

Bauxite

Neil N. Gow
687 Powell Court
Burlington, Ontario L7R 3E8

Gian Paolo Lozej
73 Ellerbeck Street
Toronto, Ontario M4K 2V2

INTRODUCTION

Clay-like sediments composed mainly of alumina and iron oxide and practically devoid of silica were first described by Berthier in 1821 from Les Baux, in south-east France; such sediments were later named "bauxite" from their type locality. The term bauxite is now used for lithified or unlithified, residual weathering products rich in alumina and low in alkalis, alkaline earth and silica (Table 1 provides definitions of terms used in this review). From an industrial perspective, bauxite is a natural material that can be economically processed to high-purity alumina in the Bayer Process, thus making bauxite the principal ore of aluminum.

Bauxite consists primarily of a mixture of aluminum hydroxides. Gibbsite, boehmite and, to a lesser extent, diasporite are the main aluminous minerals. Other components, deleterious to alumina production, are clay (mainly kaolinite), iron oxides, quartz, titanium oxide, water and a variety of other minerals.

Bauxite can be structureless, granular or earthy, pisolitic and concretionary, massive or stratified, or largely pseudomorphous after the parent rocks. Older bauxites that may have been subjected to burial are hard and compact, with boehmite and diasporite commonly being the dominant aluminous minerals. More recent bauxites are generally softer, with gibbsite commonly being the dominant aluminous mineral.

Bauxite is found throughout the geo-

logical sequence, from the Precambrian to the Recent. The distribution of bauxite in geological time seems to indicate that late Paleozoic, Middle to Late Cretaceous and Middle to Late Tertiary were favourable periods for bauxite formation. This distribution is a result of climatic and tectonic conditions which favoured sustained weathering processes leading to the enrichment of aluminum hydroxides. Such conditions may also be characterized by thick terrestrial and paralic formations on shield and shelf regions, extensive blankets of sandstones and kaolinite clays, coal deposits, ferrallitic soils and sedimentary iron ore.

The geographical distribution of bauxite suggests that bauxite deposits can be grouped into large provinces such as the Caribbean Province in Central America, the Guyana Shield Province and the Brazilian Shield Province in South America, the Guinea Shield Province and the Cameroon Province in Africa, and the Australian Province. Smaller provinces include those of Indonesia and Malaysia, China, the [former]

USSR, Southern Europe, and Arkansas in the United States (Fig. 1).

ALUMINUM PRODUCTION

Production of aluminum metal from bauxite is a two-stage process. The first stage, the Bayer Process, involves the refining of bauxite ore, resulting in the production of pure alumina. The second stage, the Hall-Heroult Process, involves the electrolytic reduction of alumina to aluminum metal.

Bauxite Production

Bauxite is the principal ore for the production of aluminum metal. Most bauxite production comes from surficial deposits which formed in tropical or subtropical environments, located in areas which are comparatively stable tectonically.

More than 80% of the world's bauxite production is extracted from shallow open-pit mines. Deposits are usually 2-3 m thick, and overburden is only a few metres at the most. While some deposits are lithified, requiring explosives for their mining, most bauxite is presently

Table 1 Definitions of terms used in this review.

Alumina	High-purity aluminum oxide (Al ₂ O ₃). Pure alumina (100% Al ₂ O ₃) contains 52.9% aluminum and 47.1% oxygen.
Aluminum	Aluminum metal is the thirteenth element of the Periodic Table. It is produced by electrolytic smelting of alumina in the Hall Heroult plant.
Available Alumina (AA)	The amount of alumina extractable in solution from bauxite by the Bayer process, a hot, high-pressure, caustic soda (NaOH) leach.
Bauxite	Bauxite is a soil or a rock formation which is composed mainly of aluminum hydroxide minerals. From an industrial perspective, bauxite is a natural material from which alumina can be extracted in a Bayer plant.
Bauxite Ore (Metallurgical Grade Bauxite)	A bauxite body which is economically minable at present or in the foreseeable future. Currently, its composition would normally be >45% Al ₂ O ₃ , <20% Fe ₂ O ₃ and <5% SiO ₂ .
Chemical Grade Bauxite	Commercial bauxite used for the production of chemicals, mainly aluminum sulphate (alum). Bauxite composition must conform to accepted specifications for different uses.
Reactive Silica (RSiO ₂)	Silica phases present in the bauxite, generally as clays and fine-grained quartz, which cause caustic soda loss in the Bayer Process. Quartz, if present as coarse silt or sand, is unreactive in the Bayer Process.
Refractory and Abrasive Grade Bauxite	Commercial calcined bauxite used for the production of refractory and abrasive materials. Calcination of bauxite requires temperatures of 1600-1700°C.

mined without explosives.

In 1989, ten countries produced more than 1 million tonnes of bauxite. The five leading producers in 1989 included Australia (37.8 million tonnes), Guinea (17.0 million tonnes), Jamaica (9.4 million tonnes), Brazil (8.2 million tonnes) and India (3.9 million tonnes). Total world bauxite production in 1989 amounted to 102.9 million tonnes; these five countries produced 76.3 million tonnes, or about 76% of the total.

Alumina Production

The Bayer Process, patented in Germany by Karl Bayer in 1888, exploits the relatively high solubility of aluminum oxide minerals in caustic soda solution. Following separation of the insoluble residue (called red mud, and rich in iron oxides and quartz) from the pregnant solution, trihydrate aluminum oxide is precipitated from the solution by cooling and seeding with gibbsite. As a final step, this oxide is calcined at about 1000°C to produce high-purity alumina.

Certain features of bauxite deposits control the efficacy of the Bayer Process. The most important are the relative amounts of the alumina-bearing

minerals, and the presence of deleterious minerals which also react with caustic soda. The two main aluminum oxides in bauxite react differently in caustic soda solution: gibbsite is more soluble than boehmite. Therefore, deposits in which the only ore mineral is gibbsite have a lower energy requirement at the refining stage and are inherently more valuable. Diasporic bauxites, which require more energy than either gibbsitic or boehmitic bauxites in their treatment, are less valuable. Other minerals in the ore which react with the caustic soda, such as clays and fine-grained quartz, cause caustic soda losses in the Bayer Process.

