GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 33

BAUXITE MINERALIZATION IN THE DARLING RANGE, WESTERN AUSTRALIA

by
A. H. Hickman, A. J. Smurthwaite, I. M. Brown, and R. Davy

DEPARTMENT OF MINES
WESTERN AUSTRALIA

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 33

BAUXITE MINERALIZATION IN THE DARLING RANGE, WESTERN AUSTRALIA

by
A. H. Hickman, A. J. Smurthwaite, I. M. Brown, and R. Davy

Perth 1992

MINISTER FOR MINES
The Hon. Gordon Hill, J.P., M.L.A.

DIRECTOR GENERAL OF MINES
D. R. Kelly

DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
Phillip E. Playford

National Library of Australia
Cataloguing-in-publication entry

Hickman, A. H. (Arthur Hugh), PhD.,1947–
Bauxite mineralization in the Darling Range, Western Australia

Bibliography.
ISBN 0 7309 4472 7

1. Bauxite — Western Australia — Darling Range.
2. Mineralogy — Western Australia — Darling Range.
3. Aluminum mines and mining — Western Australia — Darling Range.
I. Hickman, A. H. (Arthur Hugh), 1947–.
II. Geological Survey of Western Australia. (Series: Report (Geological Survey of Western Australia); no. 33).

549.53

ISSN 0508–4741

Copies available from:
Director
Geological Survey of Western Australia
100 Plain Street
EAST PERTH Western Australia 6004
Telephone (09) 222 3222

Contents

Chapter 1 Introduction

Chapter 2 Bauxite deposits

Chapter 3 Controls governing bauxite formation and deposit location

Chapter 4 Methods of exploration, mining and alumina production

Chapter 5 Mining and the environment

Appendices

Plate

Figures

Tables

Acknowledgements

The authors acknowledge the cooperation and assistance of exploration and mining company personnel, in particular G. Baker and G. Kemp from Alcoa of Australia Limited, and A. Grubb and R. Hinde of Worsley Alumina Propriety Limited. The authors also wish to thank J. Bartle of the Conservation and Land Management Department, and D. Gardner of the Department of State Development for technical information. G. Meddings compiled data from records of many thousands of company drillholes to produce the basis for Plate 1.

Permission to use unpublished company exploration data is gratefully acknowledged.

Bauxite mineralization in the Darling Range, Western Australia

Abstract

The Darling Range, southeast of Perth, is the world's leading alumina producing region. In 1989/90 alumina refined from bauxite mined at Jarrahdale, Del Park, Huntly, Willowdale and Mount Saddleback, totalled 6.65 million tonnes valued at $2336 million, and constituted 16% of total world production. Bauxite deposits occur throughout the Darling Range, but economic and potentially economic deposits are concentrated in a 5000 km^2 area between the Avon and Harris Rivers. In 1988 total economic bauxite resources (demonstrated and inferred) of the Darling Range were over 3500 million tonnes, with a contained alumina value exceeding $200 billion.

Economic bauxite mineralization is confined to the lateritic upland geomorphological division of the Darling Plateau. Deposits occur as lenticular, alumina-enriched orebodies in laterite. Mining techniques and economics require a minimum bauxite thickness of 2.0 m and a minimum orebody size of about 70 000 t; refinery requirements dictate a minimum content of 27.5% available alumina, a maximum reactive silica content of 5% (preferably 2%; used for resource calculations in this report), and a maximum of 2% extractable organic carbon. The largest bauxite deposits each contain between 10 and 25 Mt, and are generally 4–10 m thick; however, maximum recorded thicknesses exceed 20 m. The general (background) bauxite content of the laterite varies between 0.2 and 1.5 Mt/km^2 and exhibits a regional zoning with the higher contents (greater than 3 Mt/km^2) being concentrated in the Huntly–Willowdale district.

The distribution, composition, thickness and areal extent of the Darling Range bauxite deposits reflect interacting depositional and erosional controls related to climate, parent rocks, drainage, topography, and vegetation. Partly dependent on these factors, and probably of critical importance, groundwater Eh and pH conditions were locally conducive to bauxite formation. The largest and highest grade deposits are preserved in the Jarrahdale–Willowdale–Mount Saddleback region because, at the time of lateritization and bauxite formation in the Late Eocene and Early Oligocene, this region possessed a favourable combination of high rainfall, high temperature, chiefly granitic bedrock, moderate relief, appropriate groundwater Eh–pH conditions, adequate drainage, and dense vegetation.

High rainfall and good drainage promote deep chemical weathering and the removal of rock components such as Si, Ca, Na, K and Mg, and permit the alteration of clay minerals to bauxite minerals. High rainfall also dilutes humic and carbonic acids which could otherwise inhibit conversion of kaolinite to gibbsite; low gibbsite/kaolinite ratios are characteristic of eastern areas with lower rainfall. High temperatures increase the rate of chemical reactions involving groundwater and bedrock and, combined with high rainfall, promote luxuriant vegetation.

The Al content of parent rocks is not a critical factor in bauxite formation, but other features such as mineralogy, homogeneity and structural fabric appear to be important. Parent rock mineralogy and chemistry strongly influence the composition (especially with respect to SiO_2/Re.SiO_2, iron oxides and clay) of bauxitic laterite formed at any given locality. The physical properties of a parent rock influence the development of topography and drainage. The distribution of the large, potentially mineable, bauxite deposits indicates that jointed (but otherwise massive), relatively homogeneous granite possessed the most favourable combination of mineralogical, chemical, and physical features for bauxite formation in the Darling Range.

Good drainage, but not rapid runoff, has promoted bauxite formation by providing the large volumes of percolating groundwater necessary for extensive chemical weathering, and by providing a medium for removal of weathering products such as silica in solution. Dense vegetation promotes deep lateritic weathering by 'fixing' the soil and providing organic acids for leaching. Abundant vegetation may also increase rainfall and promote penetration of water into the soil.

Bauxite exploration and mining take place in a region characterized by finely balanced ecosystems. These ecosystems are still poorly understood, and any developmental work (mining, damming of valleys for water, clearing of vegetation for agriculture, roads, or timber production) has adverse effects. Every effort is made to minimize the impact of bauxite mining on the environment, and to rehabilitate areas immediately mining operations have been completed. By mid-1989, 71% (4567 ha) of the total area so far cleared to permit bauxite mining operations (6445 ha) had been rehabilitated, and pit rehabilitation was generally occurring within two or three years of pit clearing. Research by company staff, and outside bodies such as Government departments and tertiary institutions, is continually assessing the success of current rehabilitation techniques, and examining ways of improving results.

KEYWORDS: Bauxite, alumina, Darling Range, Western Australia, laterite, geomorphology, geology, mining, processing, rehabilitation.

Chapter 1

Introduction

Darling Range bauxite in Western Australia's economy

The world's leading bauxite and alumina producing region is the Darling Range, southeast of Perth. In 1989/90 alumina production, using bauxite from the five Darling Range mines at Jarrahdale, Del Park, Huntly, Willowdale and Mount Saddleback, totalled 6.65 million tonnes, and represented 16% of total world production. The value to the State's economy that year was $2336 million, which ranked alumina as Western Australia's second most important mineral commodity, after gold. At the end of 1988, demonstrated economic resources of bauxite (containing about 30% extractable alumina) in the Darling Range were 725 million tonnes, and total resources (demonstrated and inferred) were over 3500 million tonnes, with a current value in excess of $200 billion. Production has been increasing in recent years at a rate of between 5 and 10% per annum, and increasing prices have seen the value of alumina production triple since 1980. Expansions underway at the Wagerup and Worsley refineries will boost total Darling Range production by about 15% from 1993.

Present study

The study leading to this report commenced in the period 1972–1978 with mapping of the PERTH, PINJARRA, COLLIE, and PEMBERTON–IRWIN INLET* 1:250 000 Geological Sheets (Wilde and Low, 1978, 1980; Wilde and Walker, 1982, 1984). This mapping established the regional geology of the Darling Range and the precise distribution of laterite. Specific investigations of the laterite and its bauxite mineralization commenced in 1982, and were undertaken firstly by I. M. Brown (1982–1985), and subsequently by A. J. Smurthwaite (1986–1988). In addition to field and laboratory investigations, and a general literature review, this work made extensive reference to exploration reports, other sources of company information, and departmental records. Meanwhile, R. Davy had been undertaking detailed mineralogical and geochemical studies of laterite profiles in the Darling Range and at Boddington (Davy, 1979b; Davy and El-Ansary, 1986). In 1990 A. H. Hickman compiled the report, partly using text and figures already produced by A. J. Smurthwaite, I. M. Brown, and R. Davy.

The main aims of the study have been to describe and attempt to explain the regional distribution of bauxite mineralization, and to describe the salient features of the principal deposits. As only part of the prospective area has been adequately explored, it is hoped that determination of the controls governing bauxite mineralization will permit easier identification of the prospective areas in the remaining 70% of the region.

The region covered by this report includes all known bauxite deposits, and those areas considered to have significant bauxite potential, in the Darling Range. It is bounded by latitudes 31°S and 34°S and longitudes 115°30'E and 117°E, and corresponds to the area covered by the PERTH, PINJARRA and COLLIE 1:250 000 Geological Sheets (Plate 1). Laterite deposits extend beyond this area, particularly to the south, but limited investigations of these other regions have not as yet indicated the existence of economic bauxite mineralization.

Background information on bauxite

Definition and classification

Bauxite, as a component of the regolith largely composed of aluminium hydroxides, is the most important raw material used by the world's aluminium industry. It is a secondary product, which has originated from a pre-existing rock by a combination of weathering and soil formation. Rocks such as nepheline syenite, and deposits of alunite, are not regarded as bauxite, although they are used as a source of alumina and contribute about 4% of the world production.

Berthier (1821) introduced the term 'bauxite' for sediments (terra rossa soils) rich in aluminium hydroxides, which overlie Carboniferous limestones at Les Baux in the region of Les Alpilles, in the south of France. Liebrich (1892) extended the term to include the aluminous variety of laterite, rich in gibbsite, after an investigation of lateritic weathering products overlying basalt at Vogelsberg, Germany.

Bauxite deposits are widely distributed throughout the world; they occur in a variety of geological, climatic and geomorphological settings. Classification is therefore difficult and many suggestions have been put forward. One classification used by Valeton (1972) divides bauxites into karst and lateritic types. A modification to this

* 1:250 000 map sheet names are printed in capitals to avoid confusion with identical place names.

classification was proposed by Schellman (1975) referring to carbonate (karst), and silicate (lateritic) types. This classification is not ideal, since some bauxite deposits (for example, those of Jamaica) are both karst and lateritic; moreover, karst features can appear in rocks other than carbonates, while transported bauxites fall into neither category. Karst bauxite which overlies aluminosilicate rocks has been referred to as the 'Tichwin' type by Bárdossy (1979).

Classifications based on mineral composition, on the purity of the bauxite or on geomorphological position are not widely accepted. However, such a classification by Grubb (1973) is relevant to this report since it originated in part from his studies of bauxite in the Darling Range.

Because bauxite in the Darling Range area is essentially lateritic in origin, classification into karst, lateritic and transported types is most appropriate for this report.

Karst bauxites: these are concentrated in solution depressions in mainly carbonate rocks (Patterson et al., 1986). They are the result of the weathering out, and subsequent reworking, of the detrital components (in particular of clays) within and adjacent to the carbonate rocks. The clays subsequently break down, releasing silica and leaving a concentrate of aluminium hydroxide minerals.

Lateritic bauxites: these are normally formed from underlying aluminosilicate rocks as a result of tropical weathering. They are considered to be essentially in situ in origin, though in most cases contain a proportion of material which has been transported.

Leaching has removed almost all alkalis, alkaline earths and silica to produce aluminium hydroxide minerals. Alternatively and perhaps more commonly, aluminosilicate minerals are first weathered into clay minerals which, on continued weathering, lose silica to form bauxite. Most lateritic bauxite deposits are found in tectonically stable areas.

Transported bauxites: these overlie both aluminosilicate and carbonate rocks, but have no genetic relationship to them. The material from which the bauxite is formed has been transported to the present site.

The principal economic minerals in bauxite are gibbsite, boehmite, diaspore and corundum. Gibbsite is aluminium oxide trihydrate ($Al_2O_3.3H_2O$); boehmite and diaspore are both monohydrates ($Al_2O_3.H_2O$), differing in crystal structure rather than chemical composition. Corundum, present in very small amounts, is anhydrous aluminium oxide (Al_2O_3). Gibbsite is the main aluminium mineral of lateritic bauxites, whereas a mixture of gibbsite, boehmite and diaspore in approximately equal proportions is characteristic of karst bauxites.

The aluminium oxides are accompanied by varying amounts of quartz (silica), hematite, goethite and maghemite (iron oxide/hydroxides), kaolinite and halloysite and lesser amounts of other clays, and rutile and anatase (titanium oxides) together with accessory amounts of minerals such as monazite and zircon.

Global distribution

Bauxite deposits are found predominantly in tropical regions. Where they occur in temperate climatic zones, the environments are believed to have been tropical at the time of bauxite formation.

The main period of bauxite formation began in the Upper Cretaceous and extended into the Eocene. The largest areas of lateritic bauxite occur in northern and northeastern South America, West Africa, India and western and northern Australia. Most karst bauxite occurs in the Caribbean, Mediterranean and Pacific regions. Tichwin-karst deposits are confined to the Urals and Northern China (Fig. 1). Lateritic, karst and Tichwin deposits account for 85%, 14% and 1%, respectively, of the world's bauxite.

Individual karst bauxite and lateritic bauxite orebodies range from small, discrete pockets containing a few hundred tonnes to large basins containing millions of tonnes.

Global resources

The terminology used for resources and reserves in this report is that of the Australasian Institute of Mining and Metallurgy (1989).

Bauxite resources in the world are conservatively estimated at 40–50 Gt (Patterson et al., 1986); reserves (proved and probable) in 1984 were 21 Gt. Guinea has the largest known reserves (5.7 Gt, according to Patterson et al., 1986) whilst Australia has economic reserves of 2.9 Gt (Knight, 1988) and total resources of 7.6 Gt (BMR, 1989). Australia produces about 30% of the world's alumina, well ahead of the USSR (13 %) and USA (9%). In terms of bauxite mining, Australia (37%) leads Guinea (16%) and Jamaica (8 %).

Refinery requirements

Alumina refineries are designed to handle specific types of bauxite and specific grades of ore, under precise digestion conditions. Management and metallurgical research aim at achieving maximum alumina extraction at lowest cost, having regard for the necessity of a quality alumina product.

Gibbsitic bauxites are generally low in reactive silica (Re.SiO_2)*, and are normally easy to grind and relatively cheap to process. In contrast, extraction from monohydrate or mixed mono-trihydrate bauxites is expensive; their digestion requires high temperatures and

* Some definitions and abbreviations are detailed in Appendices 1 and 2

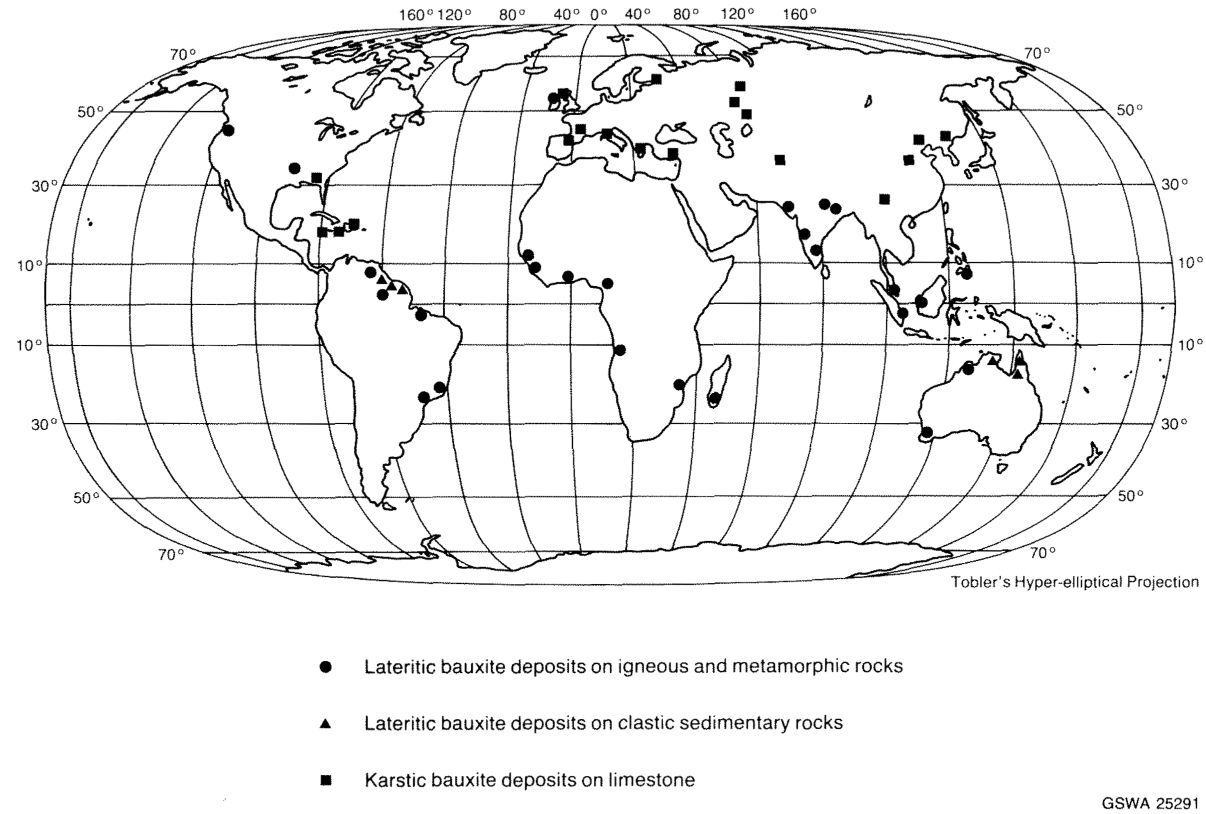


Figure 1. Global distribution of major bauxite deposits (modified from Patterson, 1967).

pressures, and large amounts of caustic soda. They are more difficult to grind and, consequently, require higher inputs of energy.

The main impurity in bauxite is silica, which occurs as quartz and in clay minerals. Quartz is essentially unreactive and does not cause loss of either Al_2O_3 or caustic soda during refining; however, excessive quantities of quartz increase the volume of ore processed and accentuate wear in plant equipment. Reactive silica is that silica in silicate minerals such as clay, which combines with caustic soda to form insoluble sodium silicate compounds. When this happens both alumina and caustic soda are lost from the process liquor. Production declines and caustic soda must be replaced, thus increasing costs.

Iron and titanium oxides are the other important impurities and their effect varies. Goethite, for example, is an unpredictable mineral during alumina refining, because its hardness depends on its crystallinity and grain size. It usually contains a proportion of inextractable alumina bound up within its crystal lattice.

Worldwide, most alumina refineries use bauxite that has an available alumina ($Av.Al_2O_3$) content of 40% or more. In the 1940s the required $Av.Al_2O_3$ content was 55%. Improvements in the refining process since then have made it economically viable to treat bauxite with lower $Av.Al_2O_3$ contents.

Properties and uses of aluminium

Aluminium takes its name from alum (Latin *alumen*), a white transparent mineral (usually potassium aluminium sulfate) used in dyeing and tanning. The element constitutes 8.3% of the Earth's crust but, because of its strong affinity with oxygen and silicon, does not occur in nature in metallic form.

Aluminium's properties make it a most useful metal. It is light, with a specific gravity of 2.7. It has good electrical conductivity (38.5×10^6 S/m at 20°C), a modest coefficient of linear thermal expansion (23.6×10^{-6} /C° between 20°C and 100°C) and melts at 660°C. It is malleable and ductile, and therefore easily worked. Because of a surface layer of oxide it does not tarnish, and polished aluminium is a good reflector of heat and light.

In its pure state aluminium lacks tensile strength and is used mainly as a metallic foil and as a catalyst in the petroleum industry. Most aluminium produced for construction purposes is alloyed with other metals. Common alloying metals include copper, magnesium, manganese, silicon, zinc and tin. Copper increases aluminium's strength and hardness. Magnesium increases aluminium's weldability and marine corrosion resistance. Heat-treatable alloys are produced by addition of silicon, which lowers aluminium's melting point and improves its casting properties. Combined with magnesium, silicon increases aluminium's formability and corrosion resistance. Manganese additives produce a general purpose alloy; one which is strong, corrosion resistant but not heat-treatable. Tin improves anti-friction characteristics in bearing alloys, while boron adds to aluminium's electrical conductivity. In turn, aluminium itself is used as an alloying element with antimony, beryllium, copper, iron, nickel and stainless steel.

Aluminium-dominant alloys are divided into two broad groups: wrought alloys and casting alloys. Wrought aluminium alloys account for 70% of the semi-fabricated products consumed by industry. These are produced in a variety of shapes: rolled (plate, sheet foil), extruded (rivets, screws, bolts, tubes, rods), drawn (wire, rods), and forged (forgings and stampings). They are used in the building, construction and transportation industries where the alloy's high strength-to-weight ratio is important. Casting aluminium alloys are produced as ingots mainly from secondary or recycled aluminium. These alloys feature prominently in the electrical, chemical, and automotive industries.

Aluminium alloys have made spectacular advances over the past 30 years and find applications in virtually all segments of industrialized economies. Measured in either quantity or value, aluminium's use exceeds that of any other metal except iron. On a world-wide basis, aluminium products are of major importance in transport, containers and packaging, construction, electrical and electronics, and consumer durables.

The metal's combination of low weight and high strength has won the attention of vehicle manufacturers who use it to save fuel. For example, 50% of the aluminium produced in the USA, and 90% of that produced in France, is used by those countries' automotive industries. Aluminium castings are the principal products used in cars: bumpers, hoods, pistons, cylinder heads, radiators, heat exchange systems, wheels, and decorative trims.

The aerospace industry uses aluminium for airframes, wheels, landing gear, propellers, engines and interior components. The employment of corrosion-resistant higher purity alloys as cladding over high-strength alloys has reduced aircraft maintenance requirements.

Aluminium's light weight, corrosion resistance, and capacity to withstand severe shocks has resulted in it replacing steel in the manufacture of railway rolling stock.

Manufacturers of marine craft employ aluminium because of its light weight, tensile strength and resistance to saltwater corrosion.

Aluminium is an ideal structural metal. The building industry uses vast quantities of aluminium in roofing, wall-cladding, insulation, doors, windows, partitions, structural framing, functional components, furniture and architectural trim.

Since 1960, aluminium's penetration of the packaging and container market has grown at an annual rate of 15%. Aluminium cans now comprise 75–80% of the world's canned beer market, and over 30% of its canned soft drink market.

The substitution of aluminium for copper has been most marked in telecommunications and electricity transmission. Aluminium is only one-third the density of copper and has superior electrical conductivity.

Aluminium alloys are widely used in the production, storage, and transportation of extreme low-temperature products. Aluminium has been substituted for chromium in austenitic (iron–nickel–chromium) alloys. These so-called 'cryogenic alloys' undergo no transition from ductility to brittleness at temperatures as low as minus 250°C. They are therefore widely used in liquefaction, and in the storage of liquid oxygen, nitrogen and hydrogen.

The versatility of aluminium is evident from the wide range of consumer products which form part of everyday living (e.g. air conditioners, business machines, cooking utensils and coins).

The oxide, alumina, is also useful in its own right, having a place in the ceramic industry, because of its refractory nature, and in paint manufacture, where it is used as a filler. It is also used as an abrasive.

Production of alumina and aluminium

Early attempts to isolate aluminium metal from its oxide failed by virtue of the highly reactive nature of the metal, and the refractory nature of its oxide.

However, in 1809 Davy isolated impure aluminium by electrolysis. In 1825 Oersted also obtained impure aluminium, by heating potassium amalgam with aluminium chloride, but it was not until 1827 that Wohler, repeating Oersted's experiment with metallic potassium rather than amalgam, first obtained relatively pure metal. In 1854 Deville improved Wohler's method by replacing potassium by metallic sodium. Modifications of this process were used to produce the metal commercially for the next 40 years.

Modern methods of extraction are based on the Hall-Heroult and Bayer processes formulated in 1886 and 1888 respectively. Hall, in the USA, and Heroult in France independently separated aluminium by electrolysis. Their very similar processes involved the electrolysis of alumina dissolved in molten cryolite (Na_3AlF_6), the cryolite reducing the temperature of fusion of the alumina. Aluminium was generated at the cathode, sank to the bottom of the electrolytic cell and was periodically drawn off (molten) to be cast into ingots. Additions of fresh alumina made the process continuous. The Bayer process involved leaching bauxite with caustic soda at high temperatures and pressures, with precipitation of alumina from the resultant sodium aluminate solution. The aluminium was then obtained by electrolysis.

In the light of refinery economics and changing product specifications, both processes have been modified to treat bauxite of differing types. One early adaptation was the replacement of cryolite by the much cheaper and more readily obtainable fluorspar (CaF_2).

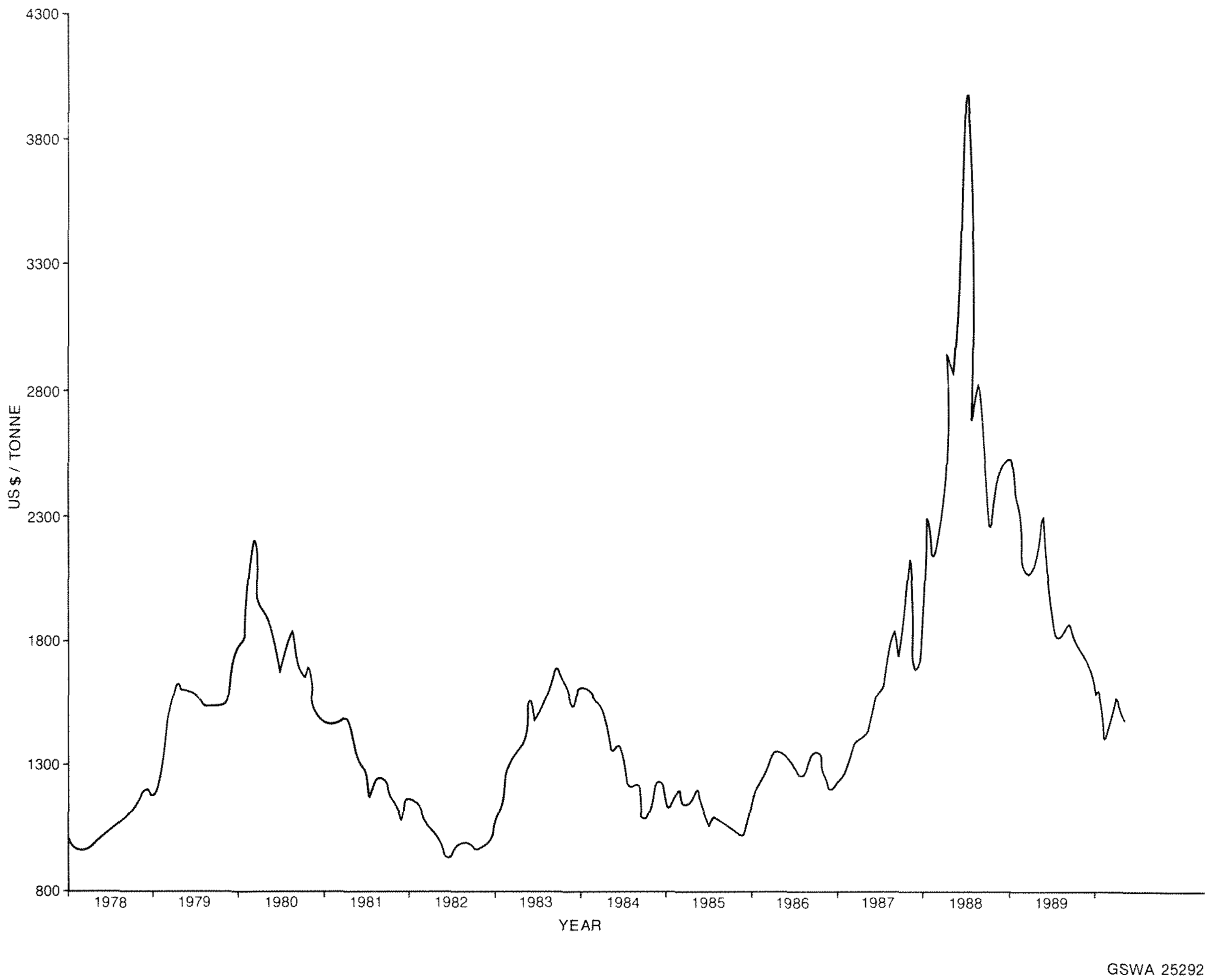


Figure 2. Aluminium prices, 1978 –1990.

