(1) Warm, humid climate

(2) Dense vegetation

(3) Suitable parent rock

(4) Elevated position with good drainage

(5) Weathering above a steadily falling water table

(6) Protection from planation.

How do these apply to Australia?

(1) Climate. Dr. Tenyakov quotes 3000-4000 mm annual rainfall and a temperature of 28°-32°C. Gordon et al. mention the importance of continuous moisture, while Grubb stresses the undesirability of large seasonal fluctuations in climate. Large seasonal fluctuations with alternating wetting and drying out, as is common in tropical Australia today, favour formation of ferruginous laterite.

The conditions stipulated do not apply to anywhere in Australia today. The bauxites themselves show evidence of climatic changes and there are relics at Weipa and Gove (Grubb, 1970) of old tropical vegetation. The deposits are all near the coast, which would be more likely to have had the appropriate climate in the past.

(2) Vegetation. Grubb (1970) considers that dense forest or jungle cover provides the greatest moisture capture capacity, maintains a high humidity, inhibits direct rain-splash, and reduces vertical corrosion in favour of uniform slope wash and percolation through the profile. Peterson (1971) and Dr Tenyakov (pers. comm.) suggest also that the organic matter provides the proper Eh-pH conditions for alumina enrichment. Grubb (1970) and Maignien (1966) note that ferruginous laterite forms beneath sparse vegetation.

These conditions no longer apply to Australia's fossil bauxites but there are remnants of pre-existing dense vegetation at Weipa and Gove.

(3) Parent rock. This has been discussed. Note should be taken, however, that Grubb in all his publications stresses the importance of permeability, as well as composition, to provide adequate subterranean drainage.

(4) Topography. Gordon et al. (1958), Grubb (1963), Maignien (1966), and Dr Tenyakov (pers. comm.) all note that an elevated, well drained position is essential to provide the extreme leaching required to produce bauxite instead of laterite.

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In Australia this criteria is certainly satisfied at Jarrahdale. It cannot be assessed at Mitchell Plateau because of the degree of subsequent erosion and reworking. Gove, and also Cobourg Peninsula, are both notable for their relief compared to the general laterite surface developed on Cretaceous rocks in the Northern Territory. Weipa is, of course, the exception with its present-day low relief. It could have had more relief at the time of bauxitization, subterranean permeability may have provided adequate drainage (Grubb, 1971a), and the deposit could simply be the result of slow, steady leaching over an unusually long period.

(5) Water table. There is full agreement that bauxite only forms above the permanent water table. Grubb (1963, 1970) stresses that only minor seasonal fluctuations in water table level can occur. A steadily falling water table is needed to accompany downwasting of the land surface and allow optimum conditions of bauxitization through the thickest possible section.

(6) Protection from planation. Grubb (1970, 1971a) stresses, as a more important topographic control, protection from planation and excessive erosion to allow a long period of bauxitization and preservation of residual bauxite. An obvious corollary to this is that where erosion does occur a suitable depression, free from further erosion, should be present for accumulation of the resulting detrital bauxite.

In Australia the obvious example of protection from planation is Weipa, while the Admiralty Gulf Syncline appears to have provided ideal conditions for accumulation of the detrital Mitchell Plateau deposit.

SIGNIFICANCE OF REWORKING

Under the optimum conditions of bauxitization - high rainfall and moderate relief - erosion can be expected to be quite high despite the equalizing effect of dense vegetation cover. It is for this simple reason that reworked bauxites are so common; it is in fact surprising that residual bauxites are preserved at all.

Grubb, in a personal communication (1972), realizes that some degree of creep or downwasting is common in residual bauxite deposits (as in Grubb, 1963) but explains that this is a long-drawn-out process whereas his concept of detrital bauxites is of horizons produced over a shorter period by more intense physical agencies. These agencies, described in Grubb (1970), are the result of eustatic changes in sea level and marine action - submergence, production of marine terraces etc.

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We would add another process, that of erosion taking place concurrently with bauxitization.

We see no evidence for marine action at Gove or Mitchell Plateau; in fact we have concluded that the deposits are freshwater continental deposits. Eustatic changes in sea level, warping etc., could easily have contributed to the history of the deposits in view of Hays' (1967) geomorphic history of the region, but marine submergence is unnecessary.