Four to seven tonnes of bauxite, depending on its composition, are required to produce two tonnes of alumina.

Aluminum Production

Electrolytic reduction of alumina (the Hall-Heroult Process) was first applied in aluminum foundries in Great Britain and Switzerland in 1888-1889 to produce aluminum at an industrial scale. The method had been independently devised in 1886 by Charles Hall in the

United States and Paul Heroult in France. The invention of the dynamo had made currents of several hundred amperes available, and gave momentum to the industrial production of aluminum.

In a modern aluminum smelter, a mixture of molten, high-purity alumina and cryolite (Na_3AlF_6) is placed in a carbon-lined steel box and a direct current of 50,000-100,000 amperes is applied at approximately 900°C. The box acts as an electrolytic cell, with the box itself being the cathode and carbon rods dipping into the box forming the anode. The oxygen from the alumina is eliminated at the anode, while the aluminum, being denser than cryolite, accumulates at the bottom of the box.

About two tonnes of alumina are required to produce one tonne of aluminum.

GEOLOGICAL CHARACTERISTICS OF BAUXITE

Mineralogy

The ore minerals in bauxite comprise several forms of hydrated aluminum oxide: gibbsite ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), boehmite

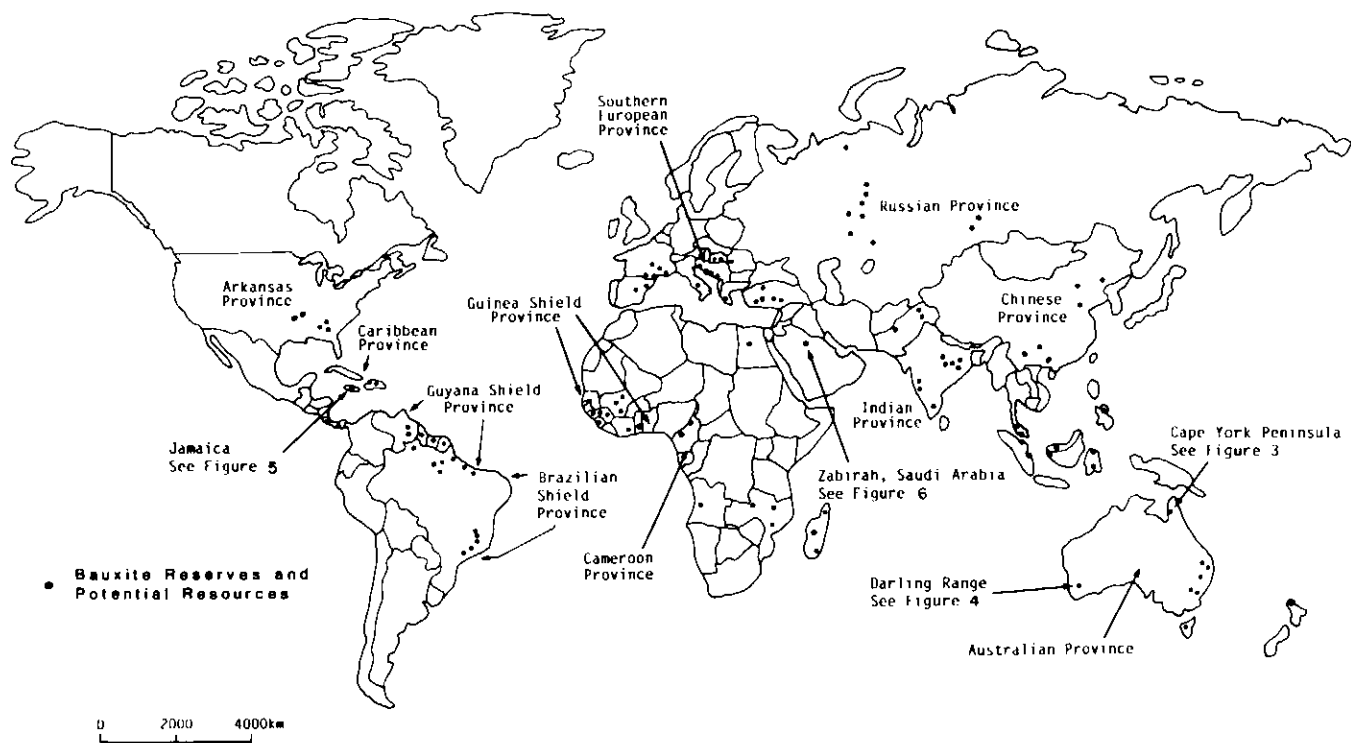


Figure 1 World bauxite provinces.

($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$) and diasporite ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$). All three, white when pure, are almost always coloured by impurities in the natural state. Gibbsite and lesser amounts of boehmite comprise the ore minerals in surficial bauxite. In rare cases, gibbsite is the only alumina mineral present. Diasporite-rich bauxites have usually undergone burial and metamorphism.

Gangue minerals in bauxite include iron oxides (Fe_2O_3), quartz (SiO_2), titania (TiO_2), and water. Minor amounts of clays, phosphate minerals, and unaltered bedrock are often present as contaminants.

Texture and Colour

Bauxite occurs in a number of textural forms, ranging from earthy through pisolitic to structured or massive. Lateritic bauxites are generally structured or pisolitic while earthy bauxite is more typical of "terra rossa" deposits.

Bauxites are usually the colour of iron oxides, red to brown or yellow, but when organic material is present they may be black or dark green.

Bauxite Chemistry

The chemistry of bauxites is variable, reflecting the geology of the parent rock and the history and geography of the deposit. A relatively complete analysis of a bauxite ore would include: total alumina ($T_{\text{Al}_2\text{O}_3}$), total available alumina (TAA), monohydrate alumina (MHA: boehmitic or diasporic alumina), trihydrate alumina (THA: gibbsitic alumina), quartz, reactive silica (RSiO_2 ; this value should be less than 4% and ideally less than 2%), Fe_2O_3 , TiO_2 , and loss on ignition (LOI: combined water).

A number of these parameters are interdependent; specifically, LOI will be high when THA is high.

Age

While there is no apparent reason why bauxite deposits might not be of any geological age, the ages of most deposits fall within a number of specific epochs. Major times of bauxite formation include the late Paleozoic, the Middle to Late Cretaceous and the Middle to Late Tertiary.