Because of costs of producing aluminium metal, Australian companies initially decided to limit processing to the preparation of pure alumina, with transhipment of the oxide overseas for further processing. An alumina refinery was opened at Bell Bay in Tasmania in 1955, and operated until 1973. A second refinery was opened at Gladstone, Queensland, in 1967 and was followed by another at Gove in 1972. In Western Australia, Alcoa of Australia Limited (Alcoa) opened the Kwinana refinery in 1963, the Pinjarra refinery in 1972 and a further refinery at Wagerup in 1983. Worsley Alumina Proprietary Limited (WAPL) opened a refinery at Worsley in the same year. All refineries except that at Bell Bay are still operational.

No aluminium smelters are operational in Western Australia, but smelters are now operating at Boyne (Queensland), Kurri Kurri and Tomago (New South Wales), Bell Bay (Tasmania), and at Point Henry and Portland (Victoria). In 1990 an estimated 1 234 000 tonnes of aluminium were produced in Australia (ABARE, 1991/1).

Prices

The world aluminium price has been very variable, reflecting variations in demand. Figure 2 shows the fluctuations in price, in US dollars per tonne, since January 1978.

Australian bauxite

There are three bauxite mining areas in Australia; Weipa in Queensland, Gove in the Northern Territory, and the Darling Range of Western Australia. Resources of bauxite also occur at Cape Bougainville and Mitchell Plateau in the Kimberley region of Western Australia, and Aurukun and Wenlock River in northern Queensland. Small quantities of bauxite are intermittently produced from Mirboo North in Victoria, but this is used in the manufacture of aluminium salts.

Total Australian bauxite resources (demonstrated economic and subeconomic, and inferred economic) are about 7.6 Gt (BMR, 1989), almost 50% of which are situated in the Darling Range. The bauxite mines of the Darling Range accounted for about 60% of Australian alumina production in 1990.

The Weipa bauxite deposits occur in a Tertiary laterite overlying Tertiary sedimentary rocks on the western side of the Cape York Peninsula, and are described by Evans (1975). The bauxite at Weipa averages about 2.4 m in thickness and is pisolitic, available alumina being present in gibbsite and boehmite. The Gove bauxite deposits average about 3.5 m in thickness, occur in laterite capping areas of dissected plateau (Somm, 1975), and are underlain by Mesozoic sedimentary rocks. The Kimberley deposits occur within the axial region of a syncline, and form part of a Tertiary laterite deposit developed on Proterozoic basalt of the Carson Volcanics. The average thickness of the bauxite at Mitchell Plateau is 3.2 m, and at Cape Bougainville the bauxite averages 8.6 m in thickness (Joklik et al., 1975; Parker and Sadleir, 1984).

Darling Range bauxite

Discovery

The idea that laterite existed in Western Australia was first proposed by Clarke in 1878 (Maitland, 1907), whilst actual bauxite occurrences were first recorded by Simpson in 1902. Simpson (1902) detected bauxite as a result of analysing laterite from Wongan Hills, and subsequently through examination of lateritic road gravels from several localities in the Darling Range.

Following these early discoveries the number of localities identified as containing 'bauxite', or the mineral gibbsite, increased substantially in Geological Survey of Western Australia publications. Most attention was focused on localities in the Darling Range, close either to Perth or to railway lines servicing towns such as Toodyay and York. These early discoveries included laterite at Smiths Mill (Glen Forrest) and Bakers Hill. The Smiths Mill deposits contained up to 50.68% total alumina (Maitland, 1919).

The Geological Survey mapped the extent of laterite in the Darling Range, close to Perth, to determine whether it contained commercial deposits of iron or aluminium ore (Maitland, 1919). Of 46 samples of laterite analysed, 26 contained 35% or more available alumina — the lowest grade of bauxite then regarded as payable. Maitland (1919) assumed that bauxite in the Darling Range was confined to the duricrust part of the profile, and did not realize the possibility of bauxite occurring in underlying friable units.

By 1938 bauxite deposits were known to be common throughout the Darling Range from Moora and Ballidu in the north to Northcliffe and Denmark on the south coast, an area of 350 miles (560 km) long by 25 to 50 miles (40 to 80 km) wide (Government Chemical Laboratories, 1938). During World War II several localities, including Mundaring, Boddington and Dwellingup, were identified as places where bauxite might become economic (Matheson, 1942).

Geological Survey interest in Darling Range laterite as an economic source of aluminium continued during subsequent decades, and Simpson (1951) reviewed all known occurrences of gibbsite within a general summary of minerals in Western Australia. However, by the late 1950s exploration had been taken over by mining companies.

Later investigations of various aspects of bauxite mineralization in the Darling Range have been described by Tomich (1964), Grubb (1964, 1966, 1971, 1973), Baker (1972), Kirke (1973), Sadleir (1974), Owen and Hargreaves (1975), Sadleir and Gilkes (1976), Murray (1979), Loughnan and Sadleir (1984), Ball and Gilkes (1985, 1987) and Gilkes (1988): these contributions are discussed later.

Exploration history

The earliest non-government exploration for bauxite was carried out in 1918 by the Electrolytic Zinc Co. of Australia Pty Ltd. This company's assessment was influenced by the view that bauxite was confined to lateritic caprock. The exploration showed not only that 70–80% of the total alumina was available to the Bayer process, but that Re.SiO_2 was low. The company concluded that material averaging 30% Av.Al_2O_3 was probably available, that some individual deposits had considerable extent, and that other deposits, though individually small, could collectively constitute a large deposit. However, the deposits were generally low grade and not of commercial value.

No further exploration took place until 1957 when Western Mining Corporation Ltd (WMC), seeking to diversify from gold, began to explore for bauxite in the Darling Range. Following a regional reconnaissance, a joint venture company, Western Aluminium NL (WANL), formed by WMC with North Broken Hill Ltd and Broken Hill South Ltd, explored temporary reserves over a large portion of the southwest.

Exploration by WANL initially assumed that the bauxite would be in the form of loose and cemented pisolites, as at Weipa in Queensland, but was redirected once field relationships were documented between Av.Al_2O_3 and the weathered granites and dolerites found in situ. Profiles were sampled using road cuttings and breakaways. Samples were then collected at quarter mile (400 m) intervals along main roads (for example the Albany and Brookton Highways). Selected lateritic ridges and plateaus were sampled at 90 m intervals along chain and compass traverses. Most major occurrences identified in this manner, with the significant exceptions of the Chittering and Mount Saddleback areas, were later included within the boundaries of a Special Mineral Lease (ML 1SA) granted to WANL in 1961.

Scout drilling and duricrust sampling revealed the presence of mineable deposits in the Jarrahdale–Dwellingup area, and the dimensions of these high-grade areas were confirmed by closer spaced surface sampling and drilling. Trial parcels of ore from Cobiac, southeast

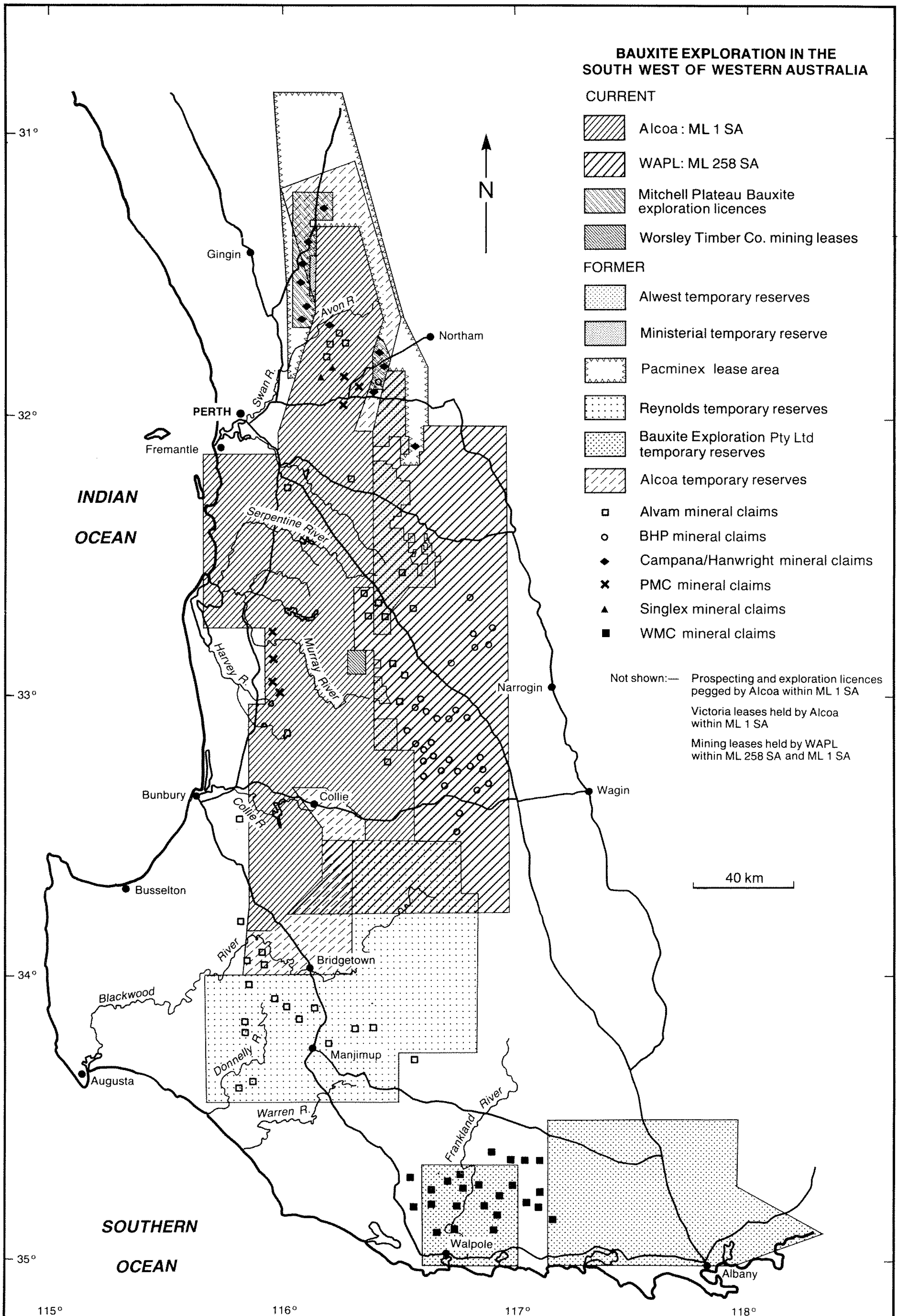


Figure 3. Bauxite exploration in the southwest of Western Australia.

of Jarrahdale, and Plavins, east of Dwellingup were successfully processed, encouraging WANL to continue exploration. By late 1961 the company had delineated 37 Mt of bauxite at an average grade of 33% Av.Al_2O_3. In the same year the company joined with the Aluminum Company of America Ltd (Alcoa US). Increased funds from the American partner allowed additional systematic exploration of lease ML 1SA (Fig. 3). Holes were drilled initially on 370 by 185 m centres. Progressive in-fill drilling down to a spacing of 45 by 45 m blocked out the ore at Jarrahdale and was followed by grade-control drilling. Commercial mining was finally started in 1963 to supply the new refinery at Kwinana. In 1977 WANL became Alcoa.

Away from Jarrahdale the final exploration strategy involved drilling a series of north to south strips of country, each 8 kilometres wide. A 240 by 120 m grid was established by chain and compass, and all terrain types (however geologically and topographically unfavourable) were drilled. Following this, areas at regular intervals were closed up employing a hole spacing of 120 by 120 m and, eventually, selected one-mile square areas were drilled at 60 by 60 m. Comparisons were made between predictions based on the results of drilling at the various grid spacings, and it was found that correlation factors could be applied to 'coarse' exploration data to estimate mineable bauxite present in areas not subjected to closely spaced drilling.

Alcoa's success encouraged other companies to explore in areas adjacent to ML 1SA; exploration of the Mount Saddleback area, east of this lease, began in 1962. Bauxite Holdings Pty Ltd outlined the presence of significant bauxite deposits. The area changed hands several times, but in 1979, Worsley Alumina Pty Ltd (WAPL), a consortium comprising Reynolds Australia Alumina Ltd (40%), the Shell Company of Australia Ltd (30%), Broken Hill Pty Ltd (20% — later redistributed among other partners) and Kobe Alumina Associates Australia Pty Ltd (10%), commenced development of a mine at Mount Saddleback within Mining Lease 258SA (ML 258SA).

The Alumina Agreement Act (1961) of the Western Australian Government gave WANL (later Alcoa) rights to mine bauxite within State Forest. By the late 1960s bauxite exploration was also being conducted by other companies on private property within the northern portion of ML 1SA. By 1972 sufficient bauxite had been delineated by Pacminex, a wholly owned subsidiary of the Colonial Sugar Refining Company Ltd (CSR), in the Wannamal–Chittering area for a proposal to site an alumina refinery at Upper Swan (later changed, because of conservation restrictions, to a site near Muchea). Pacminex withdrew in 1975 because of grade balance difficulties, environmental constraints, and a depressed aluminium market. These deposits are now controlled by Mitchell Plateau Bauxite Pty Ltd (MPB — a subsidiary of Comalco), but bauxite mining is unlikely to proceed in the near future.

Exploration by other companies in the southwest has not delineated other potentially mineable deposits.

Definition of ore

Ore comprises that part of the overall bauxite mineralization from which alumina is recoverable economically. What constitutes ore therefore depends not only on grades, overall composition (including the effects of impurities) and volume, but also on the costs of extraction and market prices. Total alumina and silica contents are of negligible importance in defining bauxite ore: ore is defined in terms of its Av.Al_2O_3 and Re.SiO_2 contents.

Alcoa and WAPL use methods to define mineable material which, though differing in detail, generally follow a common path. The zone bounded by a 20% Av.Al_2O_3 contour (obtained from exploratory drilling) is considered potentially viable. Within this zone, the most prospective areas are drilled using holes spaced at 60 m intervals, with less prospective areas drilled at 100 m centres. Samples are collected at vertical intervals of 0.5 m, pulverized and analysed for Av.Al_2O_3, Re.SiO_2 and total iron. The magnetic susceptibility of each sample is measured. The information gained is used to formulate an 'ore boundary' for individual deposits. A three-dimensional model of the deposit provides a geologically derived tonnage estimate; the thickness, lateral extent and continuity of the ore are used to indicate the relative strength of the mineralization and nominate areas for subsequent grade-control drilling. Ore blocks are defined at two levels, using cut-offs of 25% and 27.5% Av.Al_2O_3 respectively, and a minimum vertical thickness of 2.0 m. Detailed geological mapping, and interpretation of duricrust texture and mineralogy, ensure that all potential ore within the drill pattern is included.

The approximate mining cut-off point is currently 27.5% Av.Al_2O_3: a lowering of this level results in increases in Re.SiO_2 offsetting gains made by increased alumina tonnages. The typical average mined grade of 30–35% Av.Al_2O_3 alumina is low by world standards: Re.SiO_2 must be less than 5%, and preferably be less than 2%. The minimum size for an orebody which can be economically mined is 70 000 t, and most orebodies are about 300 000 t.

Bauxite contains impurities other than silica, for example, titanium minerals, gallium, heavy accessory minerals, and clays. Most of these are unreactive during ore treatment and eventually finish in the residual red muds. However, if levels of Re.SiO_2 exceed 5%, the rock is unusable despite a high content of Av.Al_2O_3. Free SiO_2 and iron oxides are merely diluents, but 'ore' can be rejected when these are high because of their abrasive effects. Darling Range bauxite also has a relatively high organic content (roots, decomposed vegetation) typically 0.3–5.0%. During treatment, organic compounds oxidize and react with reagents, so that the maximum acceptable level of extractable organic carbon (EOC) in the ore is 2%.

Classification of Darling Range bauxite, according to origin and composition, is discussed in Chapter 2.

Chapter 2

Bauxite deposits

Introduction

The existence and location of bauxite deposits in the Darling Range are, of course, constrained by the distribution of the host rock, laterite. Present-day laterite distribution, thickness, and composition are partly influenced by geomorphology, and partly by bedrock geology. Other factors such as climate and vegetation are also significant, chiefly in terms of laterite composition.

Before describing the bauxite deposits and prospects, it is appropriate to outline their regional setting. Accordingly, some general introductory information summarizing the area's geomorphology, bedrock geology, and laterite deposits is provided.

Geomorphology of the Darling Range

Although no fully comprehensive study of the area's geomorphology has yet been undertaken, sufficient is known to distinguish its main geomorphological divisions: the Swan Coastal Plain, the Blackwood Plateau, the Dandaragan Plateau and the Darling Plateau (Fig. 4). These divisions essentially follow those outlined by Churchward and McArthur (1980) who refer to information acquired during several earlier studies. Because bauxitic laterite is confined to the Darling Plateau, only this division is described here.

The western boundary of the Darling Plateau is defined by the Darling Scarp, rising abruptly 100 to 300 m above the low-lying, subdued topography of the Swan Coastal Plain and the other two plateaus. The position of the scarp closely corresponds to that of the Darling Fault which separates resistant Precambrian rocks to the east from more easily eroded Phanerozoic sedimentary rocks to the west.

The height of the Darling Plateau varies between 250 and 350 m above sea level, with the surface sloping gradually to about 250 m in the east and south; land above 400 m is confined to isolated hills above the general plateau surface, and these are restricted to the central part of the area within a distance of 50 km from the Darling Scarp. Dissection of the plateau has created three distinct subdivisions: lateritic uplands, deeply incised valleys, and wide valleys with intervening low hills.

Lateritic upland constitutes the remnant part of a once-extensive peneplain, and thick profiles testify to a long period of bedrock weathering. The surface of the lateritic upland is composed of laterite, lateritic gravel and sand; sand is usually situated in shallow depressions at the heads of drainage lines.

Deeply incised valleys are restricted to the western part of the Darling Plateau where streams and rivers have cut narrow, steep-sided valleys through the surface of the lateritic upland. Erosion is commonly sufficiently deep to expose unweathered bedrock in the lower slopes and valley floors.

The eastern part of the Darling Plateau is occupied chiefly by a relatively mature landscape of wide, alluvial, commonly terraced valleys, and intervening areas of low hills and numerous tributary streams. Small areas of laterite preserved in interfluves represent remnants of the lateritic plateau surface; bedrock is locally exposed in the more hilly areas. Topographic relief in this subdivision, which includes the most westerly part of the Wheat Belt, is generally subdued although deep valleys are associated with major drainages such as the Avon, Williams and Murray Rivers.

Other units which have been distinguished within the area of the Darling Plateau are the Collie and Wilga Basins (Churchward and McArthur, 1980; Wilde and Walker, 1982). These 'basins' are chiefly geological, rather than geomorphological units, although their underlying Phanerozoic sedimentary rocks do produce lateritic terrain somewhat different from that developed on the surrounding Precambrian igneous and metamorphic rocks.

The relationship between geomorphology and the distribution of bauxite deposits is discussed in Chapter 3; however, at this stage it is relevant to note that all mineable and potentially mineable deposits of bauxite and bauxitic laterite are confined to the 'lateritic upland' subdivision of the Darling Plateau.

Bedrock geology

The area bounded by latitudes 31°S and 34°S and longitudes 115°30'E and 117°E is underlain by two major geological units separated by the Darling Fault. To the west of the Darling Fault lies the Perth Basin containing a 15 km-thick succession of Phanerozoic sedimentary rocks, whereas to the east the Darling Range is underlain by Archaean rocks of the Yilgarn Craton. Because

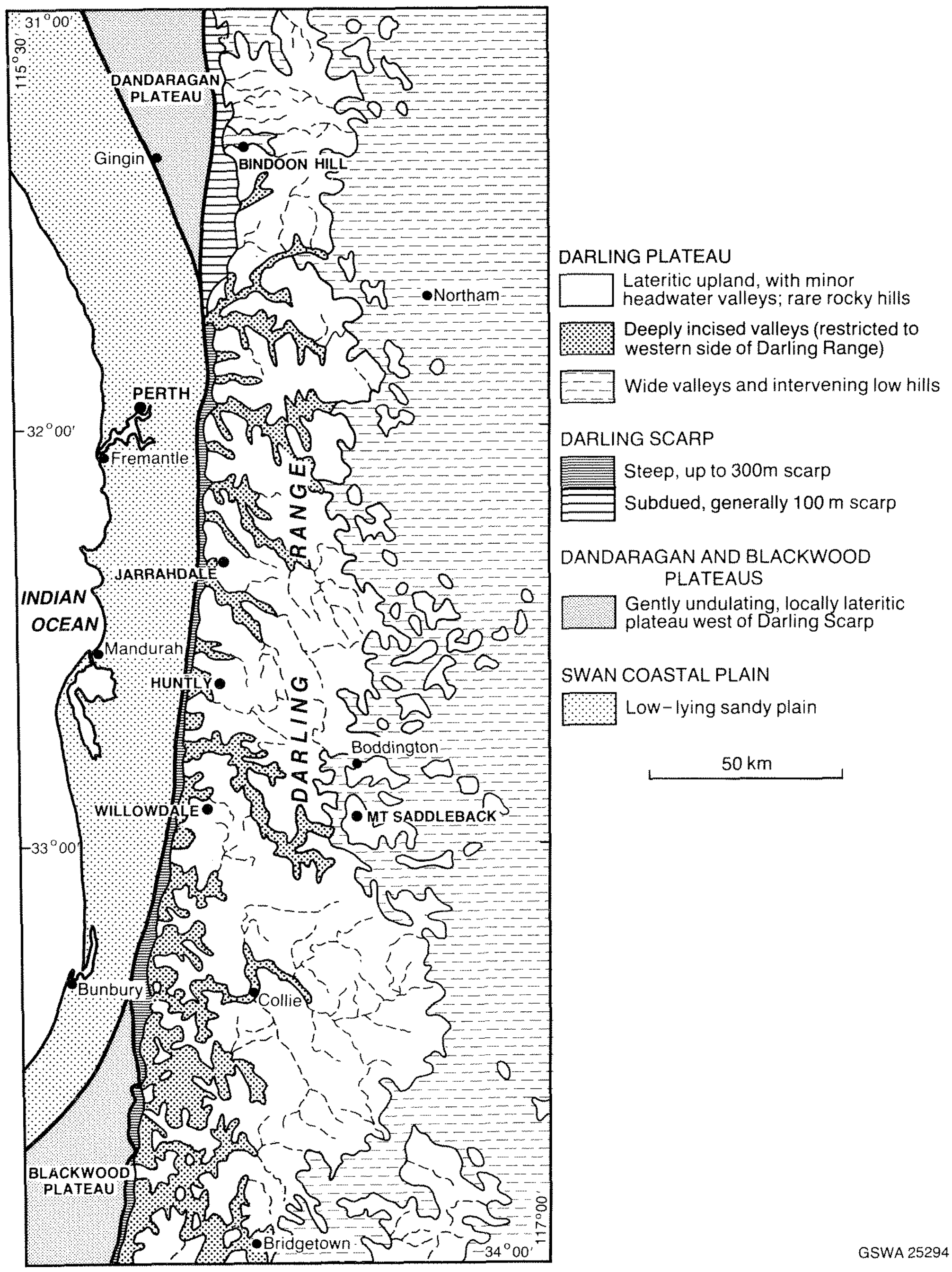


Figure 4. Geomorphological divisions of the Darling Range and adjacent areas.

economic and potentially economic bauxite deposits are confined to the Darling Range, the geology of only the Yilgarn Craton is relevant here.

The Darling Range occupies the most southwesterly part of the Yilgarn Craton, a major geological unit which extends eastwards beyond Kalgoorlie and northwards beyond Meekatharra and Wiluna. The southwestern part of the Yilgarn Craton is a distinctive section (or 'province') referred to as the 'Western Gneiss Terrane' (Myers, 1990). In the Darling Range area the Western Gneiss Terrane is composed of granitic gneiss, paragneiss, metagranite, granite, and one greenstone belt at Mount Saddleback. Numerous north-northwest to north-striking dolerite dykes have intruded the predominantly granitic rocks of the area, and commonly constitute over 10% of bedrock.

The bedrock geology of the region is summarized in Figure 5. The oldest geological components are the Jimperding and Balingup Gneiss Complexes (Myers, 1990), and the Chittering Metamorphic Belt (Wilde and Low, 1978). These are essentially heterogeneous complexes of orthogneiss and paragneiss exhibiting evidence of repeated deformation and metamorphism, with mineral assemblages in granulite or amphibolite facies. Limited isotopic data suggest ages ranging from 3.34 Ga (Nieuwland and Compston, 1981) to 2.76 Ga (Fletcher et al., 1985).

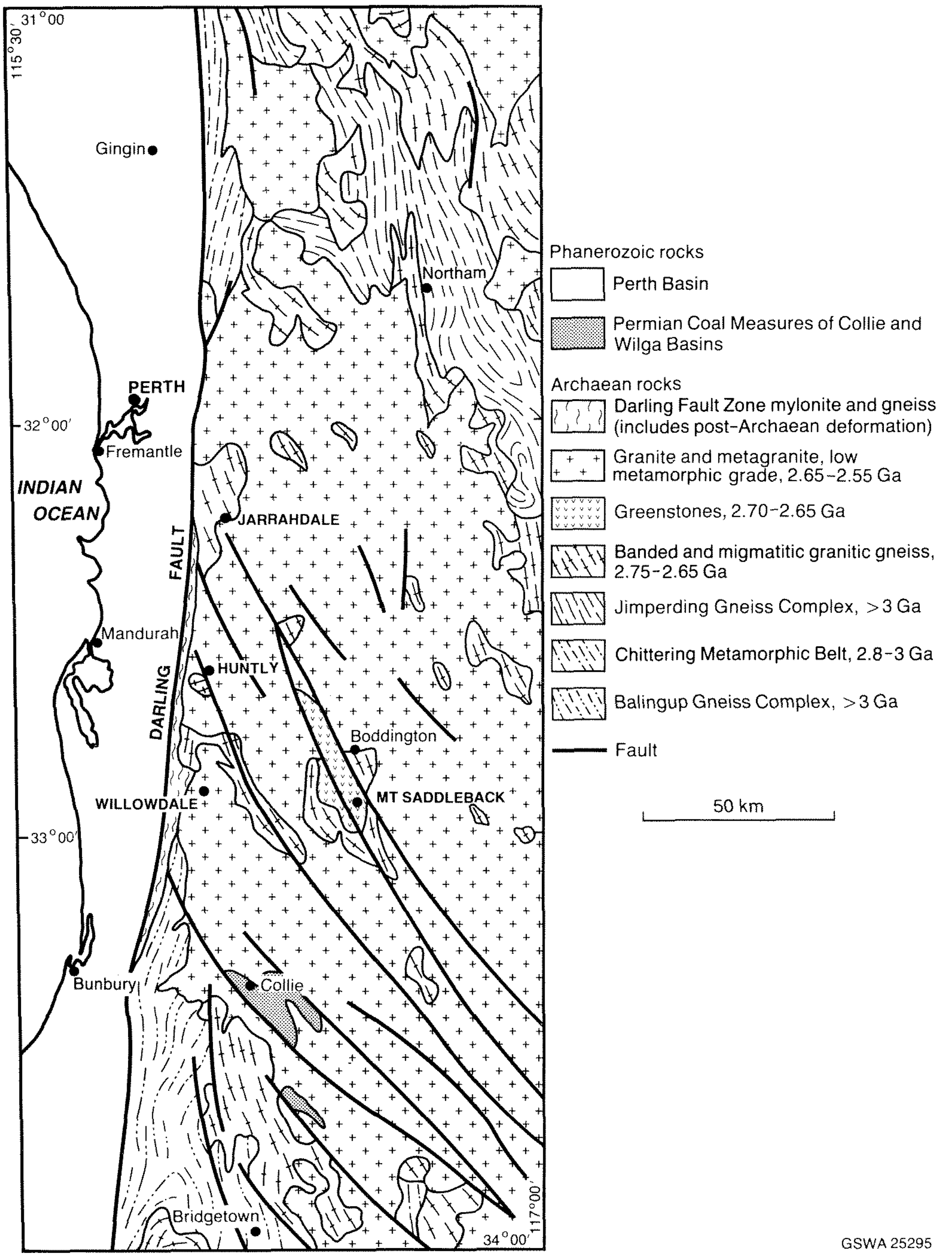


Figure 5. Bedrock geology of the Darling Range.