Probably erosion concurrent with bauxitization would be dominated by chemical transport, slope wash etc., and form deposits such as the cemented pisolites because of the protective action of the vegetation cover. Eustatic uplift, sparse vegetation, and highly seasonal climates would produce more intense mechanical erosion and deposits such as conglomerates, breccias, etc. The range of deposits suggest both processes must operate and overlap each other.

Reworking under the right physical and chemical conditions can provide an excellent opportunity for further chemical and mechanical sorting of bauxitic material to upgrade a deposit. Silica would be readily removed. Groundwater studies at Yirrkala by Grubb (1970) show very selective precipitation of alumina. The wrong conditions, on the other hand, could reverse the process.

RELEVANCE TO PROSPECTING

What guides can this study give to aid prospecting for further deposits? Many of the conditions for bauxitization are not directly relevant because our deposits are fossil bauxites. Briefly the principal clues are:

(1) Palaeoclimate

(2) Parent rock

(3) Topography

(4) Vegetation.

(1) Palaeoclimate. We know little about Tertiary climates in Australia, but it is likely that the most humid areas were near the coast, just as they are today. This is borne out by the distribution of the deposits known to date. Tertiary marine transgressions have been demonstrated over wide areas of Australia and suitable climates could have existed far inland from the present coastline, but present-day near-coastal regions must provide the primary targets.

(2) Parent rock. Basic and intermediate igneous rocks and permeable aluminous sedimentary rocks. Acid igneous rocks and sedimentary rocks with a high quartz content, although they can produce bauxite, are not good targets.

(3) Topography. Despite the enigma of Weipa, preference should be given to areas of moderate elevation and relief of the surface of deep weathering. Having located such areas special attention should then be given to depressions on this elevated surface, rather than peaks, because of the probability of accumulations of detrital bauxite.

(4) Vegetation. The vegetation present at the time of bauxitization is now gone and of no help, but the present-day vegetation developed over the bauxites, because of the special soils developed, provides perhaps the most valuable guide available to local identification of bauxites during the reconnaissance stage of prospecting.

All the bauxite deposits visited have a specific vegetation development, each deposit unique to itself and unusual within the broad pattern of north Australian vegetation. The types observed, in simple terms, are:

Weipa. Open moderately tall eucalypt forest, no undergrowth, good grass.

Gove. Open moderately tall eucalypt forest, abundant 'sand palm' undergrowth.

Marchinbar Island. Dense jungle.

Mitchell Plateau. Stunted eucalypts and abundant, unusually tall (up to 3m) 'sand palms'.

Couchman Range (Kimberley). (Observed by author 1965) Open eucalypt forest, very little grass or undergrowth.

Jarrahdale. Tomich (1964) records a distinctive rain forest, mostly lofty jarrah eucalypt.

In all cases the vegetation produces distinctive patterns on aerial photographs, even within areas of more widespread ferruginous laterite surrounding them.

RECOMMENDATIONS FOR FURTHER STUDIES

This review has raised more questions than it has solved. Many avenues of investigation still await study, particularly in the field.

Most data accumulated to date have been concerned simply with economic assessment of the deposits, sampling generally being provided by auger cuttings. Natural exposures of laterite and bauxite are generally notoriously difficult to study. It is only now that artificial exposures are being provided by mining that critical structures and relationships can be observed and mapped, and a full three-dimensional picture of the deposits built up. Long-term programs, involving many years of periodic mapping of faces as quarrying proceeds, either by company or government personnel, will be most valuable.

Weipa. Problems of the regional setting of Weipa have already been outlined. Extension of the profile descriptions of MacGeehan (1972) will be valuable. Careful statistical and textural studies of numerous profiles should provide a test of the hypotheses outlined in this review. Useful features would be: (i) vertical variations in the quantity and nature of the matrix; (ii) descriptions of pisolite types; and (iii) statistical variations in pisolite types through vertical profiles. Rapid techniques could be developed for pisolite study - e.g., rough polishing of araldite-mounted specimens; thin sections are not necessary.

Gove and Jarrahdale. The range of bauxite types makes these deposits very useful as models of bauxite processes. Three-dimensional mapping of the bauxite rock types should provide models from which the weathering, erosional, and depositional histories of the deposits can be built up. The mapping can be combined with petrographic and statistical comparisons of pisolite types, detrital fragments, and other possible indications of environment. Useful preliminary cross-sections could probably be constructed now from existing drill-hole data (based on simple descriptions such as loose pisolites, cemented pisolites, tubular bauxite) without immediate identification of profiles as residual or detrital.