It is difficult to constrain the age and time of formation of bauxite deposits and to date the land surfaces upon which they lie.

CLASSIFICATION

Bauxite deposits have been classified using several criteria, including mineralogy, chemical composition, geomorphology and host rock type. The classification used herein divides bauxite deposits into two types based on host rock. The first type includes those developed in karst on carbonate rocks, the "terra rossa" deposits. The second type includes those deposits developed on other rocks and referred to as "lateritic" deposits. Such a classification is supported by genetic and paleogeographical considerations. Either type may be subjected to burial or may be reworked.

About 14% of bauxite production is from terra rossa bauxite, about 85% is from lateritic bauxite, and the remaining 1% from allochthonous (transported) bauxite (Bardossy, 1982).

GENETIC MODEL

Bauxite is the product of pedogenic processes under weathering conditions which are conducive to progressive desilication and alumina concentration in the residual soil. Such conditions are prevalent in, but not restricted to, tropical and equatorial regions.

The general discussion on the origin of bauxite which follows is based, to a large extent, on the work done and concepts developed by many workers. The principal contributions to be acknowledged are those of Hose (1960, 1986), Grubb (1963), Valetton (1966, 1972), Norton (1973), Duchaufour (1977), Bardossy (1982) and Butty and Chapallaz (1984).

Controls on Weathering Processes Conducive to Aluminous Residual Soils

The main factors in physical and chemical weathering which control the development of aluminous soils are climate, vegetation cover, chemical conditions, bedrock composition and texture, groundwater circulation, relief, time and tectonic conditions.

Weathering is a function of temperature and amount of water percolating in the bedrock. High, regular rainfall and absence of low temperatures are important factors favouring the development of aluminous residual soils in equatorial areas. Abundant vegetation favours mechanical weathering through root penetration of the bedrock, production of soluble organic compounds which ac-

celerate chemical weathering and aluminum concentration. It also limits water loss due to evaporation, and protects weathering products from erosion. Progressive desilication is promoted by alkaline conditions which result from base release in solution (hydrolysis) during rock dissolution. Conversely, concentration of hydrolyzed Al ions in solution and their removal from soils decreases drastically with increasing pH. Formation of organometallic complexes (chelates) and phenolic acids by direct action of micro-organisms or through leaching of organic matter has an important role in enhancing weathering processes leading to alumina enrichment.

In principle, there are no minerals capable of withstanding sustained weathering conditions. Mineral phases of bedrock are unstable in the near-surface environment. Weathering of bedrock to a soil is the result of the transformation of the mineral phases to attain equilibrium with the prevailing conditions. The order of mineral stability is the reverse of the order of mineral crystallization, and felsic rocks composed mainly of tectosilicates have a greater resistance to weathering than mafic rocks which are rich in layer silicates. Texture is also important because it affects porosity and permeability, which control the rate of solution of the mineral phases.

Groundwater movement is responsible for the concentration of alumina and the dissolution of many of the deleterious rock components. Ground conditions which favour bauxite formation and preservation (e.g., sink holes, plateau areas) are an important factor in the development of bauxite deposits. The time required for bauxite formation depends on a variety of factors. Under favourable conditions, however, bauxite deposits would be likely to form over a period in the order of 100,000 years. Tectonic stability is critical because it allows chemical weathering to dominate erosional processes. Continued stability is essential to encourage preservation of the deposit. Tectonic stability appears to be less important for "terra rossa" bauxites than for lateritic bauxites.

Aluminous Soil Formations and the Evolution of Bauxite

The most important of aluminous soils which can evolve to bauxite are lato-

soils, andosols and podsoles. The process of ferralitization of one of these soil types is considered an essential precursor to bauxite in the sequence of pedological evolution.

Latosols are lateritic soils and are commonly confined to old peneplains in warm, humid climatic regions. Amongst the latosols, the "ferralitic soils" are particularly rich in Fe and Al oxides. The Mediterranean and Caribbean aluminous red soils (terra rossa) are ferralitic soils.

Andosols are residual soils derived from volcanic ash. They are commonly rich in aluminous minerals and are characterized by a dark, friable top-horizon rich in organic material. The development of andosols requires both a humid climate and a parent material rich in volcanic glass.

Podsoles form from weathering-resistant, quartz-rich, coarse-grained, acid rocks under humid, cold and temperate climates, as well as in hydromorphic conditions in coastal plains of tropical regions.

Bauxitization of each of these soil types involves a process of ferralitization and the formation of ferralitic soils. The process includes mineral destruction and the release of silica, iron oxides, alumina and bases. Aluminum and, to a lesser extent, iron are concentrated in the soil (Fig. 2). The end result of this process is bauxite.

Genesis of Karst Bauxites

Bauxite hosted in karsted carbonate rocks is the result of ferralitization of aluminosilicate residue derived from the dissolution of limestones, volcanic tuffs, or alluvial material from adjacent formations. The theories on the genesis of specific karst bauxites are, as a rule, divided according to these alternative parent rocks. Recent research (Lyew-Ayee, 1986; Bardossy *et al.*, 1977) favours the concept of a volcanic source for most of the typical karst bauxites of the Caribbean and Mediterranean regions.

Chemical and physical erosion are preconditions to the formation and preservation of karst bauxite. Acidic conditions promote carbonate dissolution. This generates the karst-related porosity and attendant internal drainage which is critical to the removal of the residual silicates. Carbonate solution is enhanced by high production of CO_2 and intense nitrification as a result of biodegradation of organic matter. Liberated Ca ions encourage hydrolysis of the silicates, destruction of two-layer clays and precipitation of organometallic complexes of iron and aluminum.

Residual phases from decarbonization are generally iron- and aluminum-rich red ferralite (terra rossa). Residual ferralite is transported during periods of intense rainfall and accumulates in sink holes and caves in the karsted carbonate topography. Bauxitization is ac-

complished through progressive desilication, which is most likely to occur after redeposition of the ferralitic soil in the karst cavities where optimum drainage conditions prevail.