The Jimperding Gneiss Complex is composed of metasedimentary rocks, mainly fuchsite-bearing quartzite, quartz–feldspar–biotite–garnet(–orthopyroxene) gneiss, andalusite and sillimanite schist, banded iron-formation, and minor amounts of calc-silicate gneiss, together with mafic rocks, ultramafic rocks, and banded quartzo-feldspathic orthogneiss. Most units are intruded by porphyritic granite. All these rocks were strongly deformed together, and most metasedimentary rocks are now schistose, whereas the granite has become tectonically foliated and includes augen gneiss. The main tectonic foliation and banding are flat-lying in the southwestern part of the belt, and steep, easterly dipping in the northeast. There is an increase in the grade of the last major metamorphic imprint, from retrograde low-amphibolite facies in the southwest to prograde granulite facies in the northeast. This metamorphic pattern is superimposed on folds and tectonic fabrics, but is cut by granite intrusions which, by analogy with similar intrusions elsewhere in the Western Gneiss Terrane, may have ages of about 2.7–2.6 Ga. Some granites in the vicinity of the Jimperding Gneiss Complex have given Rb–Sr whole-rock and model ages of between 2.68 and 2.5 Ga (Nieuwland and Compston, 1981).

The metasedimentary units of the Jimperding Gneiss Complex include arkosic paragneiss, indicative of stable shelf sedimentation. However, the Chittering

Metamorphic Belt is rich in pelitic and greywacke assemblages, and is devoid of quartzite and banded iron-formation, suggesting rapid deposition in a trough-type environment (Fletcher et al., 1985).

As described by Wilde (1980), the Chittering Metamorphic Belt extends northwards from near Perth and is bounded to the west by the Darling Fault. It is about 100 km long and averages 10 km in width. The chief rock type is quartz–feldspar–biotite(–garnet) gneiss, interlayered with, and grading into quartz–biotite–muscovite schist that is locally rich in kyanite, sillimanite or staurolite. In the southern part of the belt, there is an extensive development of fine-grained, melanocratic quartz–feldspar–biotite granofels. Gradational relations between these units suggest that all were originally sediments. However, there are zones in the northern and southern parts of the belt of medium- to coarse-grained orthogneiss with an augen texture, representing deformed porphyritic granite infolded in the metasedimentary sequence.

The regional trend of the units is northerly, with steep dips to east or west. Mylonite zones are common along the western side of the belt and lie subparallel to the present Darling Fault, but metamorphic features indicate that the deformation occurred during the Precambrian time.

The Chittering Metamorphic Belt has amphibolite facies assemblages. In contrast to the Jimperding Gneiss Complex, the presence of kyanite, sillimanite and staurolite in the aluminous schist, and the calcic composition of plagioclase in hornblende-bearing rocks, indicate that moderate- to high-pressure conditions prevailed.

The Balingup Gneiss Complex (Myers, 1990) consists mainly of metasedimentary rocks: interlayered quartzite, quartz–mica schist, quartz–feldspar–biotite–garnet gneiss, and banded iron-formation, together with minor layers of quartzo-feldspathic gneiss, amphibolite, calc-silicate gneiss, and ultramafic rock. About 30% of the complex is orthogneiss, mainly porphyritic granite which has been deformed and infolded with the paragneiss.

The metamorphic grade of most rocks is amphibolite facies, but granulite-facies assemblages occur locally in both orthogneiss and paragneiss. Samples of gneiss have given Sm–Nd T_{CHUR} model ages of about 3.07 and 3.11 Ga (Fletcher et al., 1983). The Balingup Gneiss Complex is intruded by granite similar to that which is widespread throughout the Western Gneiss Terrane, and which has an age range of 2.7–2.6 Ga.

Throughout the complex, there are abundant mylonite zones near to the Darling Fault. Near Harvey, the progressive westward increase in deformation of a porphyritic granite body results in the formation of layered quartz–feldspar–biotite orthogneiss with zones of blastomylonite.

Banded and migmatitic granitic gneiss is common in the northern part of the area near Northam, and between Collie and Bridgetown (Fig. 5). The rocks are less deformed than the gneiss complexes, but metamorphic grade is upper amphibolite to granulite facies. The unit commonly invades the margins of the gneisses and contains trains of enclaves. The palaeosome may be gneiss, greenstone material or deformed granite, but the neosome is invariably less deformed granite occurring as veins, dykes or larger intrusive bodies. The banded and migmatitic gneiss is 2.75 to 2.65 Ga, and is probably a high-grade equivalent of the granite–greenstone rocks in the greater part of the Yilgarn Craton to the east.

The only large mass of greenstone material in the area occurs at Mount Saddleback, and is referred to as the Saddleback Group (Wilde, 1976a). The Saddleback Group extends for 43 km north-northwest from near Boddington, and is between 5 and 12 km wide. It consists of a weakly metamorphosed sequence of felsic and mafic volcanic and pyroclastic rocks, with minor sedimentary units, largely fault-bounded against granite and migmatite. However, contact relationships in the southwest confirm that the volcanogenic sequence pre-dates granite emplacement.

Units in the Saddleback Group dip east at moderate to steep angles, and the rocks have predominantly greenschist facies assemblages, with a local extension to lower amphibolite facies in the southwest part of the belt close to the granite contact. Zircon U–Pb results indicate that felsic volcanism extended from 2.67 to 2.65 Ga, and this was followed by metamorphism, deformation and granite intrusion at 2.64 Ga (Wilde and Pidgeon, 1986). The Saddleback Group is similar in age to various 'younger' greenstone sequences of the Yilgarn Craton, and may therefore be a remnant (perhaps a down-faulted portion) of a once more extensive cover of volcanics overlying the gneisses.

The most extensive unit of the Darling Range area consists of granite and metagranite which are intrusive into the gneiss and the greenstones. Isotopic evidence indicates that the rocks are generally 2.65 to 2.55 Ga (Myers, 1990), but slightly older (2.7 to 2.65 Ga) representatives appear to be present in some areas, suggesting some degree of contemporaneity with the Saddleback Group. The composition of the granitic rocks ranges from granodiorite to monzogranite and granite, metamorphic grade rarely exceeds prehnite–pumpellyite facies, and textures vary from even-grained, through seriate, to porphyritic. Hornblende-rich varieties are common close to intrusive contacts with amphibole-bearing gneisses and greenstones. Unlike the gneisses and greenstones, these granitic rocks of low metamorphic grade are unfoliated or only weakly foliated. Compositional homogeneity on a local scale, and an absence of any strongly developed tectonic foliation have combined to result in relatively uniform weathering, generally without much topographic relief. This feature has probably contributed to laterite development and preservation, as discussed in Chapter 3.

The Darling Fault Zone represents a major crustal dislocation extending from the south coast northwards for 1000 km, almost to Gascoyne Junction. Within the Darling Range area, its position closely corresponds to that of the Darling Scarp, and it separates Archaean rocks of the Yilgarn Craton from Phanerozoic rocks of the Perth Basin. Movement along the zone first occurred in the Late Archaean at about 2.6 Ga (Blight et al., 1981; Compston et al., 1986). Bretan (1985) records evidence of early sinistral movement followed by much later reverse and normal displacements. Deformation along the western margin of the Yilgarn Craton is expressed as zones of shear, mylonite, phyllonite and augen gneiss. Such deformation rarely extends more than 10 km from the main fault, and is intermittent along the fault, apparently being most marked where the pre-fault structural grain of the Archaean rocks trended north (parallel to the fault).

Dolerite dykes are extremely common in the whole Darling Range area. Within 20 km of the Darling Fault, they are generally metamorphosed to amphibolite and many are sheared and altered. The dykes are early to late Proterozoic in age and belong to several suites, but all are tholeiitic, quartz dolerite. Most belong to a north-northwest trending suite which is particularly well represented close to the Darling Fault; other suites trend east and east-southeast whilst a few dykes strike northeast. The dykes are vertical or subvertical and range in thickness from less than 1 m to over 200 m, averaging about 10 m. Where they occur in areas of bauxitic laterite their lithology exerts a significant effect on laterite profiles and composition, with important implications for bauxite potential.

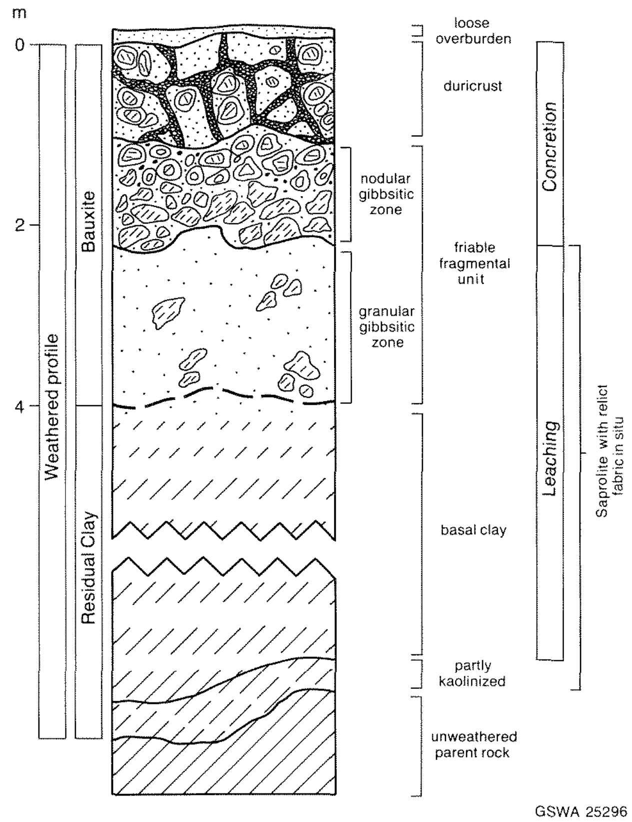


Figure 6. Generalized laterite profile.

Laterite

Distribution

The distribution of residual laterite in the Darling Range area coincides with that of the lateritic upland geomorphological unit shown on Figure 4. Laterite remnants are thickest and most extensive over a 150 km long region between the Avon and Harris Rivers, and within about 50 km of the Darling Scarp. The laterite occupies gently sloping (3°) to horizontal upland areas with an average elevation of 280 to 300 m, and high annual rainfall. Steeper slopes may have a thin cover of partly transported laterite but, in general, bedrock is present near-surface. Above 340 m the laterite is penetrated by monadnocks of bedrock which rise above the general topographic level. Below 200 m incised drainage has removed much of any pre-existing laterite. Blocks of laterite, released by headward erosion of streams, decay to lateritic gravels on the lower slopes of valleys. These pass laterally into alluvial sands and silt in the valley floors.

In most areas the laterite is underlain by low-grade granitic rocks rather than gneissic rocks, although between Bolgart and Gingin cataclasis associated with the Darling Fault Zone has imposed a gneissic fabric on the western part of such a granitic unit.

Composition

A typical laterite profile (Fig. 6) averages about 20 m in thickness and consists of four layers: overburden, duricrust, mottled zone (friable fragmental unit), and pallid zone (basal clay). However, it should be noted that, in detail, profiles are extremely variable. The extent to which the profile is retained depends on local post-laterite erosion. Likewise, the thickness of sand and soil overlying the laterite depends on local depositional conditions since laterite formation. For the purpose of this report, surface sand and silt are not considered as part of the normal lateritic profile since they often contain a transported component, even including windblown material (Glassford and Killigrew, 1976; Brimhall et al., 1988).

Overburden, excluding surface sand and silt, comprises laterite fragments and 'pisolitic' gravel in a sandy matrix, and overlies and surrounds duricrust outcrop and loose boulders. It ranges in thickness from 0.2 m to about 4 m, and averages 0.5 m.

Duricrust over granitic rocks reaches thicknesses of 1–2 m: at Mount Saddleback, duricrust developed over mafic volcanic rocks is up to 5 m thick. Duricrust may be either essentially residual in origin (though there are always some indications of movement, in the form of recemented blocks, infilled solution cavities, etc), or be more definitely transported and recemented. In low- to intermediate-rainfall areas duricrust is intermittent in distribution, or has been only incipiently formed. In duricrust which is largely residual, some indications of the parent rock may be detected. For example, duricrust over a porphyritic granite may preserve the original fabric (Fig. 7); original quartz grain and feldspar laths, represented by gibbsite pseudomorphs, are retained. Another excellent example of gibbsite pseudomorphing feldspar is seen in hardcap developed over porphyritic dolerite ('Leopard Rock') at Dwellingup (Figs 8 and 9).

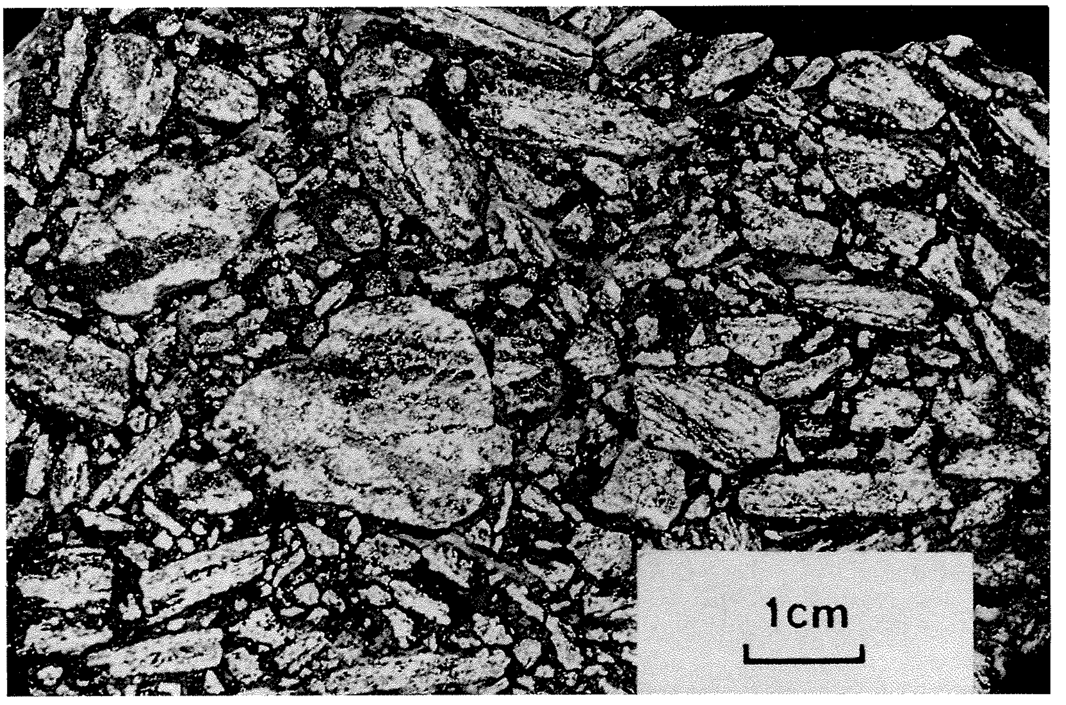


Figure 7. Laterite hardcap derived from porphyritic granite. Feldspar crystals have been replaced by gibbsite pseudomorphs. Original crystal orientation is preserved.

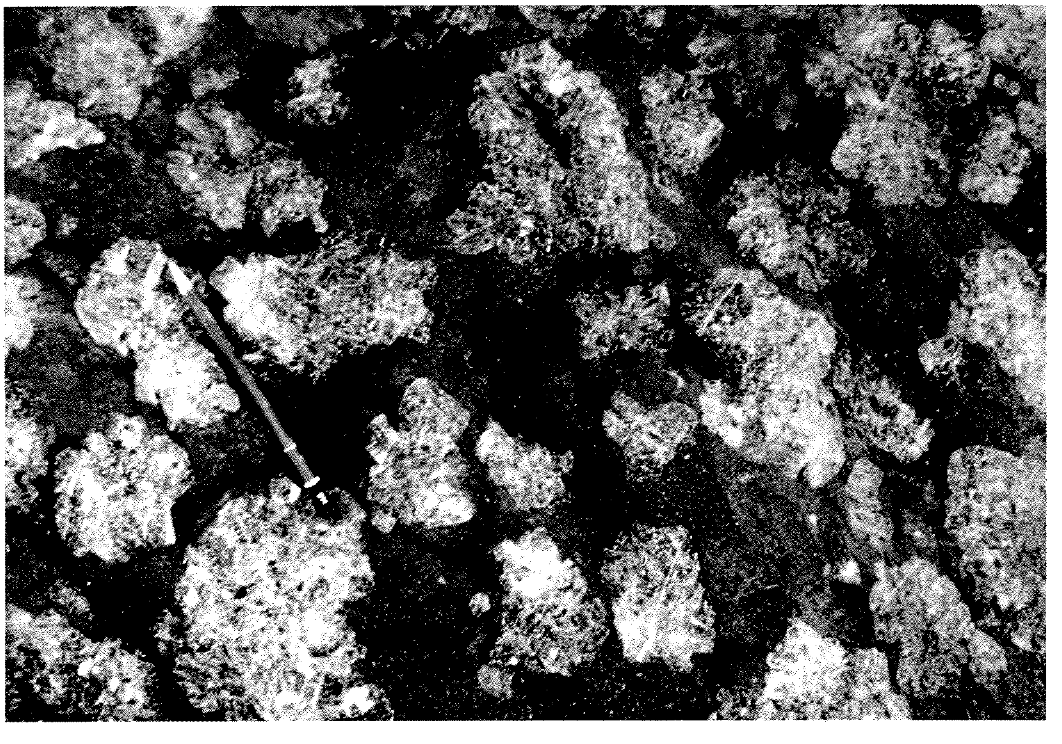


Figure 8. Outcrop of porphyritic dolerite ('Leopard Rock') near Dwellingup. Large clumps of feldspar (labradorite) phenocrysts are set in a typical dolerite matrix.

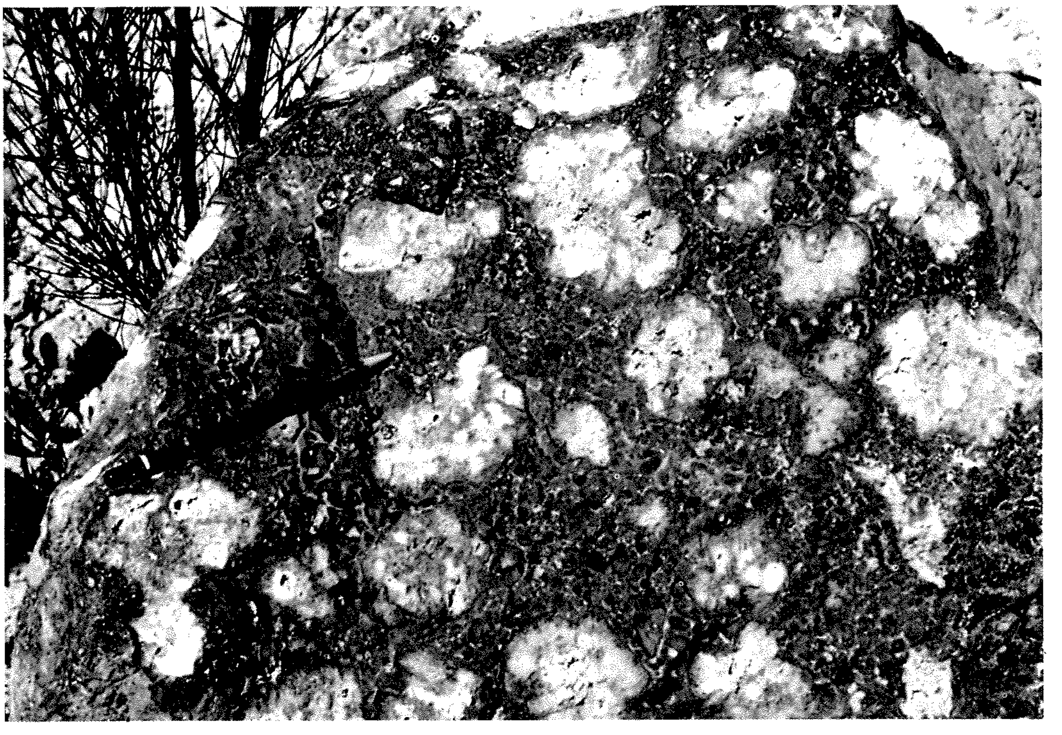


Figure 9. Texture of porphyritic doleritic (see Fig. 8) preserved in iron-rich hardcap near Dwellingup.

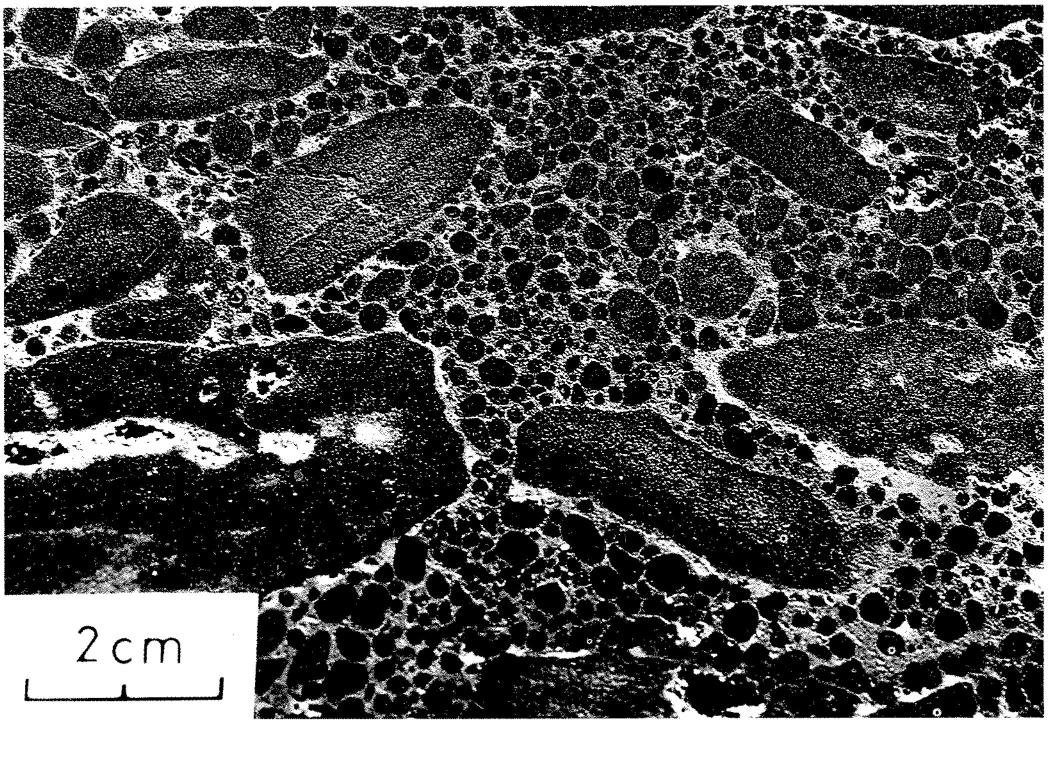


Figure 10. Pisolitic and nodular texture revealed in a thin section of iron-rich hardcap developed over metabasalt, Mt Saddleback.

The friable fragmental unit immediately underlies the duricrust, the two layers being separated by an abrupt contact. The unit is commonly about 2 m thick, although in mid-slope sites on large laterite ridges it can be up to 10 m thick, and at Mount Saddleback it reaches 20 m. The unit contains rounded to angular nodules, pisoliths and weathered rock fragments in a fine-grained, loose earthy or sandy matrix (Fig. 10). The coarser material ranges in size from less than 2 mm to over 10 cm and, occasionally, isolated 'floaters' of duricrust of the order of 1 m in diameter are present. Contacts between different bedrock types can sometimes be traced in the friable fragmental unit, using colour, fabric and textural variations arising from a combination of physical, chemical and mineralogical differences.

The upper part of the friable fragmental unit is characterized by nodules of gibbsite, and is usually stained brown by iron. This passes downwards into granular gibbsite (smaller grains) with, normally, less pronounced but still definite iron-staining.

The contact between the friable fragmental unit and underlying (basal) clay is commonly abrupt. The upper part of the clay may be mottled, but the clay zone becomes increasingly pallid with depth. The clay zone is normally 20–30 m thick. It passes downwards into greenish clay and then into altered bedrock, before fresh bedrock is reached. Where the clay overlies dolerite its basal contact is commonly very sharp, and may occur over a few centimetres. Over granites the contact between fresh rock and clay is often gradational over 2 m, and over metasediments may be as wide as 5 m.

The topography of the surface of unweathered bedrock is much more irregular than that of the duricrust at the surface (see an illustration in Davy and El-Ansary, 1986, p. 126–127). Pinnacles of bedrock, and isolated corestones can occur high in the profile, lessening the thickness of laterite.

Table 1 compares the overall mineralogical composition of laterite developed over granitic and mafic rocks, and Figure 11 examines vertical variations through typical profiles.

Gibbsite reaches maximum concentration in the duricrust and friable fragmental unit, decreasing quite rapidly as the granular part of the latter passes into the clay zone (Fig. 11).

Boehmite is often present in small quantities in the profiles (Grubb, 1971; Davy, 1979b). It is found mainly in the upper part of the duricrust and in overlying loose nodules, but Grubb (1971) also recorded it lower in the profile. Diaspore is not common, but is found with corundum in duricrust (Grubb, 1971).

Quartz is abundant (to 20%) in profiles derived from granitoids, but is much lower (<4%) in profiles derived from mafic rock (Fig. 11). Large quartz veins are rare, but small quartz veins are common, especially in association with major dolerite dykes. Where there are veins in the bedrock, residual quartz persists, getting gradually more disaggregated towards the surface.

Goethite may be found anywhere in the profile, but especially in the upper parts; it is totally absent only in the most extreme part of the pallid clay zone. The proportion of goethite usually drops at the contact between the friable fragmental unit and the underlying clay. Hematite, although much less abundant is nevertheless common, particularly in the duricrust (Sadleir and Gilkes, 1976). Where the profile is derived from mafic rocks, as at Mount Saddleback, hematite persists through the clay zone (Ball and Gilkes, 1985). Most maghemite occurs in the duricrust, and in pisolitic gravel overlying the duricrust, but some may also occur low in the profile. At the surface this magnetic mineral appears to result from dehydration of goethite; heat generated by bushfires may be sufficient to alter goethite to maghemite (Anand and Gilkes, 1987), and perhaps also gibbsite to corundum. At depth, maghemite may be formed by alteration of magnetite.

The main clay minerals are kaolinite and halloysite. Montmorillonoids and chlorite are present near the base of the clay zone. Kaolinite is present throughout the profile, but only in small amounts in good quality bauxite. However, it is much more common than gibbsite in poorer quality bauxites and ferruginous laterite, where it persists in abundance to the surface in an intimate admixture with iron oxide minerals. The exact relationships between halloysite and kaolinite distributions are not known.

Muscovite may persist throughout the profile over granitic rocks, though it is commonly reduced in the duricrust. Biotite, however, is represented by illite in the weathered profiles and may be totally decomposed in the duricrust. Rutile, monazite and zircon remain unaffected during lateritization, but sphene and ilmenite are altered to anatase or pseudorutile in the upper parts of the profile.