CONCLUSIONS

1. Australian bauxite deposits show a full spectrum of origins from essentially residual (Weipa), through those with relics of residual in situ bauxite preserved amongst abundant detrital bauxite (Gove, Jarrahdale), to intensively reworked sedimentary bauxites in which no residual in situ material remains (Mitchell Plateau).

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2. All the deposits are of approximately similar age - middle to late Tertiary - but may differ in detail. Weipa probably formed over a longer time-span than the other deposits.

3. Variations within the detrital bauxites reflect their environments of deposition or local geomorphic and climatic histories.

4. Weipa is the result of an exceptional combination of factors, perhaps unique to its position on the flank of the young Carpentaria Basin, and a similar deposit may not be present anywhere else. It has formed by in situ weathering or bauxitization, combined with downwasting and local redeposition of the upper layers. The critical factors in its formation and preservation are (1) permeable clay-rich parent rock; (2) structural position - a shallow depression on a stable high; (3) suitable relief for optimum drainage without excessive erosion; and (4) an ideal balance between rates of bauxitization, downwasting, deposition, and fall in water table; (5) a long period of bauxitization leading to an advanced state of equilibrium.

5. Under optimum conditions of bauxitization - high rainfall and moderate relief - erosion of the bauxite and redeposition as detrital bauxite is almost inevitable. Erosion will be accentuated by decreased vegetation cover due to climate changes or uplift, both of which have occurred in most bauxitized areas in Australia.

6. All Australian deposits were modified during Quaternary changes in climate; the climate became drier and more seasonal than during bauxitization.

7. The best guides to prospecting for bauxite within areas of widespread laterites are (1) proximity to the coast; (2) suitable parent rocks - intermediate to basic igneous rocks or permeable aluminous sediments; (3) moderate elevation and relief within the lateritized surface; and (4) strikingly different vegetation and air-photo pattern in areas of widespread thick laterites.

8. Now that the deposits are being exposed by mining, further studies of the geology and origins of the deposits will be greatly facilitated and valuable.

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APPENDIX 1

RUSSIAN CLASSIFICATION OF BAUXITES

(Precis of talk by Dr V.A. Tenyakov)

The present classification is based on that of N.M. Strakhov, A.V. Peive, and N.A. Shtrace (1947). The classification developed in the USSR because Russia has the widest variety of types, despite a relative scarcity of major economic deposits.

The classification is based on the tectonic positions of the deposits, rather than on their origin (e.g., in the Urals there are Mesozoic platform bauxites overlying Devonian geosynclinal bauxites). The important point is, however, that the various environments have specific sequences associated with the bauxites.

In platform regions, where the source of transported bauxites can be identified, the maximum distance of transport is 5 km; the average is only 1.5-2 km.

In geosynclinal environments no source has been recognized for transported bauxites. The bauxite occurs on a karst surface above clean limestone, and is overlain by more clean limestone. The French first identified geosynclinal bauxites in 1880.

Over the years a whole series of research workers have tried, generally unsuccessfully, to recognize an origin of bauxite by means other than weathering and lateritization. The main group has followed the idea that the alumina is precipitated from hydrothermal solutions by some sort of geothermal introduction into basins such as along fault-zones, fluids from volcanic cones, etc.

CLASSIFICATION

1. BAUXITES FOUND IN GEOSYNCLINAL REGIONS
   (a) Bauxites formed by in situ weathering
   (b) Sedimentary (transported) bauxites.

2. BAUXITES FOUND IN PLATFORM REGIONS
   (a) Bauxites formed by in situ weathering
   (b) Sedimentary (transported) bauxites.

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DESCRIPTION OF TYPES

1. BAUXITES FOUND IN GEOSYNCLINAL REGIONS

(a) In situ bauxites

In all cases a full laterite profile is formed on basic to intermediate (quartz-free) porphyrites. A full transition occurs upwards from fresh rock, through a kaolinitic zone, into primary bauxite which still preserves the textures and structures of the parent rock. The bauxite is about 1.5-2 m thick. A sedimentary break occurs above the bauxite, which is overlain by later sediments. No ferruginous zone is present in the profile; this would be expected to overlie the bauxite. The bauxites apparently formed in areas which were exposed to weathering then block-faulted down and covered by sediment, thus preserving the bauxite.

Examples are known from England, Turkey, Oregon, and Skopelos Island (Greece).