The paleogeographic setting of terra rossa deposits at the time of bauxitization is that of carbonate platforms developed in Mesozoic and Tertiary times under tropical climates on microplates of oceanic island arc belts characterized by intense tectonic and volcanic activity.

Bauxite Preservation

Bauxite formation may last from 100,000 to a few million years and stable tectonic and paleogeographic conditions are critical for the development of the bauxite profile and for the preservation of the newly formed bauxitic material. Ferricrust formation (as at the Darling Range bauxite of Australia, see below) or resilication (as at the Az Zabirah bauxite of Saudi Arabia, see below) at the top of the bauxite profile may have had a role in preserving the underlying bauxite.

Erosional processes involving transportation and redeposition of bauxite affect all bauxites to varying degrees. Drastic reworking by continued dissolution and accumulation of ferralitic material in sink holes and caves of the carbonate host is characteristic of karst bauxites. Minor to large-scale reworking from the edges of elevated plateaux

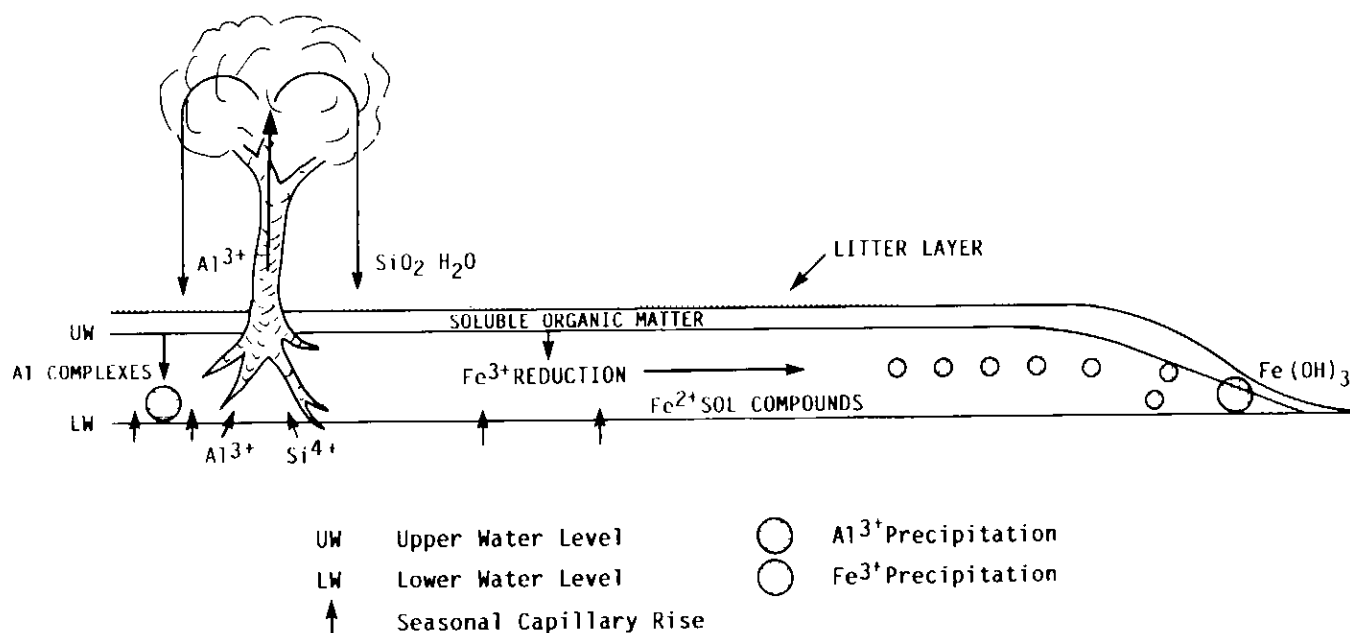


Figure 2 Geochemical evolution of bauxite soils.

and redeposition into fringing fluvial channels have been observed in many lateritic bauxites.

Changes of the local base level are critical to bauxite preservation, probably more so for lateritic bauxite than karst bauxite because of the added protection from erosion provided by the carbonate host of the latter. A drop of base level inevitably leads, over prolonged time, to total erosion of the bauxite profile, while a rapid rise as a result of enhanced tectonism may trigger high-energy sedimentary processes, causing the destruction and dispersion of bauxite in the new sedimentary regime.

Epirogenic tilting may lead to the progressive burial and preservation of deposits under sedimentary cover.

EXAMPLES OF BAUXITE DEPOSITS

Laterite-type Bauxite

Weipa, Australia

The Weipa deposits (Fig. 3) are located on the western side of Cape York Peninsula in northern Queensland, Australia. Bauxite covers an area of more than 800 km² and "inferred resources" of approximately 3700 million tonnes are claimed. Production in 1989 from the

operation was 9.7 million tonnes.

The Weipa bauxite deposits are developed on the sub-horizontal Weipa Formation of probable Tertiary Age. The Weipa Formation lies unconformably on Cretaceous sediments and consists of partly bedded kaolinic sands and clay units with some beds of rounded quartz pebbles. The maximum thickness of the Weipa Formation is approximately 30 metres. Grubb (1971) drew attention to the high permeability of the sediments present below bauxite in the Weipa area.

The bauxite is developed on flat plateaux extending up to 50 km inland from the sea. These mesas are thought to represent remnants of a Tertiary land surface (Evans, 1965). The mesas slope gently west at an average grade of about 1.5 m·km⁻¹. The present-day climate is monsoonal, with a short summer wet season and a rainfall of 160 cm per year. Average monthly maximum dry-bulb temperatures vary from 30-35°C.

A typical bauxite profile in the Weipa deposits consists of about 3.5 m (range of 1-10 m) of loose pisolite-rich material overlying an iron-rich concretionary layer which may be cemented. Locally, the pisolite layer is overlain by soil up to 1 m thick. The interstices of the pisolitic bauxite are filled with loose sandy clays. About 80% of the dry crude ore is recovered as product. The Weipa profiles are weakly stratified and tend to be relatively more boehmitic towards the top of the profile. Grubb (1971) concluded that the high boehmite content was related to a lower leaching rate during profile development. On average, boehmite makes up between 5% and 20% of the available alumina minerals.