The major chemical components of bauxitic laterite profiles are aluminium, silicon, iron and oxygen; titanium, vanadium and zirconium are minor but important

Table 1. Mineralogical composition of bauxitic and ferruginous laterite

	Darling Range high-grade bauxite, derived from granitic rock (%)	*Mount Saddleback high-iron, low-quartz bauxite derived from mafic rock* (%)	*Ferruginous, pisolitic laterite (in situ)* (%)
Gibbsite	65	62	10
Boehmite	–	–	–
Goethite	18	32	20
Hematite	7	1	10
Maghemite	–	–	45
Quartz	9	1	5
Kaolinite/halloysite	1	2	–
Muscovite	0.25	–	–
Anatase/rutile	0.5	2	trace

(From Murray, 1979; Ball, 1983, pers. comm.)

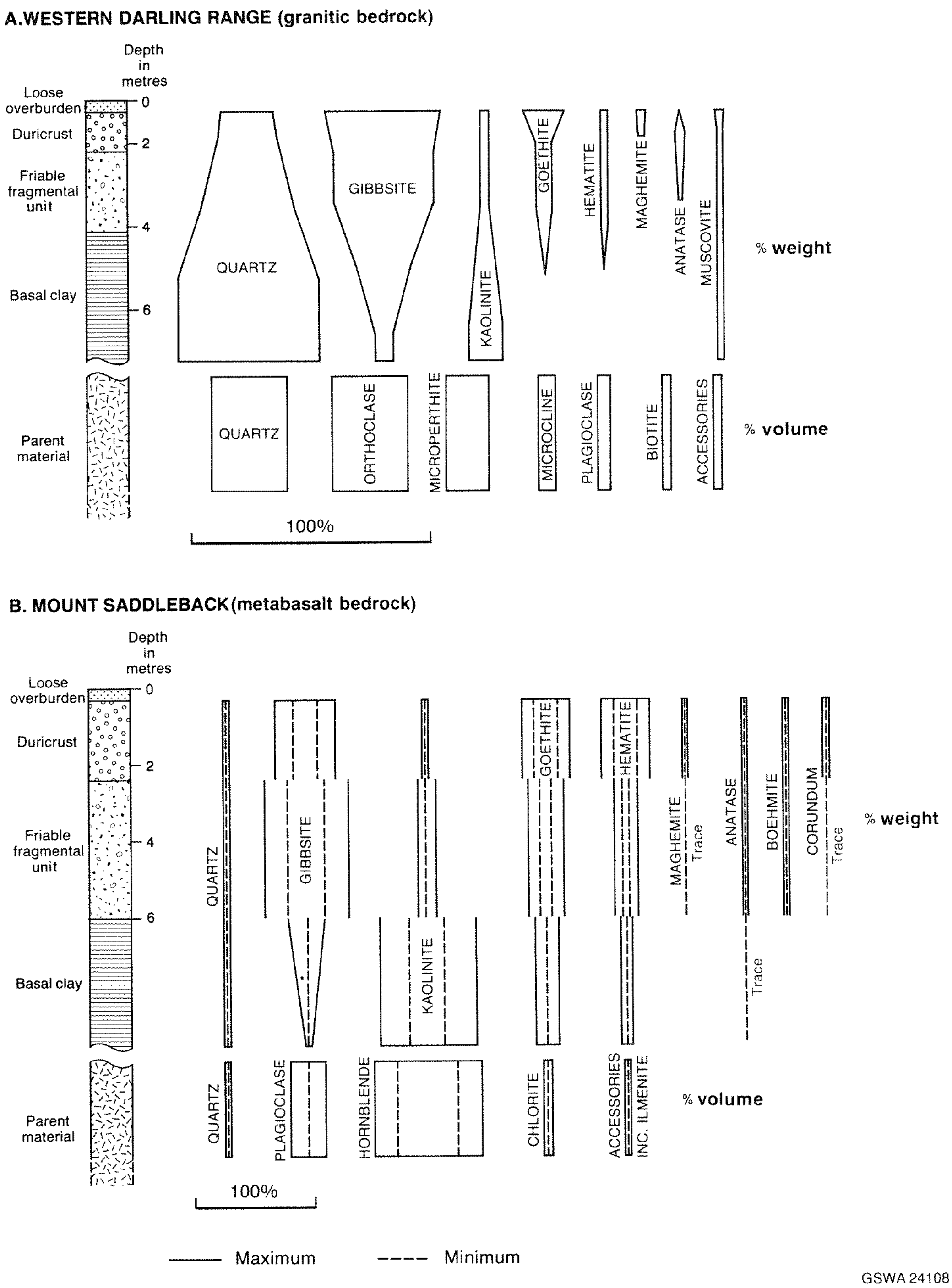


Figure 11. Mineralogy of Darling Range bauxitic laterite: (A) Western Darling Range (granitic bedrock); modified from Sadleir and Gilkes, 1976. (B) Mount Saddleback (metabasalt bedrock); from Ball and Gilkes, 1985 .

constituents. The concentration levels of these various elements are a function of bedrock geology, and the modifying influences of lateritization and subsequent weathering. Each element exhibits particular patterns of enrichment or depletion through the profile layers according to these factors.

Table 2 gives the chemical composition of typical duricrust derived from the chief rock types of the region. It illustrates the essential differences between the western Darling Range and Mount Saddleback areas, and the composition of duricrust over dolerite.

The greatest chemical changes between bedrock and the laterite profile take place at the interface between rock and clay. Elements which show the most change are the alkali and alkaline earth elements, which are substantially leached at this interface. Potassium remains in the profile

Table 2. Chemical composition of bauxitic and ferruginous laterite

	Darling Range		*Mount Saddleback*
	Bauxite derived from granitic rock	*Ferruginous laterite derived from dolerite*	*High-iron, low-quartz bauxite derived from mafic rock*
	(%)	(%)	(%)
Total Al_2O_3	40.5	16.6	35–45
Available Al_2O_3	37.5	11.5	28–35
Total SiO_2	21.8	9.8	2–3
Reactive SiO_2	0.3	0.4	1–2.5
Fe_2O_3	10.0	52.4	22–32
TiO_2	1.2	2.3	2–3
Loss on ignition	23.6	17.1	22–27

(Murray, 1979; Ball, 1983, pers. comm.)

where muscovite is present, but is lost from K-feldspar. Alteration of biotite to illite is accompanied by substantial, but not total, reduction in potassium.

Aluminium is a 'residual' element and, in comparison with bedrock, is enriched in the laterite profile. There is an abrupt rise in total aluminium at the bedrock–clay interface. Above this, the total aluminium content in the profile varies little, with only a slight increase towards the surface; however, the available alumina rises sharply between the clay zone and the friable fragmental unit. There is substantially less Av.Al_2O_3 in laterite profiles derived from dolerite because of the greater production and retention of clay near the surface.

Other residual elements include titanium, vanadium and zirconium, all of which have higher concentrations in duricrust than in bedrock, and tend to increase progressively from bedrock to the surface. Brimhall et al. (1988) concluded, however, that both rutile and zircon have been introduced into the bauxitic laterite profile from above. Rutile grains were extremely rounded and restricted to a near-surface zone extending into the duricrust, but not the friable fragmental unit; no rutile was identified in the granitic bedrock of the profile studied. Two populations of zircon were identified by Brimhall et al. (1988) — rounded grains restricted to the duricrust, and euhedral grains occurring throughout the profile. The euhedral grains were interpreted as having been derived from the granitic bedrock, whereas the rounded grains were regarded as having been introduced by translocation of exotic material from the surface.

Iron distribution in the profile varies in a series of steps which marks the contacts between duricrust and the friable fragmental unit, and between the latter and the underlying clay zone. Iron in the duricrust is always substantially

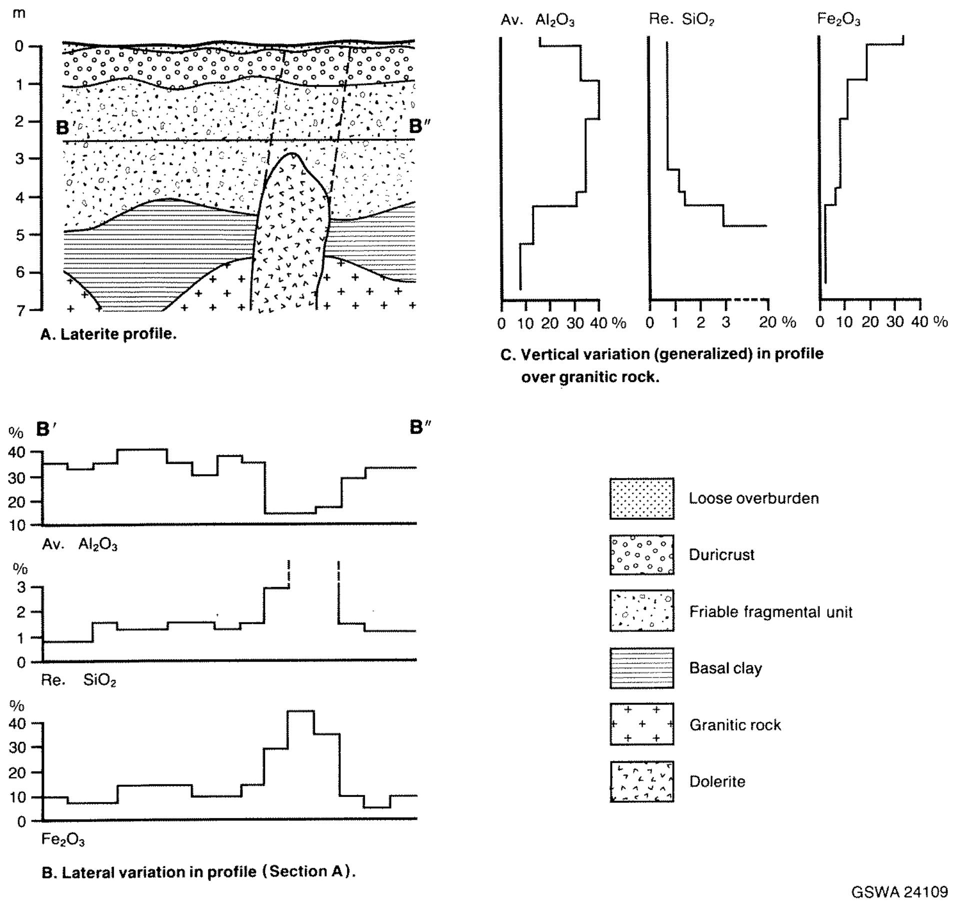


Figure 12. Laterite profile composition variations above granite bedrock intruded by a dolerite dyke (modified from Murray, 1974).

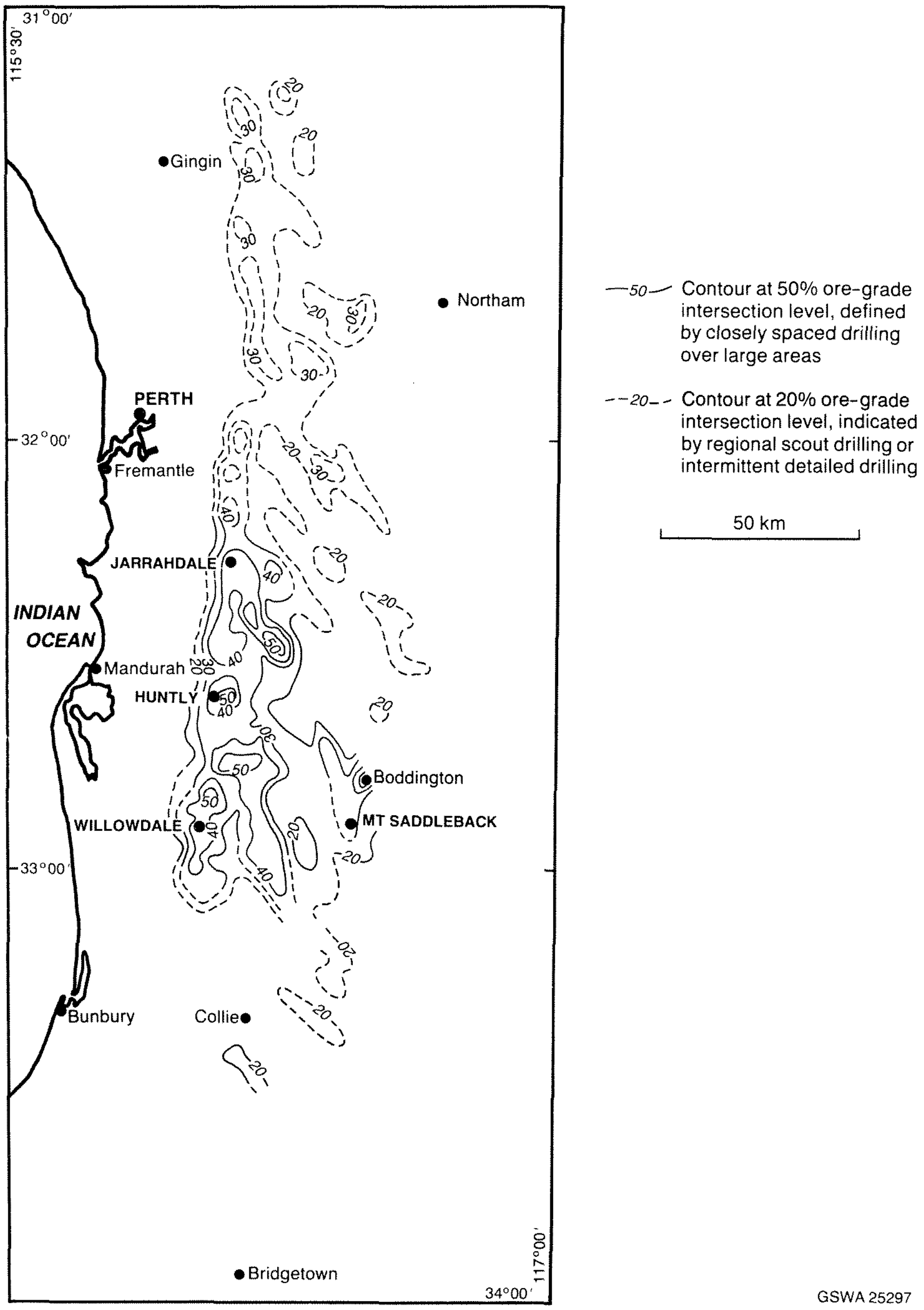


Figure 13. Distribution of bauxite in the Darling Range. Contours show percentage of ore-grade drilling intersections.

higher than that in bedrock; however, it does reflect the nature of the bedrock, with less iron in duricrust over granitoids than over dolerite (Fig. 12). Thus, there are pronounced lateral changes in iron concentration where laterite derived from granitoids passes into laterite derived from mafic rocks. Further major changes occur where residual laterite passes laterally into lower slope, transported laterite; however, these changes are not systematic but depend on the nature of the uphill duricrust, and on effects related to the transport processes of iron.

Silica patterns in the profile depend on the nature of bedrock. Silica decreases upwards across the contact between bedrock and clay but, because of bulk density changes, appears to have similar values above and below the interface. Any quartz present tends to be retained at the surface, though it gets 'fritted' with gradual dissolution of the silica. Thus, though values are always higher in the lower parts of the profiles than near-surface, surface silica values remain relatively high (up to about 25%) over granitoids and other quartz-bearing rocks such as some metasediments. Aluminosilicates are more reactive, and as they pass from primary minerals to clays, and then to gibbsite, silica is lost and there is a fairly sharp break in SiO_2 concentration between the clay zone and the friable fragmental unit. Re.SiO_2 behaves similarly; there is a

Table 3. Types of bauxite ore in the western part of the Darling Range: variations in mineralogy according to laterite origin, position in the laterite profile, and bauxite fabric.

		Laterite origin				
		Granitic or gneissic bedrock			*Basaltic or doleritic bedrock*	*Mixed: in situ and transported*
		Fragmental	*Fragmental-pisolitic*	*Pisolitic*	*Fragmental-pisolitic*	*Pisolitic*
DURICRUST						
Bauxite fabric		Angular fragmental nodules set in a goethite–hematite matrix	Composite of both angular and pisolitic nodules set in a goethite–hematite matrix; iron concentrated in pisolites	Predominantly pisolitic; iron concentrated in pisolites	Angular and pisolitic nodules set in a goethite–hematite matrix. Cellular or open, vuggy texture is common	Maghemite pisolites cemented in a very hard matrix of hematite (in situ) or weakly cemented in a hematite–goethite–gibbsite matrix (transported)
		Percentage				
Mineralogy	Gibbsite	60	60	40	40	10
	Quartz	20	20	15	5	10
	Goethite	15	15	25	35	20
	Hematite	-	-	10	5	20
	Maghemite	-	-	5	-	40
	Kaolinite	-	-	-	15	-
FRIABLE FRAGMENTAL UNIT						
Bauxite fabric		As for duricrust	Less pisolitic than duricrust	Less pisolitic than duricrust	More nodular and rubbly than for profiles formed over granitic or gneissic bedrock	Non-pisolitic
		Percentage				
Mineralogy	Gibbsite	60	60	55	45	40
	Quartz	20	20	20	5	20
	Goethite	10	10	15	35	15
	Hematite	-	-	-	-	10
	Maghemite	-	-	-	-	10
	Kaolinite	Minor	Minor	8	15	5

major drop in its proportion between the clay zone and the friable fragmental unit, and it may be effectively absent from the duricrust.

Examples of major and trace element compositions at various points through bauxitic laterite profiles are given in Sadleir and Gilkes (1976), Davy (1979b), Davy and El-Ansary (1986), and Monti (1987).

Bauxite mineralization

Bauxite deposits are alumina-enriched lenses within lateritic 'country rock' and, in the Darling Range area, ore-grade bauxite is encountered over about 20% of the area occupied by laterite (Figs 4 and 13). There is, however, a clearly defined area in which economic bauxite mineralization is concentrated. This area extends about 30 km east from the Darling Scarp, and 150 km south from Perth's eastern suburbs to the Harris River area north of Collie. Figure 13 also reveals a northwesterly linearity to zones of bauxite concentration. This orientation corresponds to both the structural grain of underlying bedrock and, commonly, lithological boundaries. The latter have influenced topography so that ridges and valleys tend to be orientated in a northwesterly direction. Factors controlling bauxite distribution are discussed in Chapter 3.

Bauxite mineralization is restricted chiefly to the duricrust and friable fragmental units of the laterite profile. Bauxite locally occurs in the clay zone, but not in economic concentrations. In some situations, where clay is absent, gibbsite in the friable fragmental unit passes directly into bedrock. Subvertical pipes and shoots of bauxite are also known where weathering has progressed more rapidly along shear zones or joints; some of the larger shoots are mineable.

The most important mineral constituent of the bauxite ore, gibbsite, not only decreases in concentration below the friable fragmental unit, but also downslope as iron content increases. Where dolerite underlies the crests of ridges, the bauxitic laterite contains more 'unwanted' constituents such as iron and clay.

Ore thicknesses over granitic bedrock range from 2 to 7 m. In the Mount Saddleback region, bauxite ore overlying mafic greenstone bedrock is generally 6–7 m thick, and locally attains a thickness of 20 m. Generally the base of the ore zone is broadly parallel to ground surface. However, in detail it is extremely irregular with levels changing by 3–5 m over horizontal distances of 10–15 m.

Bauxitic laterite is generally reddish brown to yellow with white patches. Profiles formed over granitic rocks are paler than those formed over mafic rocks.

Types or 'categories' of bauxite ore in the Darling Range can be distinguished on the basis of texture and mineral composition (Table 3). As outlined above, the differences between these categories relate to laterite profile alteration processes as they affect various types of bedrock.

Economic deposits

In addition to the five existing mines at Jarrahdale, Huntly, Del Park, Willowdale and Mount Saddleback, many other large, potentially mineable deposits are shown on Figure 14, and are briefly described in Table 4. However, there are, in fact, hundreds of potentially mineable bauxite deposits in the area, and only the largest have been distinguished. Development of many of the deposits is constrained to varying degrees by alternative landuse considerations, such as conservation parks and reserves, water catchment areas, and private land.

Jarrahdale

The bauxite deposits at Jarrahdale have been commercially mined since 1963, and to the end of 1990 total production of alumina was 30.4 Mt; current production is about 1.7 Mt alumina per annum, and bauxite resources are 26 Mt proven reserves and 114 Mt inferred resources.

Table 4. Large, potentially mineable bauxite deposits (excluding current mining areas) in the Darling Range

Deposit	*Bauxite Resources* (Mt)	*Bauxite Resources* (Mt/km2)	*Archaean Bedrock*	*Height ASL* (m)
Bindoon Hill	25	1.7	Granitic gneiss	200
Bombala	14	3.0	Granite	300
Cameron	16	1.7	Granite	300
Churchman	11	3.5	Migmatitic gneiss	300
Clarke Hill	30	2.7	Porphyritic granite	300
Clinton	36	2.4	Granite	250
Dingo Knob	17	2.2	Porphyritic granite	250
Hoffman	22	3.6	Granite	300
Holmes	43	5.0	Porphyritic granite	250
Holyoake	23	3.8	Porphyritic granite	250
Howse	70	4.0	Granite	300
Inglehope	51	3.2	Porphyritic granite	300
Julimar	(a) 10–20	(a) 1–2	Granite	300
Karnet	24	3.3	Granite	300
Lower Chittering	30	2.0	Gneiss and granite	250
Marradong	14	2.6	Basalt and sediment	300
Mount Solus	32	2.7	Granite	450
Mount Wells	16	1.8	Basalt	400
Mungalup	8	3.0	Granite	300
Myarra	30	2.5	Granite and gneiss	300
Nanga	17	3.5	Granite	250
O'Neil	13	2.0	Granite	350
Pindalup	28	2.4	Granite	300
Plavins	51	5.1	Porphyritic granite	250
Spion Kop	37	4.0	Granite and gneiss	300
Taree	22	1.4	Granite	300
Tower Hill	16	1.8	Porphyritic granite	350
Waroona	73	3.5	Granite	300
Wundowie	10	1.5	Granite and schist	300
Yarragil	40	3.0	Granite	300

(a) No detailed drilling; estimate very approximate

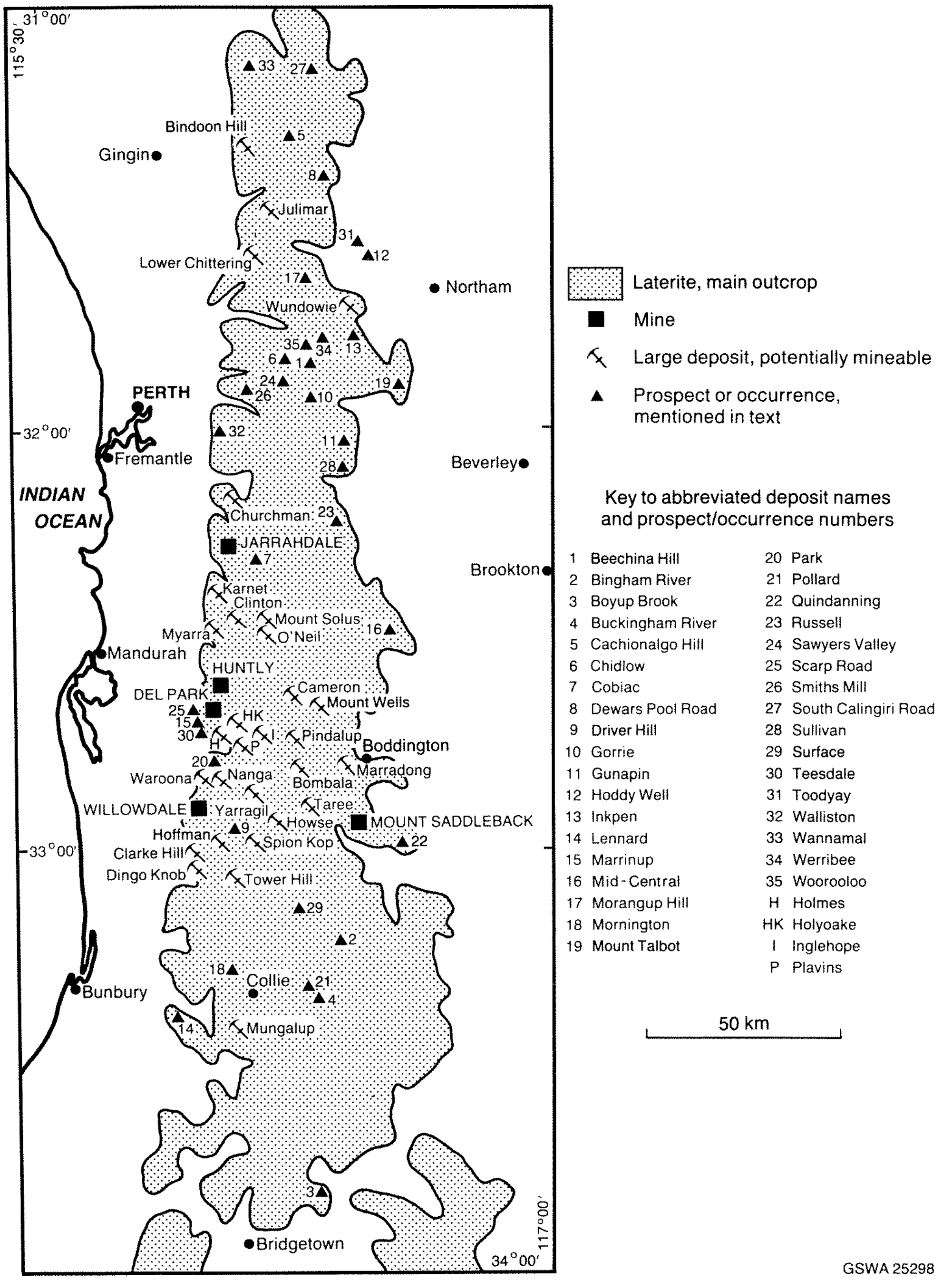


Figure 14. Bauxite mines, large deposits, prospects and selected occurrences in the Darling Range

Figure 15 shows the distribution of the bauxite deposits at Jarrahdale, and the extent to which mining has been completed within the 25-year mining plan area. The bauxite occurs in discontinuous lenses, which are best developed on hill slopes rather than crests or valley floors. Individual orebodies vary in area up to 80 ha, and locally attain a thickness of 12 m (the average thickness is 4 m).

The Archaean bedrock consists principally of low-grade, even-grained and porphyritic granite, although some migmatite gneiss occurs in the northwest part of the Jarrahdale area. Lateritized mafic intrusive rocks locally underlie ore-grade bauxite (e.g. at Cobiac), but more commonly form the boundaries of orebodies. Mafic intrusions include both dolerite and gabbro and have two dominant strike directions: north-northwest and westerly. The first set consists of dykes which are 5–50 m wide and are more numerous than those of the second set which can reach widths of up to 100 m. A third set trends north-northwest or north, and dykes of this type are generally less than 20 m wide. A few mica-rich mafic dykes have irregular (but generally low angle) dips and variable strikes.

Bauxitic laterite cover is extensive except on the steeper slopes of the Wungong and Serpentine catchments.