(b) Sedimentary (transported) bauxites

These bauxites are known from USSR, France, Italy, Greece, and Rumania, and are of uppermost Precambrian-Cambrian, Palaeozoic, and Mesozoic ages. All show the same type of sequence.

The deposits are closely related to the periphery of geanticlines or central massifs of the geosynclines, which were large islands at the time of formation of the bauxite.

The deposits overlie clean limestones, or rarely dolomites, which characteristically have an irregular kaarst-like surface and are usually of reef type. The bauxite layer, averaging 3-6 m thick, and ranging up to 12 m, can be divided into a lower red bauxite and an upper thinner grey-green bauxite. The grey-green bauxite grades into some 2-4 m of black shale, which quickly passes up into clean reef limestone similar to that underlying the bauxite. The grey-green bauxite always sits disconformably on the red bauxite, and studies (palaeontology, geochemistry etc.) show that the red bauxite is a freshwater continental deposit and the grey-green a lagoonal-marine deposit.

2. BAUXITES FOUND IN PLATFORM REGIONS

(a) In situ bauxites

These are similar to 1a described above

(b) Sedimentary (transported) bauxites.

These deposits generally lie along the margins of syneclises (large basins) or in troughs or grabens on anticlises.

Generally there is a thick sequence of clay overlain with sharp contacts by lenses of sedimentary bauxite, which is then covered by further clays, followed by various other sediments.

Commonly source rocks with some remnants of the original in situ laterite profile may be found adjacent to the sedimentary bauxite deposits. In a number of cases the material underlying the sedimentary bauxite is the kaolinitic zone of the original laterite profile, over which the sedimentary bauxite was transported.

The sedimentary bauxites of platform regions are generally fresh-water deposits of the lake-swamp type, but quite often there are cases where the breaking-up of the laterite material gives a mantle of fragmented material which does not reach the swamps or lakes but remains as a slope-wash deposit.

Platform bauxites of the type described are very common in the near-equatorial regions. In the USSR they occur as buried profiles formed in earlier periods.

Tenyakov generally distinguishes transported bauxites found very close to their source from those transported appreciable distances.

BAUXITE DEPOSITS IN RUSSIA

Compared to Australia, Russia is poorly endowed with bauxite. Deposits are comparatively small and of low-grade; they are generally mined by underground methods, and must be transported long distances (up to 5000 km) overland to sources of cheap electrical power.

It is this general lack of bauxite which has prompted the more intensive study of the geology of bauxite in Russia as an aid to exploration for the more elusive types of deposits.

The main deposits are -

1. Geosynclinal Bauxites

(a) In situ bauxites: None in USSR.

(b) Sedimentary bauxites: Strongly metamorphosed lenses of corundite in early Archaean metasediments can be shown to be simply layers of bauxite.

The oldest major deposit is that of Bohon, near the Mongolian border, about 300 km south of Lake Baikal, and is of Cambrian - Sinian age. The deposit is large, but not of very high grade, and access if very poor.

The main deposits are of Devonian-Carboniferous age in the Urals - Tien Shan geosynclinal belts. The largest deposit in Russia is in the northern Urals, and is early Devonian. Those of the southern Urals are late Devonian. Very interesting middle Devonian deposits occur in the Central Asia Range, an extension of the Ural - Tien Shan Range into Tibet. Middle Carboniferous deposits are known from the Central Asian extension of the Ural Fold Belt and the southern part of the Ural Depression.

Bauxites of early and middle Jurassic age are found in the Carpathians and in Crimea.

2. Platform Bauxites

Layers of diasporites in Middle and Lower Proterozoic rocks of the Aldan (Patomskaya Nagorge) region are bauxites of the platform type.

Very large early Carboniferous deposits of both in situ and sedimentary origin occur in the central part of European USSR. In the region of Belgorod a vertical Proterozoic ferruginous bed is flanked by quartz-sericite schist on each side. Early Carboniferous weathering has developed a crust of high-grade ironstone at the surface on the ferruginous bed, and an in situ laterite profile, with bauxite, has developed over the schists. Other early Carboniferous deposits are sedimentary. Large deposits are found in the southern Timan and close to the Severnaya Onedzskaya Ozero (Northern Onedz Lake).

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The largest Mesozoic bauxite deposit occurs in the Turgainskaya Province (between the southern Urals and the Kazakstan folded belt). An in situ laterite profile of Mesozoic age occurs at Visokopolya in the Ukraine.

Bauxite of Palaeocene - Eocene age has been found in central Siberia.

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