Tectonic activity was not entirely absent from the Weipa area. Broad warping of the Tertiary land surface occurred, so that the Weipa area is on the western limb of a broad anticline, or possibly along a broad synclinal warp. However, Grubb (1971) considered that the Weipa deposit was the most stable of the Australian bauxite deposits.

Darling Range, Australia

Bauxite deposits of the Darling Range area of Western Australia (Fig. 4) are located between 31° and 34° south latitude, in a zone approximately 50 km wide between 116° and 117° east longitude.

The bauxite deposits occur on a dis-

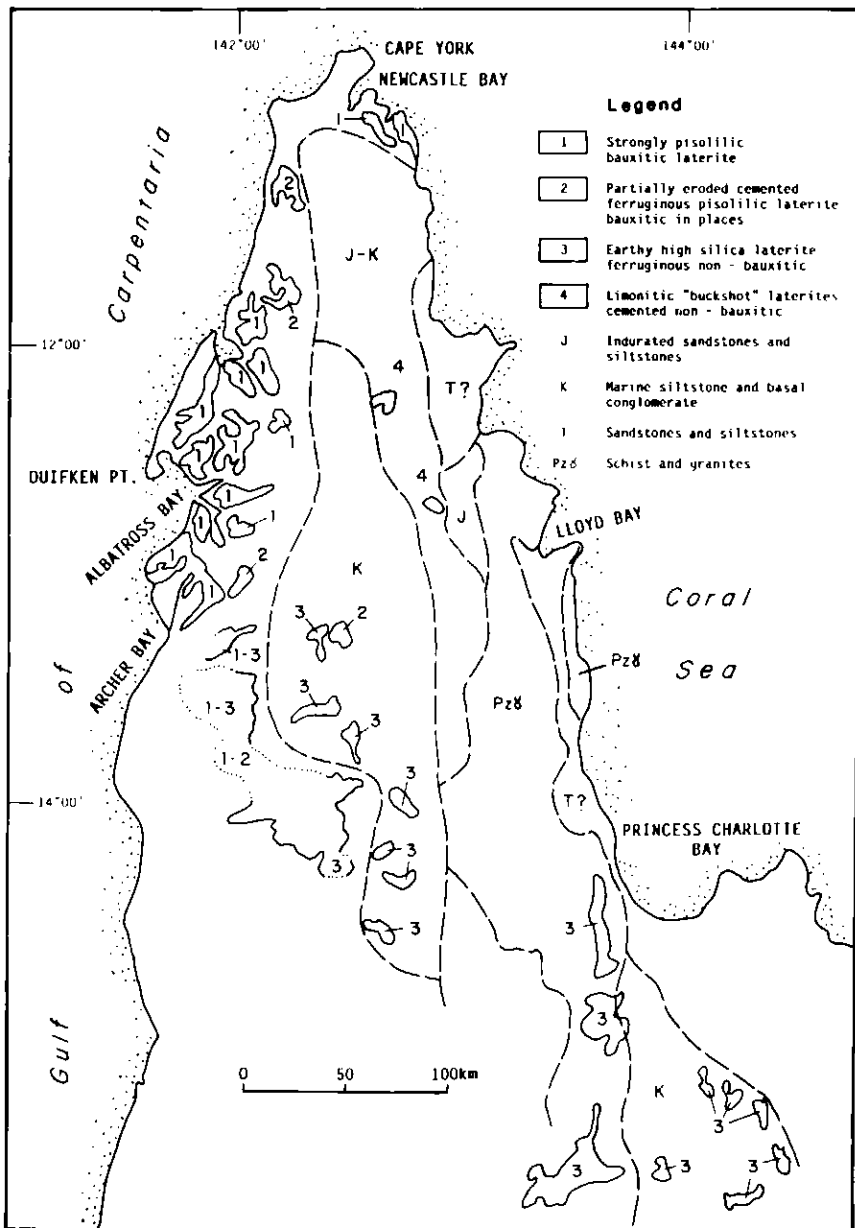


Figure 3 Geology of the Weipa bauxite deposits, Australia.

sected undulating plateau and the bulk of the bauxite is present between 250 m and 340 m above sea level, although some of the bauxitic rock extends to approximately 550 m above sea level. Slopes in bauxitized areas have mean gradients between 5° and 9° (Baker, 1975).

The bauxite deposits of the Darling Range occur as a number of separate bodies which show varying amounts of clustering. Where individual deposits are grouped, they may be separated by 30–300 m (Webb, 1980). The deposits are located on the flanks of ridges and individual deposits cover an area of 10–25 ha. Typically, the deposits average ~5 m deep and are overlain by <1 m of overburden.

The alumina content of the Darling Range bauxite grades between 25% and 38%, with all of the alumina present as gibbsite. The impurities are mainly iron oxides and silica, present as quartz.

The hosts for most of the Darling Range bauxite are coarse-grained granitic rocks with lesser amounts of acidic gneisses. Locally, some younger sediments have been bauxitized, but these appear to be anomalous. The presence of gold in the bauxite profile in the Boddington area attests to the residual nature of the bauxite.

Buried Laterite-type Bauxite

Az Zabirah, Saudi Arabia

The Az Zabirah bauxite (Fig. 5) was discovered in 1979 in a remote desert region of northeastern Saudi Arabia, where it is discontinuously exposed over a strike length of approximately 100 km.

The bauxite is developed along a major angular unconformity of late Early Cretaceous age which truncates a succession of sandstones, siltstones and mudstones of probable Late Triassic to Early Cretaceous age. It is overlain and progressively buried by Late Cretaceous terrigenous clastic and carbonate rocks. The bauxite is preserved at surface over an area of 250 km² and is known to occur below surface to a depth of >80 m (Black *et al.*, 1982, 1984).

The bauxite profile averages ~6 m in thickness and can be subdivided into three zones: the Upper Clay Zone, the Pisolitic Bauxite Zone, and the Lower Clay Zone. Commercial-grade bauxite is preserved in discontinuous layers and pockets up to 3 m thick in the middle

pisolitic zone. Bauxite and clay minerals form the bulk of the profile, and iron oxides are a major component only in some areas. Minor components are alunite, gypsum and calcite, as well as residual zircon, tourmaline, staurolite, kyanite and titania. Quartz is generally <1%. Both boehmite and gibbsite are major components in the bauxite, while diasporite occurs locally in minor amounts. The boehmite to gibbsite ratio is 2:1. Boehmite tends to increase down the profile.