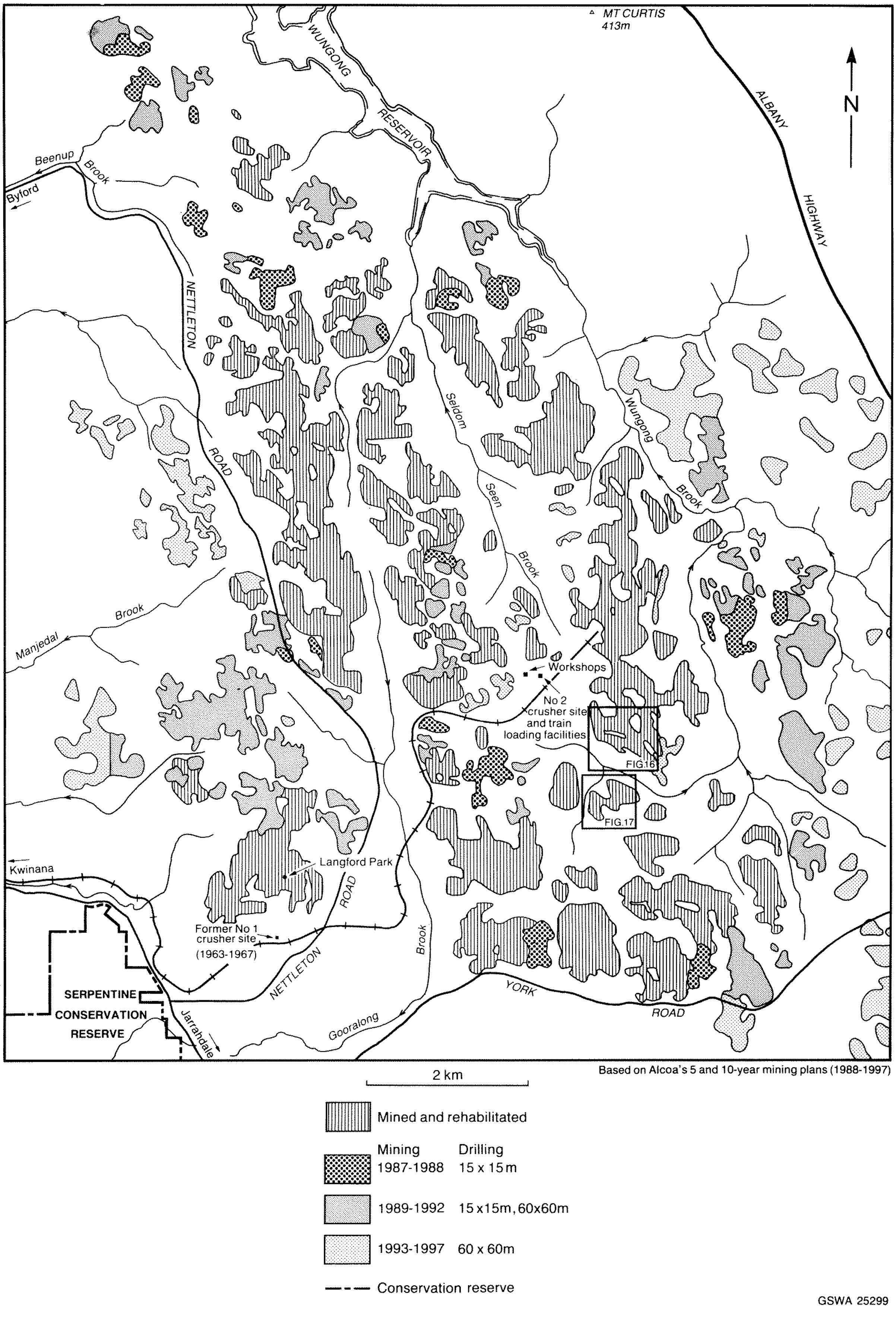


Figure 15. Jarrahdale bauxite deposits.

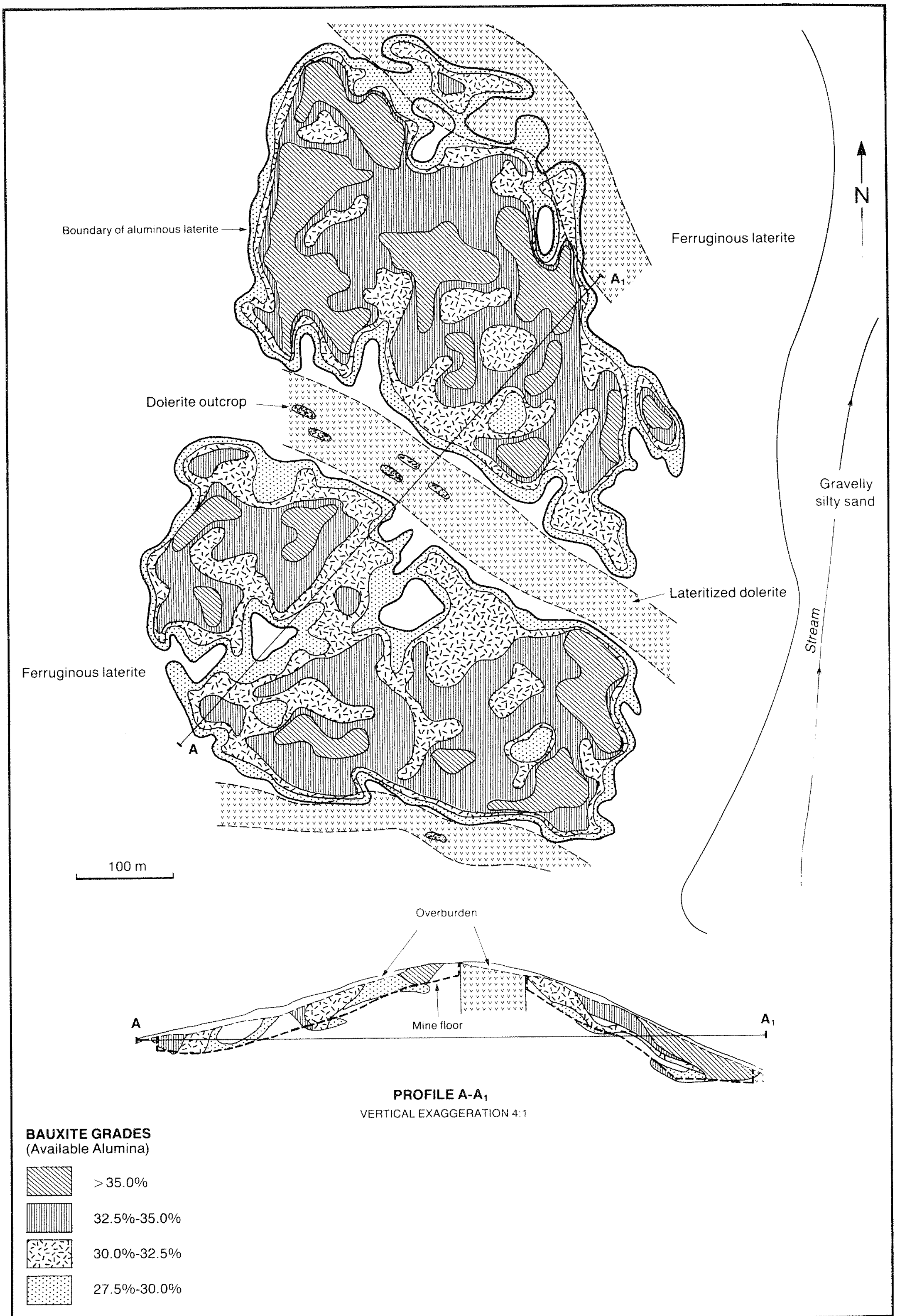


Figure 16. JW 418 bauxite deposit, Jarrahdale, showing lateral variation in Av.Al_2O_3 (modified from Kirke and Murray, 1979).

Duricrust textures are mainly fragmental-massive and pisolitic. Ferruginous fragmental and tubular textures are associated with lateritized mafic dykes. Gibbsite and quartz are abundant, and outcrops with relict bedrock textures are prolific.

Evidence of the geological controls governing bauxite mineralization at Jarrahdale is seen at three localities: JW 418, JW 415, and Jarrahdale railway cutting. Figure 16 illustrates both lateral and vertical features of JW 418, an orebody mined at Jarrahdale by Alcoa in the mid-1970s. Alumina concentrations in the mid-slope are influenced by the lateral progression from a laterite derived from granite to material derived from mafic intrusives. Ore margins are also fixed by iron accumulations along the lower slope.

The crest of the ridge at JW 418 is occupied by a large dolerite dyke represented by outcrops of fresh rock enclosed in an aureole of ferruginous laterite. The northeastern and southwestern ore boundaries are, similarly, lateritized dolerite.

The cross section included in Figure 16 shows the vertical boundary between ore and non-ore. The mine floor represents, effectively, a balance between chemical grades and the mechanical and safety capabilities of mining equipment.

JW 415 (Fig. 17) shows the disposition of mafic dykes and granitic bedrock outcrops in relation to bauxite. This deposit occurs on the southern extremity of the Seldom Seen Ridge: it is notable for its relatively high-grade bauxite, with 32.5–33.0% Av.Al_2O_3, and 1.9–2.5% Re.SiO_2. Mining reveals many features which are normally obscured by soil and vegetation. Contacts between granite and dolerite can be followed vertically up the pit face to the surface. The doleritic fabric or texture preserved in the duricrust can then be used to map the strike continuation of the contact.

Most profiles created by mining are quickly lost as mining proceeds. One of the more permanently accessible cross sections is that in the Jarrahdale railway cutting. This cutting provides a profile through the laterite to bedrock, which here consists of granite intruded by dolerite dykes; the latter can be traced vertically through the profile.

The granitic rocks in the cutting are a mixture of monzogranite and migmatite. The presence of deep shears has resulted in differential weathering to produce a large area of kaolinitic basal clay. Transported iron partly masks the contact between granitic and mafic rocks.

The subsurface geology revealed by the cutting has been extensively investigated by Grubb (1964), Sadleir and Gilkes (1976); Davy (1979b) and by Alcoa (Baker, 1972; Murray, 1979). Channel sampling in 1974 by Murray and Smurthwaite (Alcoa) established a series of traverses across the main mafic dykes. Bauxite mineralization patterns were then identified and related to the geological features revealed during mining.

Figure 12 shows the lateral and vertical grade patterns revealed in the northern face of the railway cutting. Iron content increases and Av.Al_2O_3 decreases as the sampling approaches the laterite derived from dolerite. This pattern is repeated in drill traverses in the orebody south of the railway cutting. This orebody totalled some 250 000 t and was mined between 1983 and 1985.

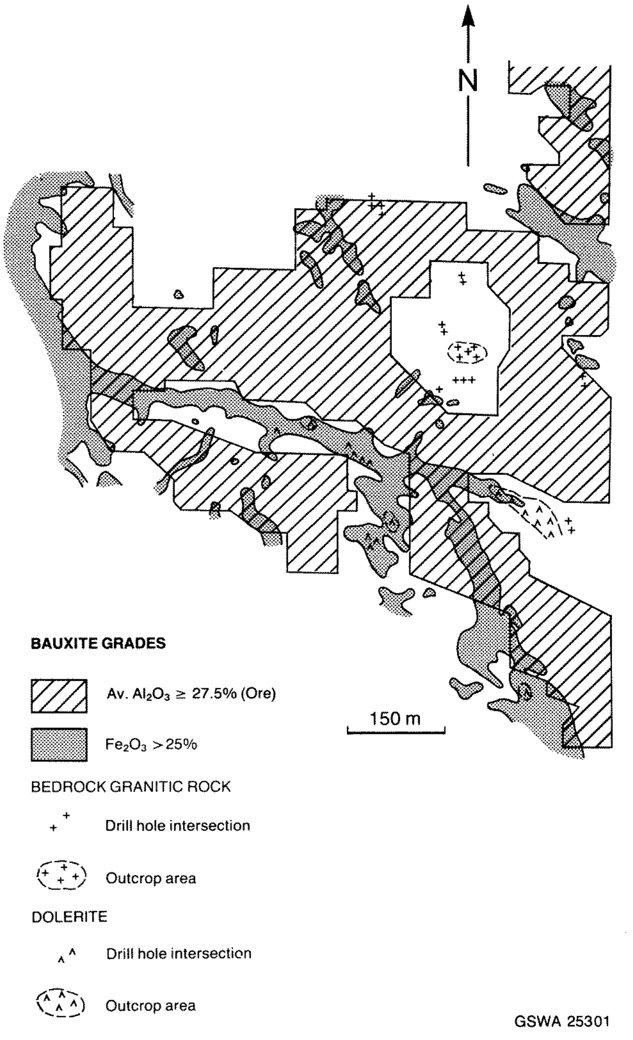


Figure 17. JW 415 bauxite deposit, Jarrahdale, showing the relationship between bauxite composition and bedrock (modified from Baker, 1975).

Up to 80% of the bauxite mined at Jarrahdale is derived from granitic rocks. 'Granitic bauxite' ore parcels have the following grades: 20–45% Av.Al_2O_3 (average 33.0%), 0.5–2.5% Re.SiO_2 (average 1.3%) and 14.0% Fe_2O_3. The remaining material contains 15–20% Av.Al_2O_3 (average 18.0%), 0.8–4.0% Re.SiO_2 (average 1.8%) and 18.0–45.0% Fe_2O_3 (average 27.0%). By a judicious mixing of these ore parcels, the Kwinana Refinery is provided with an even blend of ore.

Huntly–Del Park

The Huntly and Del Park mine sites are situated near Dwellingup, about 50 km south of Jarrahdale. Mining commenced in 1972. From 1972 to December 1990 the

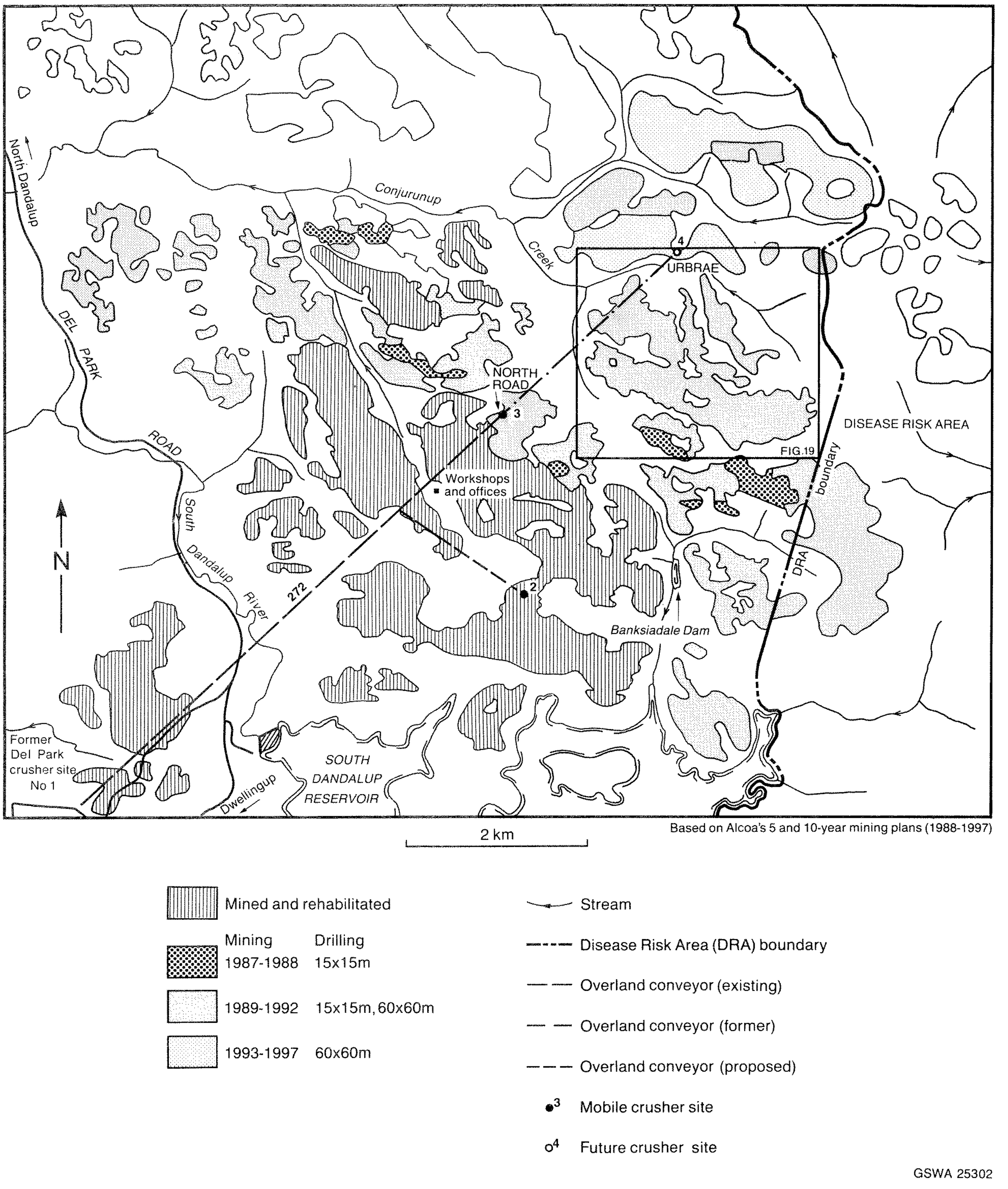


Figure 18. Huntly bauxite deposits.

combined production was 40 Mt alumina. Current production is about 2.9 Mt alumina (from over 10.3 Mt of bauxite) per annum.

The Huntly–Del Park area contains some of the thickest bauxite deposits in the Darling Range. Over 50% of Alcoa's proven reserves lie in this region. The average ore thickness at Del Park is 5 m, and the Huntly ore averages 8 m in thickness; maximum thicknesses are 11 m at Del Park and 13 m at Huntly. The orebodies are lenticular and generally elongate northwest, reflecting topography and the underlying structural grain of the granitic bedrocks. As at Jarrahdale, deposits are most fully developed in mid-slope situations, and are generally relatively thin over the crests of ridges. At Huntly the 25-year mining plan covers an area of about 150 km^2. To date, mining at Huntly has been confined to the south-western part of the 25-year plan area (Fig. 18) between South Dandalup River and Conjurunup Creek.

Bedrock is chiefly low-grade Archaean granite intruded by dolerite and amphibolitic dykes. The granite is commonly foliated, and a 'gneissic' texture has been reported from some mine faces. Where dolerite or gabbro bedrock is present iron contents rise sharply in the bauxite, and its chemistry is variable. Ore from mafic zones is blended with the chemically more homogeneous granite-derived material to minimize grade variations. Figure 11 (A) and Tables 5 and 6 summarize the mineralogy and chemistry of the bedrocks.

In most deposits, Av.Al_2O_3 and Re.SiO_2 show a marked inverse relationship. This is attributable to the desilicification of kaolinite to form gibbsite. The most significant, and sharpest change, occurs at the base of the profile where the ore zone gives way to basal clay. Similar changes are encountered laterally across the transition from laterite derived from granite or gneiss to ore developed from dolerite or gabbro. Although the inverse relationship of Av.Al_2O_3 and Re.SiO_2 and the equally sharp rise in iron are characteristic, the over-riding feature is pronounced chemical variability. High Re.SiO_2 can occur at any level within the profile. Two worked-out deposits, Scarp Road and Marrinup, had coincident high Av.Al_2O_3 and Re.SiO_2. These may have been related to weathered pegmatitic zones and localized fault breccias.

Orebodies range in size from 0.5 to 12 Mt and average 5–6 Mt. One of the largest orebodies delineated in the area is the 11 Mt deposit at Urbrae in NE Huntly (Fig. 19). This deposit has most of the salient geological features encountered in the area: these include thick ore along ridge flanks, and re-entrants with deep pockets of pisolitic gravels which are partly cemented by transported iron. Figure 19 (A–D) is based on ore production and geological data gathered by Alcoa in delineating this large orebody. By comparing Figure 19A with Figures 19B, 19C and 19D it is possible to appreciate the interrelationship between topography, geology and the resultant chemical grades and patterns. In delineating the lateral boundary of the ore, Alcoa's mining geologists have had to balance overall grade with the limitations imposed by safe mining operations.

Bauxite at Urbrae is a mixture of material derived from the weathering of granitic gneiss and from the weathering of mafic dykes. Av.Al_2O_3 grades (Fig. 19B) illustrate the homogeneity of bauxite derived from granitic gneiss compared with that derived from dolerite. The iron pattern of Figure 19C shows the strong correlation between high iron and dolerite, and also the accumulations of transported iron on lower slopes and in valley heads.

The Re.SiO_2 pattern illustrated in Figure 19D is a function of ore thickness and the highly variable nature of mine-floor gradients.

The deposit exemplifies the correlation of high iron, high Re.SiO_2 and low Av.Al_2O_3 with gabbroic dykes and ferruginous pisolitic laterite. It contrasts the homogeneity of bauxite formed from granitic gneiss with the heterogeneous nature of material derived from dykes.

An atypical occurrence of bauxite occurs at G211, Del Park, over a mafic pegmatitic dyke. The duricrust contains gibbsitic cobbles in a ferruginous matrix. The friable fragmental unit consists of a metre and a half thick mass of feldspar pseudomorphs. Lower in the profile, the partly weathered pegmatitic dyke has large labradorite laths and abundant coarse quartz. Iron staining denotes the former presence of pyrite.

Willowdale

Bauxite mining at Willowdale commenced in 1984; total alumina production to the end of 1990 was 4.6 Mt, and annual production in 1990 was 0.8 Mt. Proven bauxite reserves are currently 13 Mt, and inferred bauxite resources are 46 Mt.

Table 5. Mineralogical composition of typical Darling Range granitic and doleritic rocks

	Granitic rock (%)	*Doleritic rock* (%)
Feldspar:		
K-feldspar	20-30	-
Plagioclase (sodic)	20-30	-
Plagioclase (calcic)	-	40
Quartz	35-45	5-10
Hornblende	-	50-60
Biotite	5-7	-
Accessories	sphene, apatite white mica, opaques, zircon	iron and titanium oxides, apatite epidote, chlorite

Source: Alcoa (unpublished data)

Table 6. Chemical composition of typical Darling Range granitic and doleritic rocks

	Granitic rock (%)	*Doleritic rock* (%)
SiO_2	74.8	49.5
TiO_2	0.14	2.1
Al_2O_3	13.9	12.9
Fe_2O_3	0.78	2.6
FeO	0.97	11.4
MnO	0.02	0.35
MgO	0.22	6.2
CaO	1.9	10.4
Na_2O	3.9	2.1
K_2O	3.3	0.36
H_2O^+	0.14	2.2
H_2O^-	0.24	0.09
P_2O_5	0.05	0.16
Total	100.4	100.4

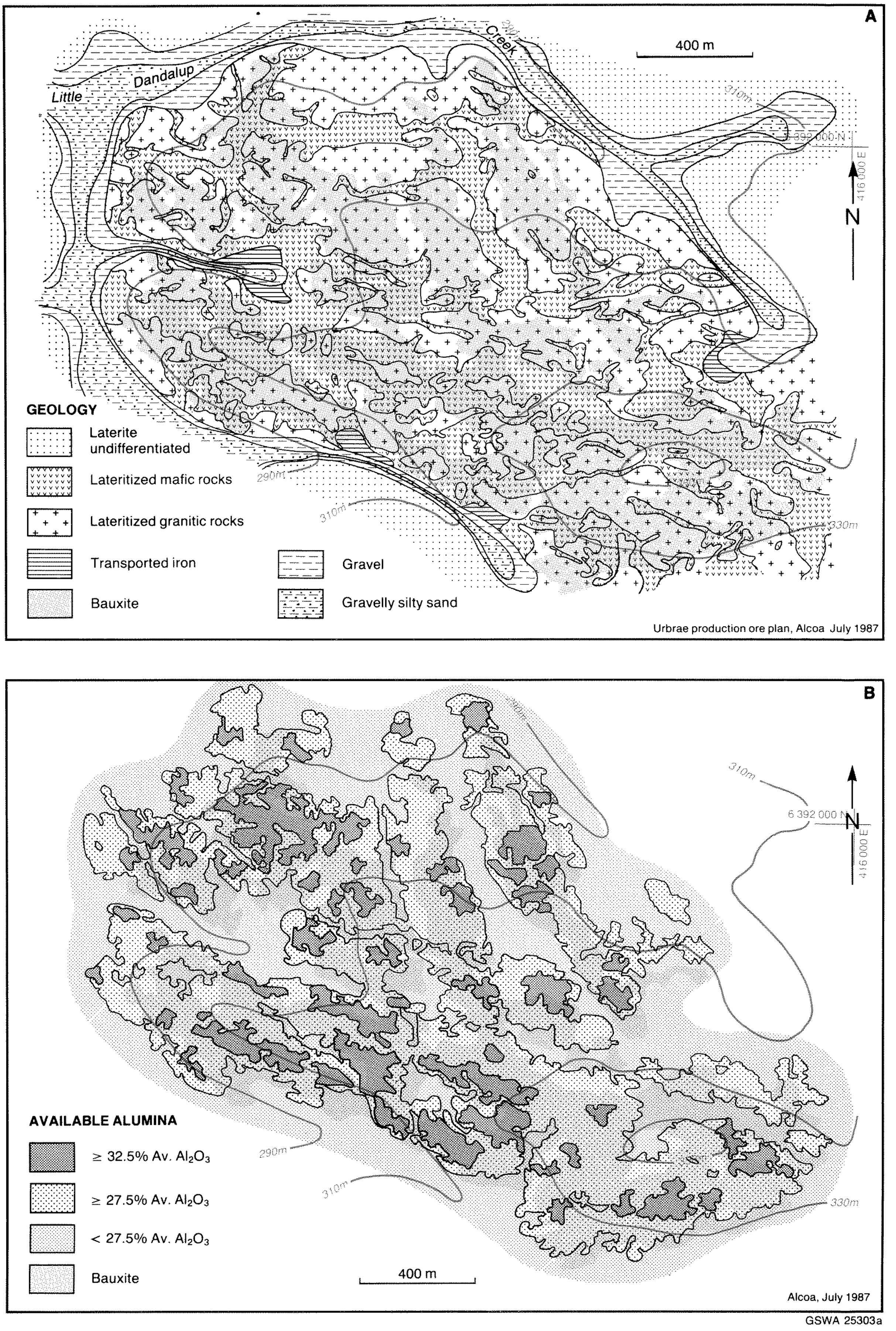
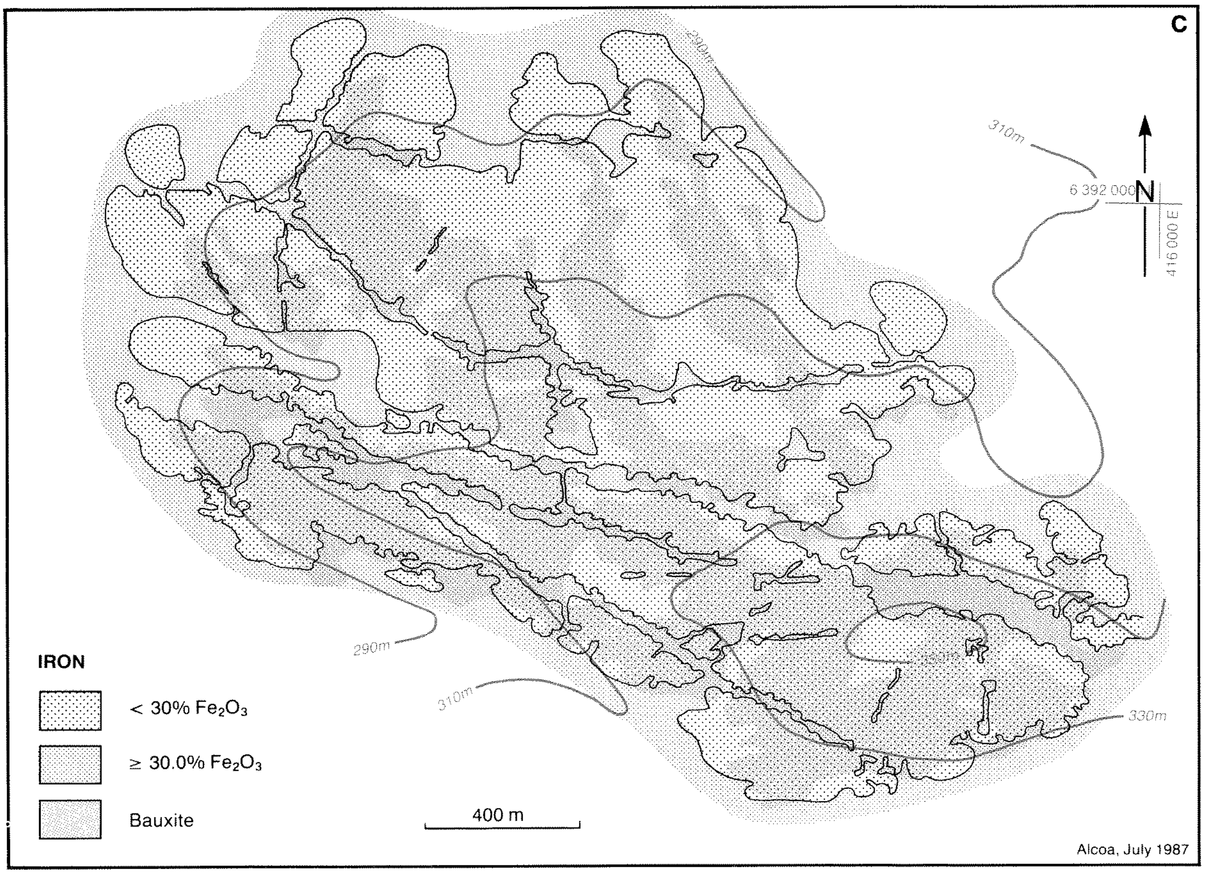
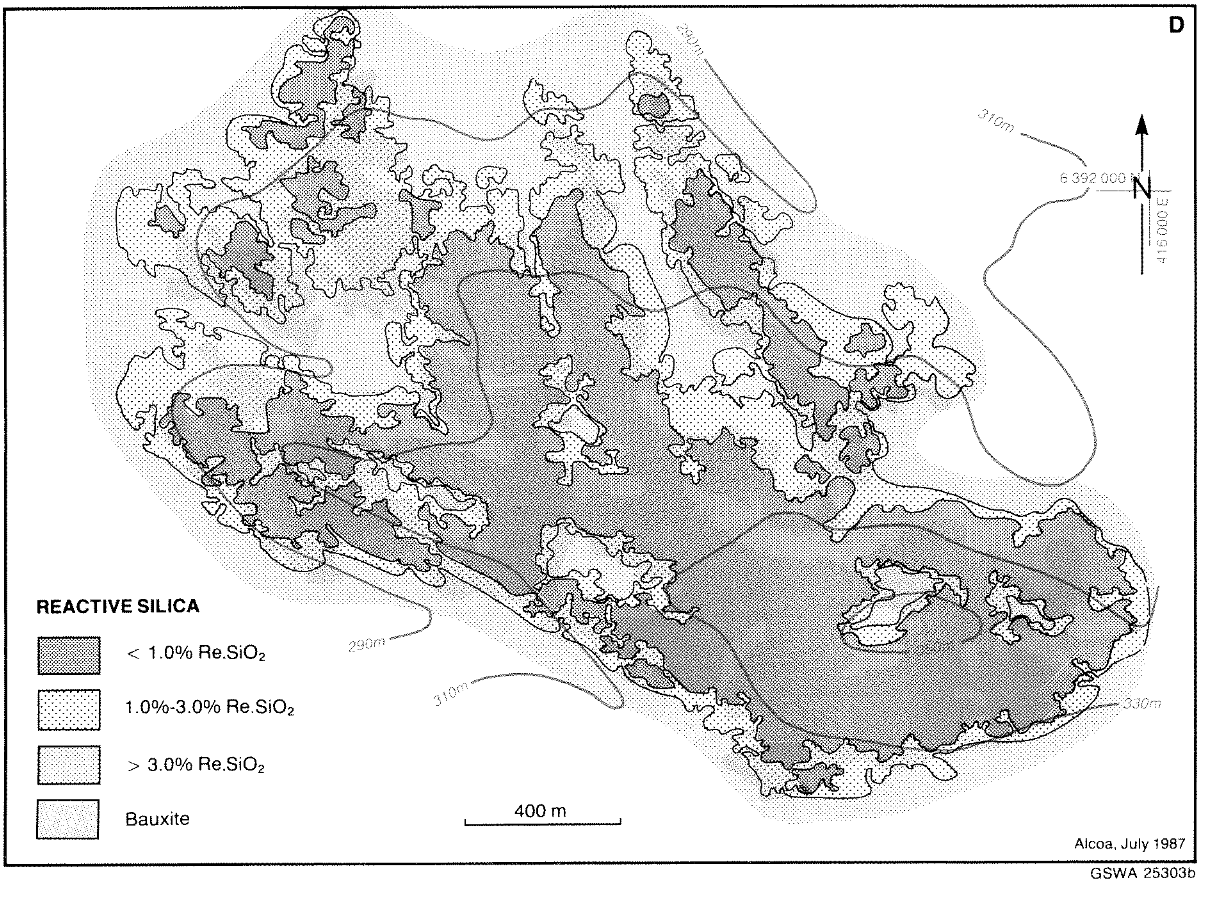


Figure 19. Urbrae mining area, Huntly: A. Geology; B. Av.Al_2O_3.