Kaolinite is the main silicate mineral and dominates in the Upper and Lower Clay zones. In the Upper Clay Zone, kaolinite is hard and compact, and appears to have formed by downward re-silicification of bauxite minerals. This process took place prior to deposition of the terrigenous clastic rocks that fringe

and overlie the bauxite.

The Az Zabirah bauxite was developed over a geologically short period during Middle Cretaceous time (Albian-Aptian). The main controls leading to bauxite formation are interpreted to be stable tectonic conditions and tropical paleogeography of the region during the Middle Cretaceous, as well as good permeability and high kaolinite content of the parent clastic lithologies.

An evaluation drilling program was conducted over the deposit during 1980–1982 (Black *et al.*, 1982). A total of ~7900 m was drilled in some 360 holes, with an areal spacing varying from 5000 m × 500–2000 m × 500 m. Some 200 million tonnes grading 57% Al₂O₃, 8% SiO₂ and 10% Fe₂O₃ at 14% SiO₂ cut-off have been delineated: they have been classified as "indicated subeconomic

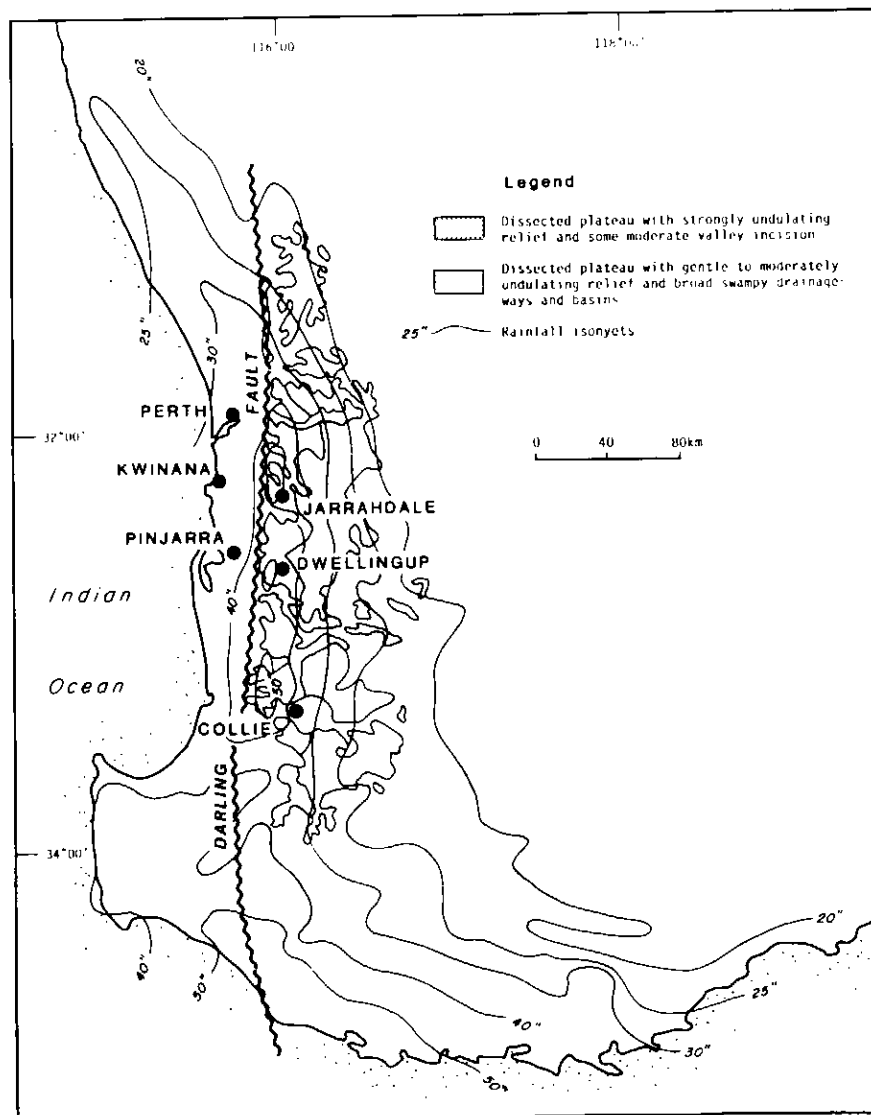


Figure 4 Geographic setting of the bauxite deposits of the Darling Range, Australia.

resources". Of these, 94 million tonnes grading 57% Al₂O₃, 6% SiO₂ and 11% Fe₂O₃ at 10% SiO₂ cut-off have been classified as "inferred reserves".

Terra Rossa Deposits

Jamaica

The main production of bauxite from terra rossa type deposits comes from Jamaica (Fig. 6). From 1952 (when industrial mining began) to 1971, Jamaica was the world leader in bauxite production. Production to 1989 totalled 304 million tonnes, and total reserves are estimated at 2 billion tons (Lyew-Ayee, 1984).

The bauxite occurs as infill of karst sinkholes, pipes and caves developed in the Late Eocene-Miocene White Limestone which covers most of Jamaica. Deposits are highly irregular in shape and vary greatly in size, ranging from small pockets only a few centimetres thick to large bodies up to 30 km long and up to 30 m thick. The average

thickness is ~7 m (Patterson *et al.*, 1986). The contact with the limestone host is generally sharp. A thin soil cover composed of clay and limestone gravel commonly conceals the bauxite.

High-grade bauxite deposits are concentrated in the central part of the island and are located on elevated plateaux between 300 m and 1000 m above sea level (plateau deposits). The plateaux are characterized by higher precipitation (>500 cm per year in places) and better drainage, and they commonly represent the upthrown block of a major fault. Bauxite is usually soft and earthy, and typically dark red (terra rossa) due to the high hematite content. Goethite predominates over hematite in the lower grade yellow bauxites that are found closer to the water table at lower elevations (valley deposits).