GSWA 25303b

Figure 19. Urbrae mining area, Huntly: C. Iron (Fe_2O_3); D. $Re.SiO_2$.

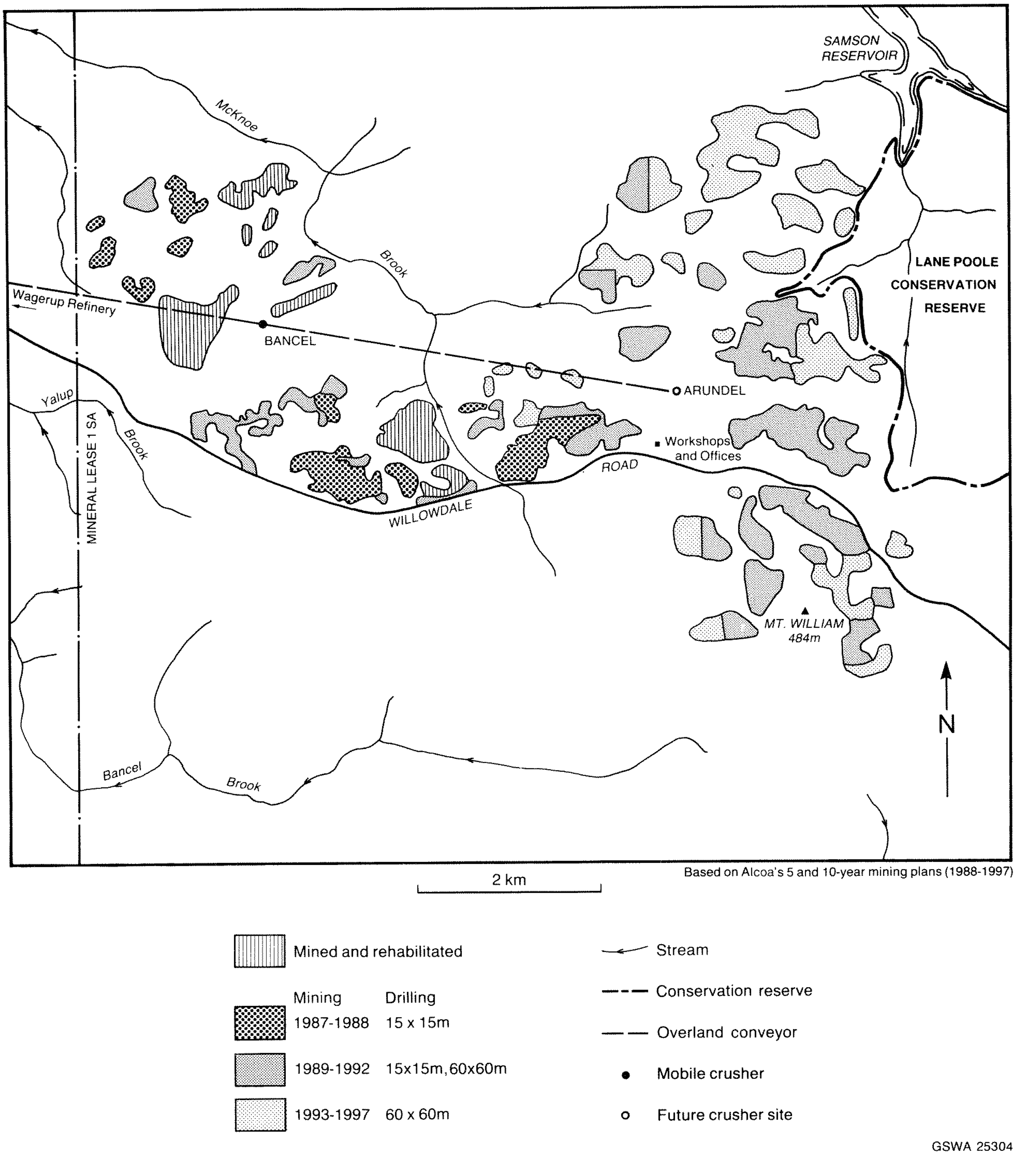


Figure 20. Willowdale bauxite deposits.

Figure 20 shows the distribution of bauxite deposits in the Willowdale 25-year mine plan area. The bauxite chiefly overlies relatively massive porphyritic granite, and as a consequence the orebodies show no preferred orientation. The western deposits, adjacent to the Darling Scarp, have formed from the weathering of gneiss and, in some isolated instances, schist.

Mafic dykes are common throughout the area and consist of dolerite, gabbro or amphibolite; discrete areas of banded iron-formation are also present.

Mafic rocks, such as gabbro and amphibolite, are abundant in the ridges near the scarp and at Kooyong; and farther south at Clarke Hill. They have weathered to ferruginous laterite and black gravel. In a few cases they have produced laterite with economic alumina grades.

Better grades occur with bauxite formed from gneiss than with ore derived from granite; similarly with ore derived from relatively massive and little metamorphosed dolerite as opposed to amphibolitic metadolerite.

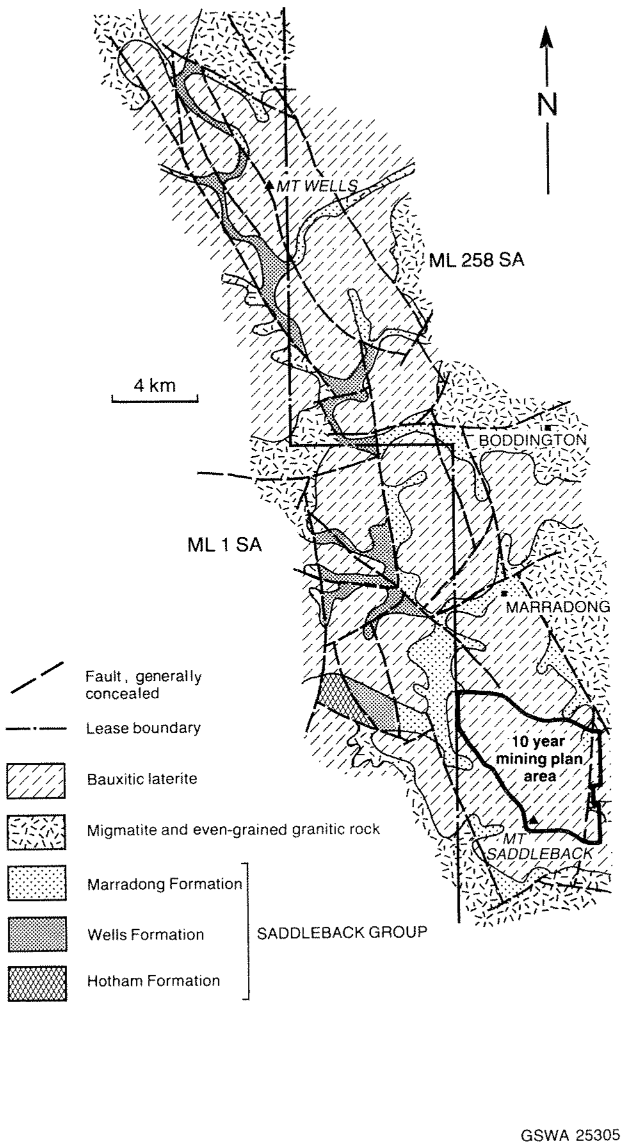


Figure 21. Geology of the Mount Saddleback area (bedrock geology simplified after Wilde, 1976a).

Bauxite deposits occur on the upper and mid-slopes of Mount William. The summit of this 482 m hill has thin laterite over large gabbroic dykes. On the northeastern slopes of the hill, gibbsitic feldspar pseudomorphs in outcrops of bauxitic laterite reveal a porphyritic granitic origin.

The Bancell crusher site utilized bauxite mined from freehold land owned by Alcoa as well as bauxite mined from forested areas.

The bauxite deposits of Bancell Ridge have almost been mined out. In early 1988, the Arundel crusher site came into operation. The shift to Arundel of the mobile crusher was earlier than originally planned. High extractable organic carbon (EOC) values at Bancell and Kooyong have obliged Alcoa to bypass bauxite from these two areas and to access better grade ore at Arundel.

The Wagerup alumina refinery's liquor stream has registered major increases in organic levels. These levels are almost the equivalent of those present in the circuit of the 27 year-old Kwinana refinery. Alcoa's strategy has been to defer mining ore which has EOC values greater than 2.0 kg/t bauxite until the Wagerup liquor stream has recovered. The expansion at Wagerup in 1990 had the effect of diluting the liquor stream. However, it is anticipated that eventually a liquor-burning plant will be installed at Wagerup.

Mount Saddleback

The Mount Saddleback bauxite mining operation of WAPL is unique among the Darling Range mines, firstly in that it is located on bauxitic laterite derived chiefly from mafic volcanic rocks, and secondly in that the deposits are located a considerable distance (about 45 km) from the Darling Scarp. Mining at Mount Saddleback commenced in 1983, and total alumina production to the end of 1990 was 7.2 Mt; in 1990 alumina production totalled 1.4 Mt, and proven reserves of bauxite were reported to be 18 Mt.

The bedrock geology of the Mount Saddleback area (Fig. 21) is described by Wilde (1976a, 1976b) and Wilde and Low (1980), and the bauxite deposits are described by Ball and Gilkes (1985). Bauxite orebodies are almost entirely confined to areas underlain by mafic volcanic rocks of the Marradong Formation. Much of the Saddleback Group is fault bounded: some contacts are intrusive. Major faults trend north-northwest while minor ones trend west-northwest. Although there is little surficial evidence of faulting, the traces of fault lines are discernible on air-photographs, and faults are exposed in bedrock north of the Hotham River. Faulting and associated brecciation have a strong influence on the depth of weathering and the extent of lateritic cover.

The bauxite deposits occupy 25 to 30% of the laterite unit, and are thickest on the slopes of ridges. Though irregular in detail, they exhibit a northwesterly preferred elongation (Fig. 22), corresponding to ridges and underlying geological trends. The average thickness of the bauxite is 6 to 7 m, with ore-grade intersections locally exceeding 20 m. The largest deposit contains a resource of up to 20 Mt bauxite and covers an area of 600 ha.

The Mount Saddleback bauxite is typically deep red-brown to yellow in colour and contains minor clay. It is made up of a medium- to fine-grained matrix containing varying amounts of pisolites and irregularly shaped gibbsitic nodules.

The pisolite content of the laterite decreases from top to bottom and pisolite is locally absent. Pisolite diameter ranges from 1.5 to 12 mm but is generally approximately 6 mm. In places, broken pisolites suggest limited re-working (and re-cementing). The bauxite is vuggy and voids up to 15 cm in diameter are common. These voids are frequently partially infilled by coatings of crypto-crystalline gibbsite. Complete filling of vugs in gibbsite nodules embedded in earthy matrix possibly indicates secondary alumina deposition.

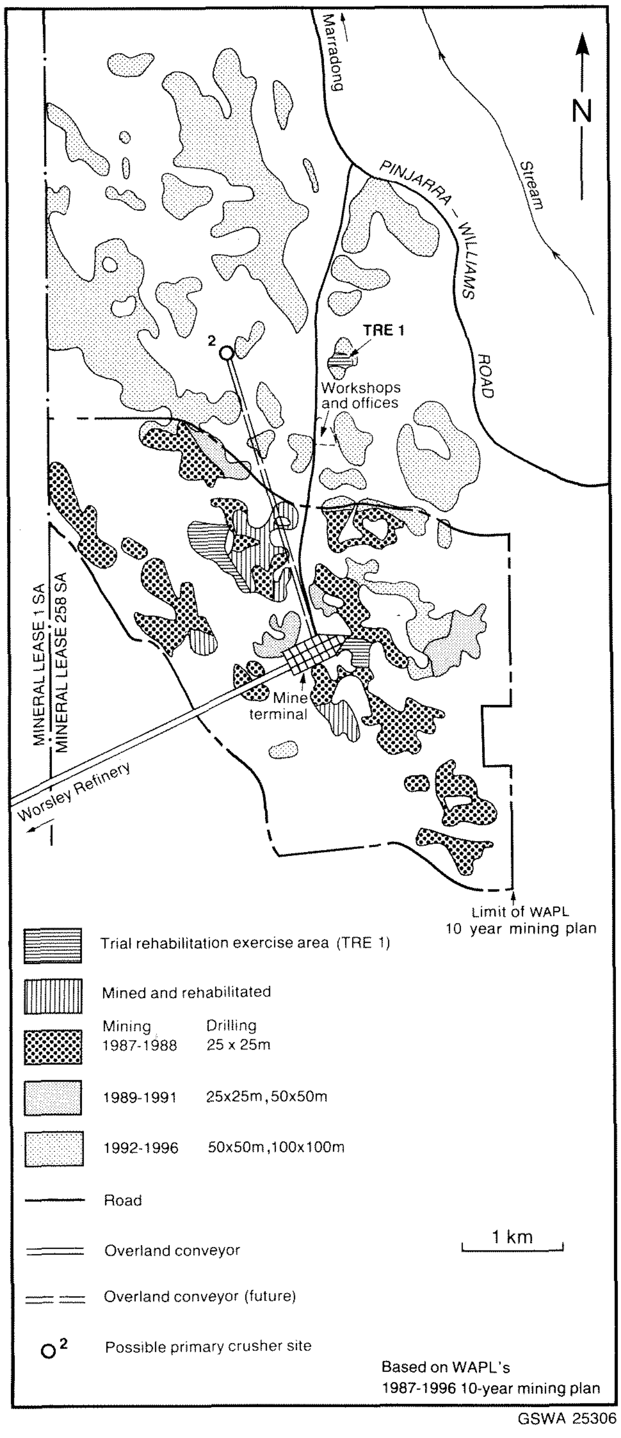


Figure 22. Mount Saddleback bauxite deposits.

WAPL geologists recognize two distinct types of laterite in the Mount Saddleback area:

(i) A high-iron/low-quartz variety derived from mafic bedrock; and

(ii) A more widely distributed (but poorly developed) high-quartz/low-iron laterite derived from felsic bedrock.

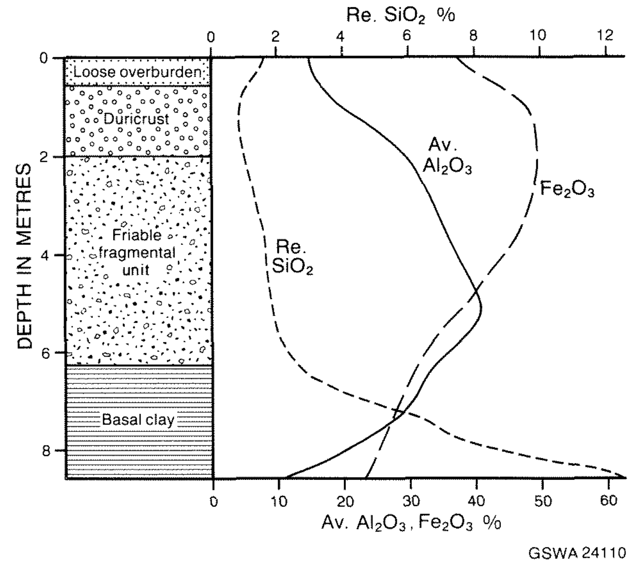


Figure 23. Variations of selected components in the bauxitic laterite profile at Mount Saddleback (modified from Ball and Gilkes, 1987).

The first type occurs as discontinuous, sheet-like deposits. These are best developed on ridge-slopes rather than on crests, and usually strike northwest. Some laterite also occurs on localized plateaus, and is present along east- to northeast-striking fracture sets. Lateral and vertical variations in alumina content are abrupt and complex, leading to significant changes in ore thicknesses over relatively short distances.

The second type (i.e. high-quartz/low-iron) is widespread. It is developed on granitic rocks, felsic volcanics and metasediments. The discontinuous surface deposits have profiles similar to those of high-iron/low-quartz bauxite. In general, an unconsolidated surface layer of quartz-rich sandy gravel (a few cms to 2 m thick) overlies a relatively thin ferruginous duricrust. The duricrust is less ferruginous than that of the first type. Underlying the duricrust the ore zone is normally pale yellow, friable and earthy, and contains abundant angular quartz grains of variable size. Nodules and pisolites are common, particularly in the upper portion of the friable fragmental unit.

Ore of the second type is usually a few metres thick but can exceed 10 m. It passes through a well-defined transition zone into basal clay and kaolinized bedrock. Lateral and vertical variations in alumina mineralization are common and are spatially complicated. These variations are portrayed in Figure 23.

Gibbsite is the principal ore mineral and generally constitutes 50 to 75% of the bauxite. Boehmite is widespread but only in insignificant amounts in the superficial zones of both bauxite types. Available alumina content is generally about 35%.

Goethite (20 to 45%), hematite (1 to 4%) and, to a lesser extent, maghemite are the main impurities in the

Table 7. Mineralogical composition of Saddleback Group rocks

	Basalt	*Andesite*	*Felsic volcanic rocks*	*Metasediment*	*Dolerite*
Quartz	minor	minor	major	major	minor
K-feldspar	–	minor	variable	variable	–
Plagioclase	major (calcic)	major (calcic)	major (sodic)	major (calcic/sodic)	major (calcic)
Hornblende/ Tremolite–Actinolite	major	major	minor	minor	major
Epidote/Clinozoisite	variable	variable	variable	variable	variable
Mica	–	minor	minor	variable	–
Chlorite	variable	minor	–	variable	variable
Accessories	opaques, sphene–leucoxene	sphene,ilmenite	sphene, zircon	opaques, tourmaline	opaques, sphene–leucoxene
Sulfides	–	pyrite, chalcopyrite	pyrite	pyrite, chalcopyrite	trace
Pyroxene	–	–	–	–	some primary

(Davy, 1977; Wilde, 1976a, 1976b; Wilde and Low, 1980)

Table 8. Chemical composition of Saddleback Group rocks

	Basalt	*Andesite*	*Felsic volcanic rocks*	*Meta-sediment*	*Dolerite*
			Percentage		
SiO_2	49–51	62–65	64–75	59–81	49–52
Al_2O_3	12–15	16–17	12–16	12–16	13–14
Fe_2O_3	2–4	1	1	1–3	2–3
FeO	8–12	3–5	2–4	1–13	9–11
MgO	6–7	2–3	0.5–3.0	1–2	5–7
CaO	10–12	4–7	1–4	0.1–2.0	10–12
Na_2O	1–3	5–7	4–5	0.2–3.0	2–3
K_2O	0.05–0.10	0.5–1.5	3–4	0.1–4.0	0.2–0.4
H_2O^+	1–4	1.0–1.5	0.5–1.5	1–4	1–2
H_2O^-	0.01–0.15	0.05	0.05–0.10	0.06–0.15	0.06–0.40
CO_2	0.02–0.09	0.05–0.10	0.01–0.10	0.01–0.20	nd
TiO_2	1–2	0.5–0.7	0.3–0.7	0.06–3.00	1–2
P_2O_5	0.2–0.3	0.2–0.3	0.1–0.3	0.1–0.6	0.2–0.3
MnO	0.2–0.3	0.1	0.05–0.10	0.02–0.30	0.2

(Davy, 1977)

high-iron bauxite. Maghemite is normally confined to the surface horizons but has been recorded at depth where it is probably associated with fractures.

Quartz content in type (i) bauxite is generally about 1% (rarely exceeding 5%) and is normally concentrated at the surface. In contrast, the quartz content of type (ii) bauxite may exceed 30%. Titanium minerals include ilmenite, rutile, anatase and brookite. Figure 11 (B) and Tables 7 and 8 summarize the mineralogical and chemical composition of Saddleback Group rocks.

Other principal bauxite deposits

Potentially mineable bauxite deposits are widespread in the Darling Range, and there are many hundreds of individual orebodies. However, outside the 25-year plan areas of existing mines, localized concentrations of ore-grade bauxite deposits can be distinguished. Figure 14 shows the locations of these large deposits, and Table 4 summarizes their bauxite resources, bedrock geology and height above sea level. No descriptions of these deposits have been published previously and the information presented in this report is based on our analysis of drilling data (detailed and scout), supplemented by field observations.

The general (background) bauxite content of the laterite in the Darling Range varies between 0.2 and 1.5 Mt/km^2, and shows overall zoning with the higher contents (greater than 3 Mt/km^2) being concentrated in the Huntly–Willowdale district. The maximum bauxite content for any individual orebody is about 10 Mt/km^2, with some of the larger groups of orebodies containing over 20 Mt bauxite. Each of the deposits listed in Table 4 represents a group of orebodies, so that overall bauxite content is diluted by sub-economic material.

Regional review of prospective areas

As noted above, bauxite potential varies both from north to south, and from west to east across the Darling Range area. These variations are accompanied by regional changes in bedrock geology, geomorphology, rainfall and laterite thickness and composition. For descriptive purposes, the area has been divided into a number of districts (Fig. 24).

Wannamal–Chittering

The Wannamal–Chittering region extends from the farming areas around Wannamal, southwards along the Chittering Valley to the Avon River, and eastwards to include the Julimar State Forest.

The region was first explored by WANL in 1958, followed by B. Campana in 1965 and by Hanwright Prospecting in 1970. Ore-development drilling was

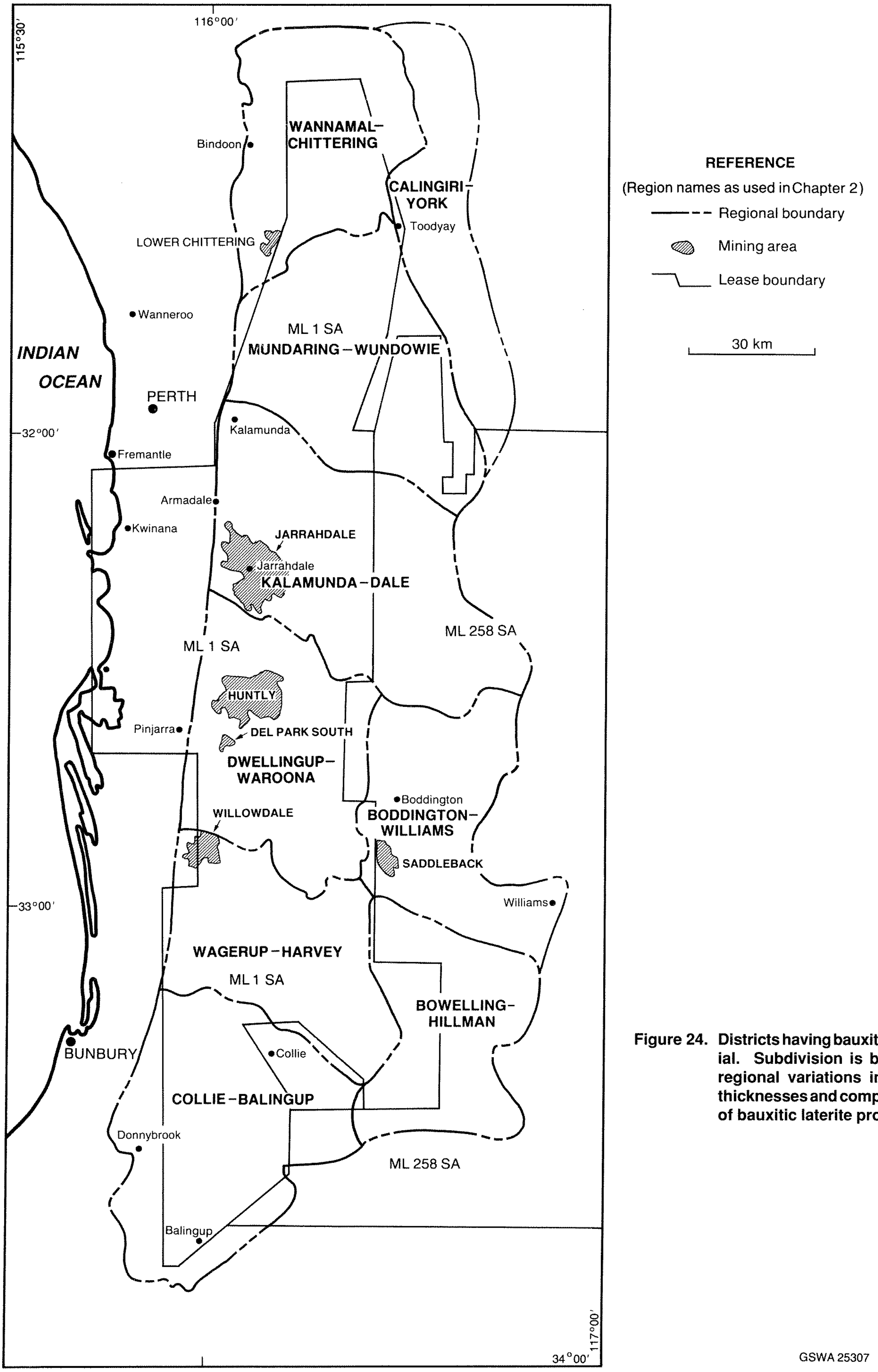


Figure 24. Districts having bauxite potential. Subdivision is based on regional variations in typical thicknesses and compositions of bauxitic laterite profiles.

carried out by Pacminex in the early 1970s at Lower Chittering and Bindoon Hill. Test pits were put down in the better grade areas, a small pilot mine established at Lower Chittering, and bulk ore samples tested.

Bauxite deposits in this district occur at four principal localities: Lower Chittering, Bindoon Hill, Julimar and South Calingiri Road. There are also smaller bauxitic areas along Dewars Pool Road and around Cachionalgo Hill (Fig. 14), but elsewhere there is limited bauxite potential.

Bauxitic laterite has formed on granitic gneiss, metasediments, and local pegmatite veins, quartzite and amphibolite within the Chittering Metamorphic Belt. Throughout the region, numerous mafic dykes intrude the otherwise mainly felsic bedrock assemblage which has been weathered to produce a predominantly ferruginous and siliceous laterite. The potentially mineable bauxite deposits overlie areas of cataclastic schist and granite gneiss.

Laterite is generally thin, laterally variable, overlain by thick gravel and silty sand, and has been extensively dissected by the Brockman River and its westerly flowing tributaries. Iron-rich laterite breakaways with saprolitic slopes and bedrock outcrops form the heads of deep valleys.

Bauxitic duricrust fabrics are mainly pisolitic–nodular. Fragmented gibbsite is noticeably absent, and coarse, angular quartz grains and fragments are abundant. Iron-enriched fragmental vermicular duricrust effectively masks the presence of aluminous material in the underlying friable fragmental unit.

Bauxite deposits are much smaller than those in the main area of mineralization between Jarrahdale and Willowdale. Ore boundaries are marked by lateritized mafic rocks and maghemite–goethite accumulations. Ore thicknesses are variable and rarely exceed 3 m. Vertically, alumina zonation is very changeable and the passage from friable fragmental unit to basal clay is usually abrupt. The ore contains some clay, is relatively thin, and includes pinnacles of lateritized bedrock.

Av.Al_2O_3 grades range from 29%–32% with an average of 30.5%. Re.SiO_2 values are high, with values of 2.5% being common. From limited data, Fe_2O_3 values are of the order of 20–25%. Taken together, these ore characteristics make the deposits uneconomic under current treatment methods. However, increasing landuse competition farther south is likely to make the deposits more attractive. Accordingly, beneficiation of the ore could make it refineable.

Mundaring–Wundowie

An extensive region of continuous and moderately well-developed laterite lies between the Avon and Helena rivers and from the Darling Scarp east to the area around Bakers Hill. About 40% of the region is covered by small farms and residential centres (e.g. Mundaring, Sawyers Valley, Chidlow). The remainder comprises State forest and nature conservation reserves.

The region was explored by WANL between 1956 and 1965, and Alvam, Hanwright, Project Mining, and Singlex from 1970 to 1972. Pacminex carried out ore-development drilling at Koojedda between 1971 and 1973. Alvam pegged drill traverses over Morangup but did little drilling.

Bauxite deposits are widespread, occurring on both private and forested land. They are grouped in six principal localities: Smith Mill Hill–Gidgiegannup, Morangup–Bailup, Chidlow–Wooroloo, Wundowie–Koojedda, Inkpen–Yetar Spring, and Sawyers–Gorrie. Other bauxite deposits also occur, but are small and unlikely to become economic.

The Mundaring–Wundowie bauxite deposits have formed over granite intruded by dolerite. At Morangup Hill bauxitic laterite is formed over metabasalt, and includes some small, high-grade deposits. Laterite ridges are separated by extensive areas of gravel, and silty sand occurs in the upper reaches of all major streams.

Depending on bedrock geology, bauxite textures are a mixture of massive, pisolitic and fragmental. Gibbsitic nodular and fragmental duricrust materials are widespread.

Surface observations and sampling results suggest that grades and thicknesses are economic in several parts of the western area. Potentially mineable deposits occur in the Chidlow–Wooroloo area, while the Sawyers–Gorrie area is highly prospective. The bauxitic laterite deposit above the vanadiferous gabbro at Coates has abundant gibbsite.

Limited information on the known deposits indicates that Av.Al_2O_3 ranges from 30–32%, Re.SiO_2 from 3–4%, and Fe_2O_3 contents are approximately 15–20%. Ore thicknesses are between 2.5 and 3.0 m.

Calingiri–York

The Calingiri–York region is poorly mineralized except for isolated ridges west of Toodyay and at Mount Talbot. Erosion has removed most of the laterite cover, and variable bedrock geology, combined with low rainfall, appears to have restricted the development of bauxite-grade material in the little laterite that remains. Isolated occurrences of bauxite around Toodyay are high grade but appear to lack continuity; most of the deposits are small and dispersed.

The region was explored by Campana and Hanwright Prospecting but Pacminex considered further development work unwarranted.

Kalamunda–Dale

Excellent bauxite development occurs throughout the Kalamunda–Dale region. Although little exploration for bauxite has taken place since the early 1960's, it is clear that there are substantial deposits on those ridges which are situated well back from the Darling Scarp, and are remote from the erosional areas associated with Piesse Brook and Canning River.

Most of the region lies within the Jarrahdale 25-year mining plan area, and is described above.

Farther to the east of the lateritic upland geomorphological division, extensive erosion by the Avon River has reduced laterite cover to between 25 and 40%. However, small, scattered bauxite deposits are preserved at localities such as Gunapin, Russell and Sullivan (Fig. 14). Gibbsitic fragmental–massive duricrust is prevalent and, on the basis of limited drilling, the laterite profile is well zoned and has ample granular bauxite material.

The eastern landscape is characterized by lateritic mesas and buttes, rugged granitic hills, and gravelly saprolitic rises; all are separated by broad sand-filled valleys. The duricrust is poorly cemented, and is predominantly pisolitic–nodular. Pallid clays and pockets of coarse gravel overlie truncated laterite profiles.

Exploration for bauxite was carried out in the 1960s by Bauxite Exploration Pty Ltd, followed by both Campana and Hanwright Prospecting in the early 1970s. Promising results led to the establishment of Alwest's temporary reserves and Pacminex's lease area.

Dwellingup–Waroona

The Dwellingup–Waroona region includes the operating mine sites of Huntly and Del Park. It also includes the mined-out deposits of Del Park North, Scarp Road and Marrinup. Mafic intrusives at Del Park North made grade control difficult, but careful ore scheduling and blending with Huntly ore overcame refinery grade control problems. Thin ore development at Scarp Road and Marrinup continues south to the area around Teesdale.

Outside the Huntly and Del Park 25-year mining plan areas, bauxite deposits on ridges adjacent to the Darling Scarp, and in the Teesdale area between Dwellingup and the Murray River, are generally thin and small. However, at Holmes, southeast of Dwellingup, there is one of the largest and most consistently high-grade deposits in the entire Jarrahdale–Willowdale area. Ore thicknesses in the Holmes deposits exceed 12 m, and Av.Al_2O_3 grades in excess of 40% are common.

East of Dwellingup there are large bauxite deposits at Inglehope and Holyoake (Table 4, Fig. 14). These, together with those at Holmes, represent a major bauxite resource which cannot be mined because of the relative proximity of the deposits to the town of Dwellingup; they are also located in high-quality forest. As a consequence, future mining is scheduled to move north and northeast of the Huntly mine site to utilize medium to large ore bodies in disease risk area (DRA) forest remote from Dwellingup and conservation reserves. A proposal to cross the Murray River and to mine the Waroona and Nanga deposits was effectively blocked because of their proximity to private property. A lack of mineable bauxite at Teesdale, nature conservation and the cost (an estimated $30M) of crossing the river is also reported to have influenced the decision to mine farther north.

South of the Murray River, at Park, lies the bauxite deposit of Murray Plateau. Here, large gabbroic dykes have been deeply weathered to form a 30 000–40 000 t deposit of 44% Av.Al_2O_3. The deposit was investigated by Alcoa in 1973 as a potential source of refractory-grade bauxite. However, values of 7% Fe_2O_3 are too high for the ore to be used in this way.

Exploration south of the Murray River was discontinued in 1973 in order to concentrate on ore development at Willowdale. Consequently there are areas north of Huntly that need further investigation as part of Alcoa's 5- and 10-year program.

Mining could conceivably take place in the recreation zone of Lane Poole (Fig. 20). The Plavins deposit (8 km east of Dwellingup), which was mined on a small scale in 1960 (15 000 t of 43.6% Av.Al_2O_3 shipped to Japan), still possesses a large resource (Table 4).

Goethite pseudomorphs replacing hematite are common in the southern and eastern margins of the Park area, and form part of the iron-rich 'black gravels' which are common on plateaus adjacent to the Darling Scarp and Murray River.

Hydrogeological investigations related to possible trial mining are underway in the Pindalup, Yarragil and Cameron catchments, and some exploratory and ore-development drilling has taken place.

Boddington–Williams

Exploration was undertaken in the Boddington–Williams region in the early 1960s, first by Bauxite Exploration Pty Ltd, and later by Alwest and Broken Hill Pty Ltd. The area considered to have most potential was consolidated into ML 258SA (Fig. 3). In 1975, with the formation of WAPL and the enacting of the Worsley Agreement in 1978, the way was cleared for mining and refining. Bauxite mining commenced on the northern slopes of Mount Saddleback (southeast of Boddington) in 1983.

Geologically, the bauxite deposits at Mount Wells (Table 4) are similar to those at Mount Saddleback, 32 km to the southeast. North of Mount Wells, at Mid-Central (Fig. 14), WAPL identified generally small and dispersed bauxite deposits; bedrock in this area is granite, and the terrain is considerably dissected.

Wagerup–Harvey

The Wagerup–Harvey region, which includes the Willowdale mining area, has the typical Darling Range landscape of northwesterly trending ridges and valleys.

Laterite is extensive and bauxite deposits are derived mainly from granite, porphyritic granite and, to a lesser extent, gneiss. Prominent laterite-covered hills such as Driver Hill and Spion Kop rise above the general 300–320 m elevation of the plateau.

Severe erosion has stripped the laterite cover from the lower slopes of valleys such as those of the Samson and Harvey Rivers. The valley of the Murray River is particularly incised, and has entrenched meanders which appear to be fault controlled. Lateritic gravels on its steep slopes are overlain or replaced in the landscape by thick red earths and mottled clays.

South of the Willowdale mining area, bauxite deposits are much smaller and more scattered. Around Clarke Hill and north of Logue Brook Reservoir, the laterite is predominantly ferruginous and its margins are obscured by extensive black gravel and grey-white sand. East of the Murray River the bauxite deposits are comparable to those found farther north at Dwellingup.

Collie–Balingup

South of the Harvey River the laterite plateau has been dissected to produce four areas of bauxite preserved on ridges: Mornington, Lennard, Mungalup and Pollard (Fig. 14). Mornington and Lennard are very dissected, and have thin lateritic profiles with high iron content. Bauxite deposits at Mungalup and Pollard are similar in grade and ore characteristics to the bauxite deposits around Jarrahdale.

East and south of Collie, duricrust outcrops are scattered and their relationship to the underlying friable fragmental unit is obscured by thick gravel and gravelly sand. Laterite ridges are long and narrow and the topography is subdued. The many broad valleys are occupied by silty sand and sandy gravel.

Scout drilling and surface sampling has indicated that the country south of the Harris River contains negligible bauxite. Farther east, discrete areas of at least 30% Av.Al_2O_3 have been located in the Buckingham and Bingham River localities (Fig. 14), but are thin and appear to be high in Re.SiO_2.

In the mid-1970s, lateritic areas west and northwest of Collie were explored by Alcoa, following a decision by the company to increase alumina refining capacity and seek bauxite reserves for a third refinery. South of Collie, drilling on a 120 by 120 m grid delineated ore resources at Mungalup but, elsewhere, only ferruginous laterite and patchy bauxite mineralization were found. Mungalup's bauxite tonnages were considered to be insufficient for an alumina refinery.

Bowelling–Hillman

The Hillman and Arthur Rivers have reduced the lateritic upland to a series of narrow ridges flanked by coarse gravels and granitic outcrop. The region has negligible bauxite potential.

Miscellaneous southern areas

Various areas close to and outside the southern limits of the area depicted on Plate 1 have been explored for bauxitic laterite.

Between Margaret River and Augusta, laterite constitutes 25 to 30% of the total landscape. It has developed in situ over the granitic gneisses and granulites of the Leeuwin–Naturaliste ridge, and the sandstones and siltstones of the Blackwood Plateau. The profile is thin; 3 m of quartz sand over 1.5 m of ferruginous laterite overlying 6 m of clay above weathered rock. Some of the upper sections of the profile may contain transported material. Duricrust commonly passes directly into weathered rock. Alumina mineralization is generally low (10–15%) and true bauxite is virtually non-existent. The clayey, earthy, quartz-rich nodular duricrust is low in gibbsite (10–25%) and high in kaolinite (30–50%). The area appears to have no bauxite potential.

The Kojonup–Manjimup region has only very limited bauxite potential. While laterite amounts to 30% of the total landscape, bauxitic laterite is confined to a few widely spaced, narrow, finger-like ridges. Bauxite rarely exceeds 20% Av.Al_2O_3. Only at Alco Tower (10 km northwest of Manjimup) is there refinery-grade mineralization, but this is an isolated and relatively small deposit. Around Kirup and Grimwade the laterite is mainly ferruginous and thin, and gibbsitic fragmental duricrust outcrops are few.

Farther to the west and to the southwest of Collie, laterite exposures are confined to the spines of narrow ridges and catchment divides. Erosion by Balingup Brook and the Blackwood River has cut back what little laterite existed before rejuvenation of drainage occurred. The result is that less than 20% of the total landscape is lateritic.

The Greenbushes area has reasonably good laterite cover but the laterite is siliceous, rather than aluminous. This may be due to much of the laterite having formed over fluviatile Eocene sediments rather than directly on bedrock. At Bridgetown and Boyup Brook extensive erosion has removed most of the laterite cover. At Dinninup and Qualeup small duricrust rises have grades of 40% Av.Al_2O_3. All profiles are thin and none is large enough to be classed as a bauxite resource.

The eastern parts of the area have only rubbly lateritic remnants. Duricrust is mainly pisolitic–nodular and is up to 3 m thick. Bedrock outcrops are widespread and are surrounded by pallid clays and gravelly saprolite.

Owing to dissection, the gneisses, metasediments and mafic/ultramafic intrusives of the Balingup Gneiss Complex are rarely covered by laterite. Granite and migmatite seem to be the main source rocks for the region's meagre bauxitic laterite.

Bauxite exploration has involved several companies. WANL explored the area between Kirup and Manjimup in the mid-1960s; Alcoa examined the Kirup–Noggerup area in the mid-1970s; and Reynolds held a temporary reserve over the Greenbushes–Manjimup area in 1962. However, none of these programs discovered bauxite.

In the Pemberton–Denmark region poor development and uneven distribution characterize laterite cover. Duricrust is weakly cemented and is broken into loose blocks. It is predominantly nodular and is generally clay-, quartz- and iron-rich. No gibbsite has been identified. Laterite formation has not proceeded beyond the creation of a nodular zone above mottled clay and saprolite.

The upper slopes of many granitic ridges, such as those at Mount Frankland and the divides of major rivers, contain laterite and lateritic gravel. Elsewhere the laterite cover constitutes around 25% of the total landscape. Bauxitic laterite occurs north of Northcliffe and around Rocky Gully. Av.Al_2O_3 values are between 25 and 30%, but these occurrences are small and scattered.

Reynolds explored the area in 1962, and WMC investigated the Walpole and Rocky Gully areas in the 1970s. Drilling demonstrated that bauxite is restricted to small patches and comprises a thin crust of gibbsitic boulders embedded in a clayey matrix. However, in compliance with dieback quarantine restrictions, WMC drilled only alongside main roads.

Bauxite is restricted to the upper 2 m of the laterite profile and there is negligible economic potential. The laterite profile is up to 6 m thick, has extreme lateral and vertical bauxite grade variations, and is hard and iron rich. Duricrust textures range from fine grained massive to coarse fragmental. Veins and joint-fillings of gibbsite are common, as are pods and pipes of iron hydroxides and clay. Quartz content can be as high as 25%. Gibbsite is the main aluminium hydroxide, but Reynolds reported boehmite in some samples. Clay overlies the bauxite and contains thin lenses, nodules and concretions of gibbsite. WMC have reported Av.Al_2O_3 values of 10–20% and Re.SiO_2 values of 3–10% at Rocky Gully.

Bauxite resources

Areas with significant bauxite potential are confined to the lateritic upland geomorphological division of the Darling Plateau (Fig. 4) between Bindoon Hill and Bridgetown. Within this area, most of the larger (greater than 5 Mt) potentially mineable bauxite deposits appear to be restricted to the Jarrahdale–Willowdale–Mount Saddleback region (Figs 13 and 14). This region, centred on Dwellingup, includes individual orebodies containing up to 25 Mt bauxite. Ore is extensive, thick, and predominantly high grade. Moving away from Dwellingup, the orebodies become smaller, thinner, and more widely spaced. In addition, bauxitic laterite gradually becomes poorer in gibbsite and richer in clay.

Table 9 summarizes the resource situation in the nine principal districts of the area (Fig. 24). The 3525 Mt resource figure indicated in Table 9A constitutes the total identified bauxite resources of Southwestern Australia and includes past production of 211 Mt (to the end of 1988) and the 500 Mt of measured and indicated ore within mining areas outlined in current planning (Table 9B).

In detailing total identified resources, it is assumed that any bauxite held by minor companies such as Bridge Oil (formerly Project Mining Corporation) and the Worsley Timber Company will be utilized by the adjacent mining company; either Alcoa or Worsley Alumina (Table 9A). The estimate also assumes that bauxite on private property

Table 9A. Identified bauxite resources (Mt), Darling Range area

Region [(a)]	*Alcoa*	*MPB*	*WAPL*	*Total*
Wannamal–Chittering	50	35	–	85
Calingiri–York	–	10	–	10
Mundaring–Wundowie	90	50	–	140
Kalamunda– Dale	430	–	20	450
Dwellingup–Waroona	1550	–	–	1550
Boddington–Williams	–	–	400	400
Wagerup–Harvey	850	–	–	850
Bowelling–Hillman	ns	–	ns	ns
Collie–Balingup	40	–	–	40
Total	3010	95	420	3525

(a) See Figure 24
ns: Not significant (i.e. <5 Mt)
Cut-off grades: >27.5% Av.Al_2O_3, <2.0% Re.SiO_2
Based upon results of systematic exploration plus geological evaluation of undrilled lateritic areas.
Estimate assumes access to bauxite on private property and within nature conservation reserves

Table 9B. Demonstrated bauxite resources (Mt) within current mining areas, Darling Range area [(b)]

	Mine site	*Measured*	*Indicated*	*Total*
ALCOA	Jarrahdale	26	114	140
	Del Park/Huntly	43	200	243
	Willowdale	13	46	59
	Subtotal	82	360	442
WAPL	Saddleback	18	40	58
	Total	100	400	500

(b) Estimate based on interpretation plus data in 5-, 10-, and 25-year Mining Plans.
Cut-off Grades: >27.5% Av.Al_2O_3, <2.0% Re.SiO_2
Measured: 15 by 15 m, or 25 by 25 m drilling
Indicated: 60 by 60 m, 100 by 100m, 120 by 120 m, or 200 by 200 m drilling.

(formerly held under a multitude of separate agreements by Pacminex) can be re-negotiated and accessed by Mitchell Plateau Bauxite Pty Ltd (MPB). Nearly 50% of the bauxite listed under the MPB heading would be so affected. Likewise, bauxite in conservation reserves is included in the total as it could be made available for mining if there was pressing economic or strategic need. Currently, access to about 40% of the bauxite resources in the Darling Range area is constrained by conservation requirements.

Resources are defined on a nominal 27.5% Av.Al_2O_3 cut-off, a maximum Re.SiO_2 content of 2.0% (where figures are available), and a minimum ore profile of 2.0 m. Measured resources are based on drilling at 15 m or 25 m centres, usually around existing minesites. Indicated resources are evaluated from systematic drilling at 60 m, 100 m, 120 m or 200 m centres.

In estimating the quantity of potentially mineable bauxite held by Alcoa and Worsley Alumina, use has been made of the medium and long-term strategy reports provided to the State Government by these two companies. Also, under the terms of their agreement acts, the companies are required to provide the State Government departments with exploration data only. These data do not include Re.SiO_2, or detailed beneficiation and refining aspects. However, technical presentations made by Alcoa, and discussions held at mine sites have assisted the authors in making a generalized estimate of bauxite resources.

To arrive at the estimates of identified resources given in Table 9A, the full extent of bauxitic laterite was established from company and Geological Survey mapping. Resources within this boundary were calculated either from the results of systematic exploration drilling, where these were available, or by using information from scout drilling supplemented by interpretation of topographic maps and air-photographs.

The 120 m exploration grid (and its equivalent imperial grid) covers a substantial area and a large variety of terrain types. Comparisons carried out by Smurthwaite (when employed by Alcoa) between results obtained from 15 m by 15 m drilling and those from 120 m by 120 m drilling, demonstrated that 120 m by 120 m exploration drilling, backed by detailed geological mapping can produce reliable resource estimates. Likewise, Smurthwaite found that measured resources calculated from mine plans correlated well with refinery results. These studies confirmed that the results of broad-scale exploration drilling could be used to estimate regional resources of bauxite.

Similar but less detailed studies involving the Pacminex and Worsley ore-development areas have been made for this report. These have resulted in previous resource estimates for some of the more northern or eastern areas being reduced to take account of high Re.SiO2 or bauxite thicknesses of less than 2.0 m.

Plate 1 and Figure 13 show the relative incidence and broad pattern of bauxite mineralization between Wannamal and Bridgetown. Both figures are based on the frequency of ore intersections identified by exploration drilling. Each drill sheet was divided into four cells and the number of holes with Av.Al_2O_3 greater than 27.5% was counted and expressed as a percentage success rate. No allowance was made for the spatial relationship of these 'successful' holes.

In Plate 1, dense hues show results from closely drilled areas, and lighter hues results from areas of scout drilling or in which inferences have been made on the basis of geological interpretation. Figure 13 uses the data employed in Plate 1, plus some additional drilling data, to produce a contoured plot of bauxite mineralization. The data are expressed in the same way as on Plate 1 (i.e. in terms of percentage of ore intersections), but the values from individual cells have been 'smoothed' by averaging groups of nine cells centred on each individual cell.

Plate 1 and Figures 13 and 14 not only show that the existing mines do, as would be anticipated, lie within general areas where economic-grade bauxite deposits are concentrated, but also reveal that many other such highly mineralized areas exist. It is clear that, apart from Mount Saddleback, the locations of existing mines have been considerably influenced by proximity to the transport routes, ports and urban centres of the Swan Coastal Plain.

Table 9(B) summarizes the reserve situation up to the end of 1987 for each of the mine sites. Cut-off grades used are equal to, or greater than, 27.5% Av.Al_2O_3, and less than 2.0% Re.SiO_2. The minimum mine face is 2 m. The estimate assumes continuation of annual production rates as stated in company mining plans.

One aim of this study was to examine the effects of lowering the cut-off grade on resources of bauxite and mining economics. This was undertaken partly in response to a suggestion by the Darling Range Study Group (1982, p. 152). Apart from increasing the total resources of bauxite, one possible benefit of a lower cut-off grade was seen as allowing more ore to be mined from each site, thereby reducing incursions of mining into new areas.

From examination of drill sections it was found that the 27.5% Av.Al_2O_3 parameter coincides with a sharp cut-off where the vertical profile passes downward into low Av.Al_2O_3 and high (greater than 2.0%) Re.SiO_2.

Frequency studies of drillholes indicated that 80 to 85% of sections show this change at or above 27.5%. Changes at greater than 27.5% are acceptable, but those below that figure indicate the probable presence of clay and, consequently, of increased Re.SiO_2 values.

Laterally, Re.SiO_2 and Fe_2O_3 values show distinct changes across geological contacts. Commonly these changes coincide with a marked decline in Av.Al_2O_3 (Figs 12, 16, 19 and 23).

Contouring of results of close-spaced drilling indicated that the fall-off in grade is quite abrupt below the 27.5% Av.Al_2O_3 limit, and that only comparatively small amounts of additional ore would become available in each ore lens if a 25% cut-off was adopted. Such ore would also have unacceptably high contents of impurities.

In practice it is found that the 27.5% Av.Al_2O_3 nominal cut-off captures 54% of the contained alumina and achieves a mean bauxite grade of 32.5%. Mineable average grades range from 30.5 to 33% as ore is scheduled from many hundreds of individual lenses.

Lowering the Av.Al_2O_3 cut-off to 25% would incur prohibitive amounts of Fe_2O_3 and Re.SiO_2. Some 25–27.5% Av.Al_2O_3 material may prove mineable, but this marginal grade ore can be used by the refineries only if the ore treated has Re.SiO_2 values below 1.8%. To achieve such an acceptable refinery feed, product parcels of 60,000–80,000 t ore with grades greater than 2.5% Re.SiO_2 may be blended with ore of less than 1.0%, Re.SiO_2 provided that their alumina contents are relatively constant.

Bauxite derived from mafic intrusives has highly variable grades, and consequently is not stockpiled to any great extent. Although no maximum Fe_2O_3 content is stipulated, in practice the 25% Fe_2O_3 grade contour generally corresponds to the 27.5% level for Av.Al_2O_3 and 2.5% for Re.SiO_2.

An exception occurs with transported bauxitic laterite where high Fe_2O_3 values may be associated with high Al_2O_3 and/or low Re.SiO_2. If Av.Al_2O_3 exceeds 27.5%, such ore is refineable.

For each tonne of aluminous material gained by lowering the cut-off grade, there would be penalties for alumina refineries in dealing with lower grade ore (e.g. increased sand loads and shortened use of residue lakes). More critically, there would be a substantial increase in caustic soda usage. Environmental impact would be increased as more forest would need to be cleared and mining areas would become larger because of the need to mine greater tonnages of bauxite to produce the same quantity of alumina.

It is therefore concluded that lowering the Av.Al_2O_3 cut-off to 25% as advocated by the Darling Range Study Group is not currently a feasible option.

Conversely, raising the cut-off to 30% Av.Al_2O_3 would reduce the viability of the mining/refining operations because there are few bauxite deposits with Av.Al_2O_3 grades greater than 34%. In effect, this would constitute a return to the 1960s (where this grade material was mined at No 1 site, Jarrahdale) and would be a misuse of the State's bauxite resource. Overall, the 27.5% Av.Al_2O_3 cut-off used by the companies seems to be the optimum figure, striking a balance between maximizing the resources extracted from any one pit without jeopardizing the economics of the operation by generating excessive quantities of impurities to be handled at the refineries.

Future exploration

Special agreement areas cover the entire prospective area between Bindoon and Bridgetown. In the short term at least, exploration will therefore be limited mainly to current tenement holders although there is still scope for other parties to explore on private land. Because the region is environmentally sensitive, these few tenement holders are themselves constrained by considerations other than ground mineral potential, and in many situations will not be able to explore further or develop the highly prospective areas already identified. Exploration will be governed by a combination of established or inferred prospectivity and land availability.

The greater part of the prospective area has not been adequately explored by systematic, closely spaced drilling. The tenement holders are accordingly engaged mainly in detailed drilling of deposits already outlined, and in drilling areas considered to be highly prospective on the basis of drilling results from adjacent areas. Geological models of mineralization controls should also be applied to future exploration.