The Jamaican bauxites consist of a mixture of predominant gibbsite, lesser boehmite and abundant iron oxides as the major components. Boehmite content ranges from <3% (Jamaica-1 baux-

ite; Hill, 1977) to 5-20% (Jamaica-2 and Jamaica-3 bauxite). Iron oxide content is generally >10%, predominantly hematite in Jamaica-1 and Jamaica-2 bauxites, and mostly goethite (20%) in Jamaica-3 bauxite. Kaolinite is the main clay mineral, and typically accounts for <3% of the composition of high-grade bauxite. Impurities rarely exceed 5%, and include quartz, titania, manganese and phosphate minerals.

The composition of a typical metallurgical-grade Jamaican bauxite is ~50% alumina, ~20% iron oxides, ~1% SiO₂, ~3% impurities, and ~25% combined water. Free moisture is approximately 20%. Because of the mixed gibbsite-boehmite composition, a higher temperature modification of the Bayer process is used to extract alumina from Jamaican bauxite.

The genesis of the Jamaican bauxites has been the subject of extensive literature. Three main hypotheses have been proposed. The "residual limestone" hypothesis (Hill, 1955; Sinclair, 1967) postulates that the bauxite is the result of limestone weathering. The "alluvial hypothesis" (Zans, 1959; Burns, 1961) suggests that bauxite derives from weathering of volcanic, plutonic and sedimentary parent material transported in the limestone host by surface and underground alluvial processes. The "volcanic ash" hypothesis (Comer, 1984; Lyew-Ayee, 1986) maintains that bauxite is due to weathering of volcanic ash.

EXPLORATION METHODS

Initial area selection will depend on political as well as geological factors. Of the geological factors, climate, relative tectonic stability, age and type of rocks will be important.

Application of the genetic model for bauxite deposits shows that the areas most likely to contain economic deposits will have been tropical or near tropical at the time of bauxite formation. The rainfall of any area prospective for surficial bauxite deposits is likely to be comparatively high. Present-day climates are indicative of climates in the near past, at least in stable geological areas. These considerations are less important in the search for buried deposits. Geological age would probably be the major discriminating factor in selecting areas to explore for such deposits.

Remote sensing may be useful in defining more highly prospective areas, and reconnaissance radiometric sur-

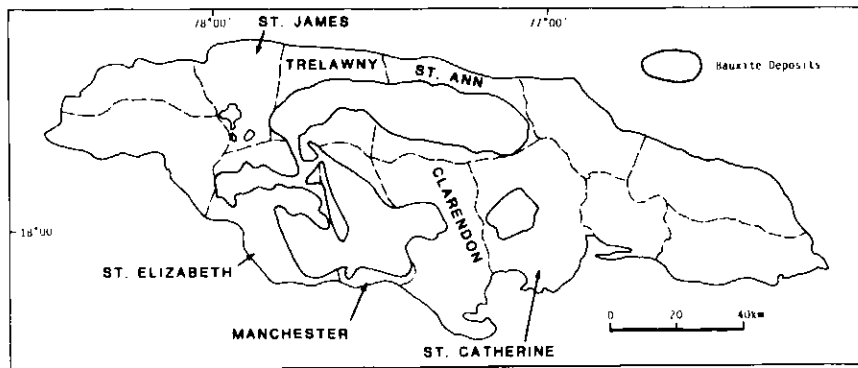


Figure 5 Location of bauxite deposits in Jamaica.

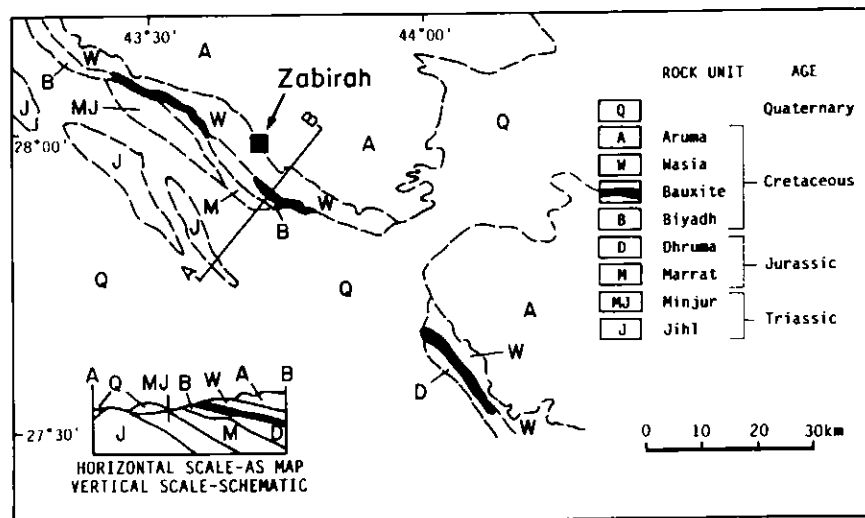


Figure 6 Geology of the Az Zabirah bauxite deposits, Saudi Arabia, in plan and section.

veying is a valuable broad-scale exploration tool. Many "terra rossa" bauxite deposits will have a radiometric response of the order of 10× background, while bauxites developed on sediments will likely have responses in the range of 2× to 3× background. Unless potential bauxites are lithified, a hand auger will be an effective sampling tool in early stage exploration.

Assaying remains a problem in bauxite testing, as reproducibility is difficult to achieve. Initial assaying should preferably include $T_{Al_2O_3}$, SiO_2 , Fe_2O_3 , TiO_2 and LOI. Loss on ignition is still a valuable field-assay technique for bauxite reconnaissance, particularly when there are delays in obtaining assay results. Combined H_2O is >34% in gibbsite and 15% in boehmite and diaspore. If gibbsite and hematite are the only Al and Fe oxides and only minor clay is present, ignition loss provides a rough estimate of the alumina content (Chowdhury *et al.*, 1965).

Development drilling is typically carried out in a grid pattern in the flatter, surficial bauxite deposits. Drill centres would likely be 30–50 m apart. The testing of "terra rossa" deposits is more complex, as grade variation between separate sink holes may occur and the bauxite-carbonate contact may be highly irregular, leading to mining and recovery problems.

CONCLUDING REMARKS

Both lateritic and karst bauxites are the result of desilication of ferralitic soils. Lateritic bauxites are derived from a variety of parent materials, and formed in a variety of paleogeographic settings, although stable continental shelves and shields are prevalent. Conversely, most of the known karst bauxites formed in tectonically active oceanic island arc settings in tropical climatic conditions, and likely derived from a combination of carbonate and volcanic parent material.

Relatively short times of tectonic and paleogeographic stability of the ocean arc settings may require bauxitization processes leading to karst deposits to proceed faster than in more stable continental environments typical of lateritic bauxites. An alumina-rich composition of the parent rock (such as a soil cover rich in volcanic ash), the tropical climate, and excellent drainage conditions of the carbonate-host terrain are the likely crucial elements for the accelerated bauxitization process required

in these mobile belts.

ACKNOWLEDGEMENTS

The writers wish to acknowledge the help and support provided by P.A. Sheahan and M.E. Cherry. The drafting was done by J. Meek. The reviews completed by I.G.L. Sinclair and B. Bognar are also acknowledged with thanks.

REFERENCES

- Baker, G.F.U., 1975, Darling Range Bauxite Deposits, West Australia, in Knight, C.L., ed., *Economic Geology of Australia and Papua New Guinea: The Australasian Institute of Mining and Metallurgy, Monograph 5*, p. 980-986.
- Bardossy, G., 1982, *Karst Bauxites*: Elsevier, 441 p.
- Bardossy, G., Boni, M., dall'Aglio, M., D'Argenio, B. and Pareto G., 1977, Bauxites of Peninsular Italy — Composition, Origin and Geotectonic Significance: *Monograph Series on Mineral Deposits*, v. 15, 61 p.
- Black, R.Y., Bognar, B., Watson, A.D. and Barnes, D.P., 1982, Evaluation of the Az Zabirah Bauxite deposit 1400-1402 (1980-1982): Saudi Arabian Ministry for Mineral Resources, Report RF-TR-01-2, 157 p.
- Black, R.Y., Lozej, G.P. and Maddah, S.S., 1984, Geology and Mineralogy of the Zabirah Bauxite, Northern Saudi Arabia, in Jacob, L., Jr., ed., *Bauxite Symposium: American Institute of Mining, Metallurgical and Petroleum Engineers, Proceedings*, p. 619-638.
- Burns, D.J., 1961, Some Chemical Aspects of Bauxite Genesis in Jamaica: *Economic Geology*, v. 56, p. 1297-1303.
- Butty, D.L. and Chapallaz, C.A., 1984, Bauxite Genesis, in Jacob, L., Jr., ed., *Bauxite Symposium: American Institute of Mining, Metallurgical and Petroleum Engineers, Proceedings*, p. 111-151.
- Chowdhury, A.N., Chakraberty, S.C. and Bose, B.B., 1965, Geochemistry of Gallium in Bauxite from India: *Economic Geology*, v. 60, p. 1052-1058.
- Comer, J.B., 1984, Geological and Geochemical Constraints on the Origin of Bauxite in Jamaica, in Jacob, L., Jr., ed., *Bauxite Symposium: American Institute of Mining, Metallurgical and Petroleum Engineers, Proceedings*, p. 152-164.
- Duchauffour, P., 1977, *Pedogenese et Classification*: Masson, Paris [English translation published in 1982 by George Allen & Unwin, London, 448 p.]
- Evans, H.J., 1965, Bauxite Deposits of Weipa, in McAndrew, J., ed., *Geology of Australian Ore Deposits: Proceedings of the 8th Commonwealth Mining Metallurgical Congress, Melbourne*, p. 369-401.
- Grubb, P.L.C., 1963, Critical Factors in the Genesis, Extent, and Grade of some Residual Bauxite Deposits: *Economic Geology*, v. 58, p. 167-1277.
- Grubb, P.L.C., 1971, Genesis of Weipa Bauxite Deposits, N.E. Australia: *Mineralium Deposita*, v. 6, p. 265-274.
- Hill, V.G., 1955, The Mineralogy and Genesis of Bauxite Deposits of Jamaica, B.W.I.: *American Mineralogist*, v. 40, p. 676-688.
- Hill, V.G., 1977, Syngenetic and Diagenetic Changes in Jamaican Bauxite Deposits: *Travaux, International Congress for the Study of Bauxite, Alumina and Aluminum (ICSOPA)*, v. 15, p. 67-80.
- Hose, H.R., 1960, The Genesis of Bauxites, the Ores of Aluminium: 21st International Geological Congress, Proceedings, Sect. 16, p. 237-247.
- Hose, H.R., 1986, Mediterranean Karst Bauxite Genesis and Plate Tectonic during the Mesozoic: 4th International Congress for the Study of Bauxite, Alumina and Aluminum (ICSOPA), Athens, Proceedings, p. 333-341.
- Lyew-Ayee, P.A., 1984, Bauxites in the Caribbean, in Jacob, L., Jr., ed., *Bauxite Symposium: American Institute of Mining, Metallurgical and Petroleum Engineers, Proceedings*, p. 262-296.
- Lyew-Ayee, P.A., 1986, A Case for the Volcanic Origin of Jamaica Bauxites: *Proceedings of Bauxite Symposium VI, 1986: Geological Society of Jamaica, Journal*, p. 9-39.
- Patterson, S.H., Kurtz, H.F., Olson, J.C. and Neely C.L., 1986, *World Bauxite Resources: United States Geological Survey, Professional Paper 1076-B*, 146 p.
- Sinclair, I.G.L., 1967, Bauxite Genesis in Jamaica: New Evidence from Trace Element Distribution: *Economic Geology*, v. 62, p. 482-486.
- Valeton, I., 1966, Sur la Genese des Gisement de Bauxite du Sud-est de la France: *Bulletin de Société Géologie de France*, v. 7, p. 685-701.
- Valeton, I., 1972, *Bauxites*: Elsevier, *Development in Soil Sciences*, v. 1, 213 p.
- Webb, M., 1980, Bauxite Mining by Alcoa of Australia Ltd. in Western Australia: The Australasian Institute of Mining and Metallurgy, *Monograph 10*, p. 365-368.
- Zans, V.A., 1959, Recent Views on the Origin of Bauxite: *Geonotes*, v. 1, p. 123-132.

Accepted, as revised, 12 January 1993.