Chapter 3

Controls governing bauxite formation and deposit location

Introduction

The present chemical and mineralogical composition, size and distribution of the Darling Range bauxite deposits result from the interaction over millions of years of factors such as climate, topography, drainage (including groundwater movement and levels), vegetation, and parent rocks. Comparisons between the respective chemical and mineralogical compositions of bauxite deposits and their parent rocks (chiefly either granite or basalt/dolerite) reveal a relatively simple relationship. Bauxitization has involved the residual enrichment of Al and Fe (with addition of H_2O) in proportion to the combined effect of Si depletion and the almost total loss of Mg, Ca, Na, and K. These changes are consistent with the congruent and incongruent dissolution of minerals such as feldspar, biotite, amphibole, pyroxene and olivine (Norton, 1973), and removal of the mobile elements. The composition of Darling Range bauxite does not indicate significant mobility of Al and Fe; this suggests a restricted range of pH–Eh conditions (Norton, 1973).

Lateritization and bauxite formation

During lateritic weathering, alkali and calcic feldspars are altered to kaolinite and halloysite (Sadleir and Gilkes, 1976; Gilkes and Suddhiprakarn, 1981).

Formation of kaolinite

$$\underset{\text{feldspar}}{4H^+ + 4KAlSi_3O_8} + 18H_2O \rightarrow 8H_4SiO_4 + 4K^+ + \underset{\text{kaolinite}}{Al_4Si_4O_{10}(OH)_8}$$

Pyroxenes weather first to chlorite and montmorillonite, iron oxides and hydroxides, and anatase. Increased leaching causes further breakdown of chlorite and montmorillonite to kaolinite. Amphiboles display a similar weathering sequence. Biotite mica weathers first to a vermiculite-like mineral or chlorite, with kaolinite forming in response to further weathering in an oxidizing leaching environment. Muscovite is leached, but relics (of hydromuscovite or illite) remain almost to the surface. Magnetite, sphene and ilmenite oxidize readily during weathering to form hematite, maghemite and/or goethite. Titanium is released and crystallizes as anatase, or leucoxene.

If leaching is intense, kaolinite and halloysite break down and silica is released with residual alumina to form gibbsite and boehmite. In extreme conditions, gibbsite may form directly from the weathering of primary aluminium-bearing silicate minerals without passing through an intermediate clay stage (Gilkes and Suddhiprakarn, 1981; Anand et al., 1985).

Formation of gibbsite

$$\underset{\text{feldspar}}{2H^+ + 2KAlSi_3O_8} + 14H_2O \rightarrow 6H_4SiO_4 + 2K^+ + \underset{\text{gibbsite}}{Al_2O_3.3H_2O}$$

Alteration of primary silicates to kaolinite takes place in zones either below the permanent watertable or in poorly drained areas. Alteration to gibbsite occurs in well-drained environments. The main weathering reaction is the breaking down of the feldspars and biotite in granite, and of the feldspars and hornblende in dolerite. Subsidiary reactions include the slow conversion of quartz to silicates which are subsequently leached.

Breakdown of the feldspars and biotite leaves the quartz grains isolated in a matrix which becomes progressively enriched in iron (goethite) and alumina (gibbsite). In the lower part of the weathering profile the relict structure of the bedrock is preserved throughout the pallid clay zone until a considerable degree of solution alteration has occurred.

Lateritization proceeds in the upper parts of the profile, usually with the development of a pisolitic matrix that surrounds fragments of less porous material. The density of pisolites formed depends on the extent of exposure to the leaching solutions. Gibbsite can develop at any stage; it then remains stable throughout the lateritization process right up to the point where an excess of iron (fixed by oxidation) excludes it from denser pisolitic areas. Pisolites appear to be the end product of this weathering, and probably represent the lowest energy state possible.

The chemistry of laterite profiles in relation to bedrock geology was described earlier and is not repeated here. Progressive lateritization results in increased dissolution of silica and removal of iron. Iron removed from the middle layers of the profile accumulates in saddles, re-entrants, valleys, and along lower slopes. The typical profile of iron-rich duricrust lying over aluminous and clay horizons gradually emerges (Fig. 6). The lateritic slope or catena (Fig. 25) made up of a multitude of iron- and alumina-bearing layers progressively takes shape, and the laterite and enclosed bauxite deposits take on the characteristic lenticular-shaped cross section with complicated vertical zonation.

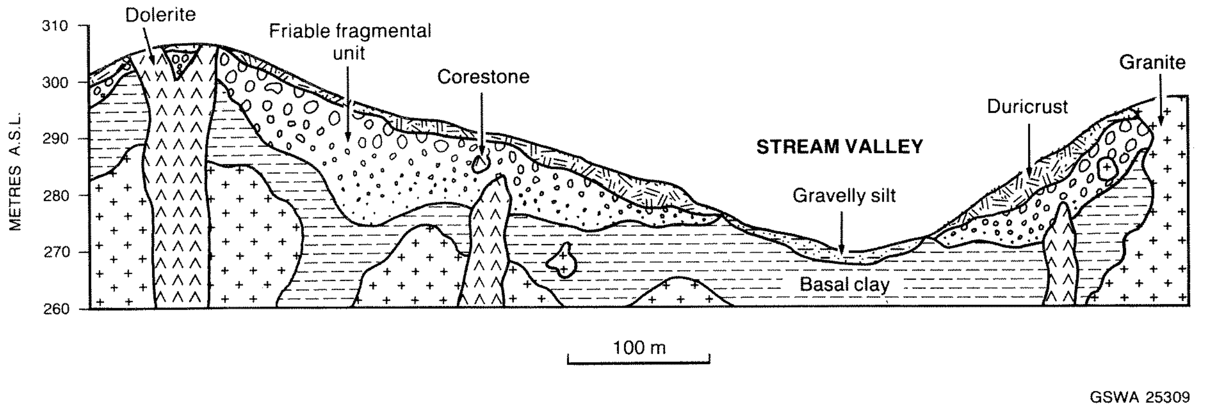


Figure 25. Diagrammatic laterite catena, showing profile variations in relation to bedrock and topography.

Climatic factors

Temperature and rainfall are the two most important climatic factors controlling the formation of laterite and influencing its bauxite content.

There is general agreement that high temperatures favour laterite formation, but uncertainty as to whether such warm to hot conditions need to be continuous or merely seasonal (Bárdossy and Aleva, 1990). Some workers (Baker, 1971; Churchill, 1973; Butt, 1976) even consider that temperate environments are adequate to promote the lateritization process.

The influence of temperature on the precise products of lateritization is also acknowledged. It is generally considered that percolating water is more effective in rock weathering if it is warm, and that with increased temperature there is increased silica solubility. Warmer water could more readily have removed silica from clay minerals to form bauxite minerals.

Rainfall is considered to be a major controlling factor in laterite formation and lateritic end-products, but opinions differ as to whether well-marked alternation of wet and dry seasons or year-round moist conditions are most conducive to bauxite formation. While McFarlane (1976) accepts that ample quantities of water are required for lateritization, and that alternating wet and dry conditions are needed for sesquioxide precipitation, she holds that such alternations are not necessarily synonymous with wet and dry seasons. McFarlane points out that stressing atmospheric climatic conditions is misleading. This is because the 'climate of the soil' and 'climate of the watertable zone' are more significant in lateritization. Neither of these micro-climates need directly reflect that of the atmosphere. Alternating wetting and drying conditions due, for example, to watertable oscillations can occur in the weathering zone under a climate which has a year-round rainfall, as well as one which has distinctly marked wet and dry seasons.

Lateritization is promoted by high rainfall which decreases the silica/sesquioxide and silica/alumina ratios while favouring the progressive alteration of clay minerals to bauxite minerals.

The influence of climate on Darling Range lateritic bauxite mineralization has been discussed by several workers. Tomich (1964) and Kirke (1973) suggested that seasonal wet and dry periods may be necessary for induration. However, Playford (1954) and Geidans (1973) doubted the need for seasonal rainfall. Geidans (1973) suggested that the process of lateritization/ bauxitization may be either continuous or seasonal. Other things being equal, the rate would be directly proportional to the volume of meteoric water available for desilication. Abundant rainfall would be required to dilute humic and carbonic acids which would otherwise lower the pH and inhibit conversion of kaolinite to gibbsite.

Tomich (1964) drew attention to the relationship between present-day rainfall and bauxite distribution. He observed that the better class bauxite appeared to correspond with areas of high rainfall (i.e. 1000 mm). He took this to indicate that either recent rainfall was a factor in bauxite development 'even if limited to secondary effects on gibbsite distribution', or that present rainfall distribution patterns were similar to those in existence when the bauxite was formed.

Essentially the same observation was made by later workers (Butt, 1976; Sadleir and Gilkes, 1976; Geidans, 1973; Loughnan and Sadleir, 1984). However Geidans (1973) noted that rainfall patterns could not explain the progressive thinning of bauxitic laterite southwards from the Willowdale–Collie area; rainfall in this southern area is similar to, or greater than, that in the Jarrahdale–Willowdale district, but temperatures are considerably lower in the south. Butt (1976) suggested that at the time of laterite and bauxite formation the present pattern of decreasing rainfall inland from the Darling Scarp may have been enhanced by an increase in orographic rainfall associated with the greater uplift of the scarp nearer the coast. During and since the main period of lateritization, therefore, the marginal areas of the Southwest have been wetter and more strongly leached than those in the interior.

Sadleir and Gilkes (1976) note that, according to Millot, (1970) the amount of kaolinitic material occurring between bauxite and its parent material in a given environment is a function of leaching intensity, or lessivage. Where leaching is particularly intense, parent material is transformed directly into gibbsite and boehmite. In the Darling Range, less than maximum leaching intensity has resulted in the formation of an intermediate kaolinite zone between bauxite and parent rock. Relatively low gibbsite/kaolinite ratios were recorded by Turton et al. (1962) and Gilkes et al. (1973) in laterite profiles to the east of the central portion of the Darling Range. These suggest that bauxite areas nearer the coast formed under conditions characterized by more intense lessivage. Tropical conditions of high temperatures and heavy rainfall were prevalent over the southwest corner of Western Australian during much of the early to mid-Tertiary. This is deduced from the recognition of palaeo-drainage channels (van de Graaff et al., 1977), particularly ones filled by debris indicative of former high-energy water flow (Wilde and Walker, 1982, p. 24–26), from plant remains (Churchill, 1973; Hos, 1975), and from palaeogeographic and palaeoclimatic reconstructions (Kemp, 1978). On the basis of the occurrence of lateritized or unlateritized strata of varying ages, the main phase of laterite formation took place during Late Eocene–Early Oligocene (van de Graaff et al., 1977), or in the Pliocene (Prider, 1966) when a wet tropical belt, considerably broader than that seen today, appears to have extended as far as latitude 60°S (Churchill, 1973). These favourable conditions ceased in the Miocene with the onset of aridity (Butt, 1979) which probably advanced from south to north (Bowler, 1982).

Brimhall et al. (1988) suggested that Al and Fe enrichment in the laterite weathering profile was partly due to the addition of eolian material transported westwards from the Yilgarn Craton. However, the close relationship between laterite composition and bedrock type indicates that eolian-derived constituents are generally minor.

Parent rocks

Most bauxite deposits of the Darling Range area are underlain by massive, unfoliated or weakly foliated, even-grained or porphyritic granite parent rocks. However, the observation that other rock types such as gneiss, schist, mafic volcanics, mafic intrusives and metasedimentary rocks also locally constitute parent material establishes that, though an important factor, bedrock lithology does not in itself completely control bauxite distribution. However, the lack of known bauxite in the Collie Basin may reflect the underlying Tertiary and Permian sedimentary rocks.

Apart from mineralogy and chemistry, the physical properties of bedrocks are important factors in controlling topography, and therefore (indirectly) local weathering regimes. Bedrock inhomogeneities, such as dolerite–granite contacts, influence orebody geometry and undoubtedly contribute to local groundwater environments, which in turn affect leaching.

Many previous workers (Simpson and Gibson, 1907; Saint-Smith, 1912; Simpson, 1912; Tomich, 1964; Grubb, 1966; Baker, 1971, 1972; Sadleir and Gilkes, 1976; Davy, 1979a; Murray, 1979; Loughnan and Sadleir, 1984) have noted the strong association between bauxite deposits and granitic parent rocks in the Darling Range. The bauxite deposits at Jarrahdale, Huntly, Del Park and Willowdale possess a chemical composition and mineralogy consistent with derivation from granite, whereas bauxite at Mount Saddleback (Ball and Gilkes, 1987) reflects a mafic parent rock (Table 2). Grubb (1971) additionally postulated a fluviatile sediment component to the bauxites at Jarrahdale.

The major chemical components of bauxitic laterite are Al, Si, Fe and oxygen. The relative concentrations of Al, Si and Fe are a function of parent rock mineralogy and chemistry, and variable enrichment and depletion processes which operate during the weathering and lateritization of these parent rocks. Because Al, and particularly Av.Al_2O_3, contents of bauxitic laterite are largely dependent on the variable concentration levels of Si and Fe, factors governing the behaviour of these elements are considered first.

Relatively high (generally 15–30%) SiO_2 contents in bauxitic laterite derived from granite (and other quartz-bearing materials such as quartzo-feldspathic sediments) are due to the fact that where SiO_2 in a parent rock is present chiefly in the form of quartz, the resistance to breakdown of this mineral during lateritization results in its retention in the profile, with only moderate loss by dissolution. In contrast, mafic rocks such as basalt and dolerite contain less total SiO_2 (about 50% compared with 65–75% in granitoids), and this is present chiefly in the form of feldspar and ferromagnesian minerals. Feldspar and ferromagnesian minerals are far more reactive than quartz during lateritization and, as they break down firstly to clay and then gibbsite, SiO_2 is liberated and leached from the laterite residue. Silica values decrease markedly up the profiles above mafic parent rocks, with major reductions occurring at the clay–friable unit boundary. The SiO_2 content of bauxitic laterite over mafic volcanic rocks is less than 5%, but most of this is Re.SiO_2 within clay minerals.

The Fe content of mafic parent rocks is far greater than that for granite (15–20% Fe_2O_3 compared with 2–5% Fe_2O_3). Iron retention or enrichment during lateritization results in bauxitic laterite derived from mafic rocks being far more ferruginous than granite-derived bauxitic laterite (Davy and El-Ansary, 1986).

In the laterite profile Fe is generally enriched towards the surface, except in the pallid clay zone where it is depleted. One reason for this behaviour is the different solubilities of the ferrous and the ferric ions. In reducing and more acidic parts of the weathering profile, the more soluble ferrous ion predominates.

Alumina contents in bauxitic laterite derived from granite and mafic rocks are similar and show enrichment to about three times the concentration in the parent rocks. The relatively high feldspar content of granite, compared with that of mafic rocks, is offset by the fact that K-feldspar, and to a lesser extent sodic plagioclase, is less susceptible to weathering than calcic plagioclase (dominant in mafic rocks). Moreover, the quartz content of granite, which substantially remains in the laterite profile, effectively dilutes the Al_2O_3 content of granite-derived bauxitic laterite. Alumina enrichment in granite-derived profiles results from partial dissolution of quartz, and major SiO_2 loss from feldspar, combined with an almost total loss of Mg, Ca, Na and K ions; Al_2O_3 enrichment in mafic rock-derived profiles results from almost total loss of SiO_2, with almost total loss of Mg, Ca and Na ions. The mineralogical changes associated with these changes have been described and are summarized in Figure 11.

The concentrations of trace elements are also dependent on the source rock. In general the concentration levels of elements such as Cr and Cu are higher in profiles over mafic rocks, whilst those of Zr and Ga are higher in profiles over intermediate-felsic rocks. Gallium and Cr, however, are enriched residually whilst Cu, Zn, Co, Ni, Mn and rare-earth elements are grossly depleted near surface (Sadleir and Gilkes, 1976; Davy and El-Ansary, 1986; Monti, 1987). Some secondary deposition of Co, Mn and, possibly, rare-earth elements may occur near the base of the clay zone, where conditions change from reducing to oxidizing. It is doubtful whether any element can be classed as truly residual; estimates based on bulk density measurements at the Boddington Gold Mine (Davy and El-Ansary, 1986; Monti, 1987) suggest that at least minor loss of elements such as Ti and Zr has occurred.

The nexus between bedrock geology and topography is noteworthy. Bedrock has influenced the evolution of the landscape on which bauxitic laterite formed, as well as having had a bearing on lateritic processes and products. The surface affected by lateritization and bauxitization had been already subjected to sufficient uplift and erosion to form a dissected plateau or 'range' of relief comparable with that seen today (Playford, 1954; Prider, 1966). The topographic characteristics of this eroded landscape were largely determined by the nature of the underlying bedrock.

Figure 5 shows that in the Jarrahdale–Collie area the structural grain of the Archaean rocks strikes predominantly northwest or north-northwest; this results in ridges and valleys with the same preferred orientation. The effect is enhanced by swarms of northwest-striking dolerite dykes that are resistant to erosion. North of Jarrahdale and southwest from Collie the dominant structural trend is northerly, and this likewise affects topography.

Lines of relative weakness in bedrock have been exploited to form major valleys. Examples are the northwest to north-northwest trending zone of migmatite along part of the Murray River, and similarly orientated contacts between granite and migmatite along the Darkin River between Mount Dale and the Helena River.

The correlation between the location of bauxite deposits and areas underlain by homogeneous, low metamorphic grade granite implies a genetic relationship. The granite differs from most other rock types in the area by being compositionally homogeneous over large distances, and possessing far fewer strongly aligned planes of structural weakness. Weathering therefore does not result in a well-developed trellised drainage pattern of parallel strike ridges and valleys, but produces a relatively subdued topography of low hills and shallow valleys, broken only by occasional deep, narrow valleys where major drainages have dissected the plateau. Low relief of an elevated area probably results in a combination of relatively high rainfall with gradual drainage, which may be expected to promote deep weathering while limiting erosion. Such conditions would favour deep lateritization and laterite preservation.

Although compositionally homogeneous and relatively massive, the granite of the Darling Range area possesses well-developed joint patterns. Such joints have permitted the deep penetration by groundwater necessary for extensive lateritization, and provided conduits for the removal of dissolved weathering products. Dolerite is also jointed but, being more resistant to weathering, has generally been decomposed to shallower depths, and produces profiles rich in iron and clay. High clay contents may, in turn, have impeded internal drainage by building up within joints, thereby blocking the water flow. The mafic volcanic rocks of Mount Saddleback are highly fractured and sheared, and have been very deeply lateritized. Such large units of mafic volcanic rock do not occur elsewhere in the Darling Range, so that it is unknown to what extent any unusually localized weathering conditions have favoured bauxite formation at Mount Saddleback.

Drainage and topography

Drainage and topography are very important factors in the formation of bauxite. The relationship between slope gradient and drainage intensity, and the influence this has on the extent of lateritization, has been appreciated for some time. Bauxite represents the final stage of the weathering sequence of alumina-bearing silicate minerals. The development of gibbsite and boehmite requires intense leaching.

The Darling Range bauxite deposits are concentrated in the Jarrahdale–Willowdale–Mount Saddleback area where topographic relief on the lateritic upland division of the Darling Plateau is relatively pronounced. Farther south, east and north, bauxite becomes less abundant; deposits are smaller in areal extent, thinner, less numerous, and more widely spaced. An exception to the overall pattern of bauxite becoming less common eastwards is the anomalously high bauxite concentration in laterite developed on the Mount Saddleback greenstone belt, where bedrock geology and topography have combined to produce locally favourable conditions for bauxite formation. East of Mount Saddleback bauxite development was severely restricted by sluggish drainage in broad, shallow, sand-choked valleys, and much of the laterite which did form has been removed by erosion.

South of the Harvey and Harris Rivers, the proportion of bauxite present in laterite abruptly decreases. The landscape of the plains around Collie is characterized by low overall elevation and very subdued relief. Farther south, major drainages such as the Collie and Preston Rivers have removed large areas of laterite. Bauxite deposits are confined to ridges northeast and southwest of Collie.

North of the Canning River, despite the occurrence of large areas of almost complete laterite cover, a gradual decline in bauxite concentration occurs. Beyond the Helena River, bauxite concentrations occur only at a few scattered localities. These areas have relatively high elevation and pronounced relief and occur close to the deeply incised valleys of Wooroloo Brook and the Avon River. To the north, northeast, and east of Wannamal, laterite is strongly dissected and bauxite deposits are virtually non-existent.

Initially, most investigators associated laterite formation with low relief. They believed that lateritization required a land surface of sufficiently low relief to permit infiltration of surface water. Steep slopes, it was contended, inhibited the ingress of water necessary for deep weathering and breakdown of rock-forming minerals, and resulted in rapid runoff with removal of surface weathering products. MacLaren (1906) and Woolnough (1918a, 1918b, 1927) went as far as to suggest that a level surface or peneplain was a prerequisite for laterite formation.

Some workers suggested lateritization is favoured by subdued topography and low altitude. Woolnough (1918b) suggested that near sea level peneplain conditions were required for laterite formation and that its present topographically high positions in the Darling Plateau resulted from subsequent uplift, local differences in laterite elevation being due to movements such as block faulting. Woodward (1908) considered that the hilly character of the surface of the South West constituted conditions which are 'utterly unfavourable' to laterite formation.

Observations by Simpson (1902), however, suggested that lateritization was enhanced by a certain amount of relief, laterite having been preferentially developed on the caps and sides of hills and flanks of ridges. Simpson (1912) observed that the accumulation of laterite appeared to be a very slow process and could not therefore take place where erosion was 'moderately rapid'. It tended instead to develop on 'well-drained' peneplains, such as the 300 m-high Darling Range peneplains, and on the upper, very gentle slopes of valleys where denudation was slow. Bare rock, clay, sand, and secondary laterite occurred at lower levels.

Later workers recognized that laterite can occur on land surfaces exhibiting considerable relief (Pallister, 1952; Stephens, 1961), and that it is not confined to low-gradient slopes, but can also occur on steep slopes (Trendall, 1962; de Swardt, 1964; Alley, 1970).

Other commentators pointed out that, even if a large part of Western Australia had been subjected to peneplanation, the presence of laterite on irregular surfaces sloping down towards the present stream valleys indicated that lateritization must have occurred after uplift. Playford (1954), Mulcahy (1960), Prider (1966), and Mabbutt (1980) supported the theory that relief may have had a positive influence on lateritic weathering.

On the basis of evidence available at the time, Clarke (1919) and Maitland (1907) pointed out that laterites on the highest ground were richer in soluble alumina than those occurring at lower levels. Geidans (1973) asserted, however, that altitude had no direct bearing on bauxite formation. There is no reason why various laterite types could not have developed at any elevation above sea level provided that physical and chemical conditions were favourable.

Tomich (1964) and Baker (1971) used exploration and mining data to comment on the relationship between relief and the occurrence of bauxite. They noted that bauxite deposits occur in gently undulating plateau areas and tend to be confined to ridge slopes rather than hill crests or valleys. In a grade contour plan of a portion of typical orebody, Baker (1971) illustrated diagrammatically the considerable lateral variation of Al content and the tendency for thicker and higher grade bauxite to occur on hill slopes. It is evident that most of the 'potentially mineable' deposits of Table 4 lie on 'mid-slopes' between 250 m and 350 m above sea level.

That bauxite formation is promoted by topographic relief, comparatively high elevation and good drainage was suggested by several workers (Tomich, 1964; Baker, 1971; Kirke, 1973; Butt, 1976; Owen and Hargreaves, 1975). It was agreed that the 'best bauxite' was generally associated with well-drained areas where hillslope gradients are appreciable.

Grubb (1966) suggested that lateritization/ bauxitization was more intensive where tectonic uplift was sufficient to maintain rapid percolation of meteoric solutions containing dissolved silica. A critical balance had to be attained: if uplift was too rapid, then the surface bauxitic horizon would be eroded. Again, the ratio of surface run-off to percolating meteoric water would increase and the rate of percolation would be too rapid to permit maximum solution of silica and iron from the bedrock. Conversely, where tectonic uplift was slow, the rate of meteoric percolation would decrease and, because of the resulting high watertable level, either surface re-kaolinization would occur or, in the case of strongly seasonal climate, a hard surface duricrust would form. Both clay and duricrust would then be effective barriers to further bauxitization.

Grubb (1971) considered that optimal drainage conditions with respect to the formation of bauxite deposits must have been met during epeirogenic uplift of the central part of the Darling Range. Because this uplift was not rapid but prolonged, spasmodic, and often accompanied by warping, good conditions for leaching existed. Drainage conditions appear to have been less favourable farther south in, for example, the Greenbushes area.

Geidans (1973) has listed relief and drainage as a genetic requirement for formation of residual laterite and bauxite. He remarked on the determining influence of relief on the ratio of physical to chemical weathering. Relief is essential to assure the movement of water required to drain saturated solutions from areas of weathering, and to lower the watertable below which laterite (and bauxite) does not form.

Changes in pH in poorly drained stagnant environments lead to 'instability of the dissolved mineral compounds and kaolinization by siliceous solutions of any gibbsite present' (Grubb, 1973); therefore the best laterite/ bauxite development is encountered in areas of moderate relief. Variable laterite thicknesses on slopes reflect differential bedrock weathering.

Geidans (1973) considered that bauxite distribution could be affected by irregular subsurface drainage possibly associated with dolerite dykes, and that topography and drainage influenced not only the degree of lateritization/ bauxitization but also orebody configurations. He noted that on hillcrests the amount of water available for weathering and silica removal is restricted to rain; slope gradients are low, the weathering environment is almost stagnant, and weathering solutions soon become saturated. Inadequate drainage inhibits removal of weathering products and hinders the introduction of fresh solvents. Weathering is thus retarded and, consequently, laterite on hilltops is typically thin or absent. Downslope, the volume of meteoric groundwater progressively increases as the amount received directly from rain is supplemented by flow from higher up the slope. A moderate gradient facilitates fairly rapid movement of solutions, dissolution of silica, removal of weathered materials and entry of new solvents. Thus mid-slope sites are well drained both vertically and laterally. Geidans (1973) observed that farther down the slope, drainage becomes sluggish with decreasing gradients, and an almost stagnant environment is the outcome. Bauxitization can no longer proceed and orebodies become narrow and terminate.

Sadleir and Gilkes (1976) and Loughnan and Sadleir (1984) have stressed that bauxitization requires vigorous internal drainage to minimize the residence time of silica-laden solutions and assure a high level of leaching intensity, and hence silica removal and bauxite development.

Views have varied with regard to the topographic nature of the pre-lateritized landsurface. Simpson (1912) considered laterite to be an efflorescence on the surface of the Darling Peneplain, and that topography at the time of laterite formation closely resembled that seen today. Woolnough (1918a) agreed with Simpson's surface efflorescence theory, but thought that the current drainage system would have been too effective to permit significant upward leaching, and that laterite was therefore produced under peneplain rather than plateau conditions. He considered that present topography was the result of post-lateritization uplift and dissection

Playford (1959) considered that the laterite had formed not on a low-lying peneplain, but on a land surface which was already uplifted and dissected. He adopted Prescott's (1931) view that laterite was deposited as an illuvial soil unit with downward accumulation of soluble or suspended material in the zone of watertable fluctuation. Playford (1959) suggested that during lateritization the land surface must have displayed more relief than remains today because a watertable always shows less relief than its overlying land surface. In contrast Terrill (1948, 1956), noting that undulating laterite zone boundaries lie roughly parallel to the present land surface, believed that Darling Range laterite formed as an eluvial unit by the leaching of bedrock constituents. Terrill's theory implies that the topography at the time of lateritization closely resembled that seen today.

Vegetation

The role played by vegetation in laterite formation has been referred to by several authors. Some have noted the close relationship between laterite and present-day vegetation. Maitland (1907) observed that in the South West the extent of laterite corresponds closely to that of the dense jarrah and karri forest. Elsewhere in the State, laterite supports only scanty vegetation. Other writers have considered that the important relationship between laterite and vegetation is that which existed during laterite formation. Playford (1954) noted that deep lateritic weathering would have required the soil to be well fixed, as is the case in areas of thick vegetation.

Vegetation is also considered to have significantly influenced the nature of the end-products of lateritization and therefore played an important role in the formation of bauxite. Grubb (1966) pointed to the favourable impact of tall-forested vegetation on the ratio of meteoric water percolation to surface runoff. Geidans (1973) confirmed this point, along with the part played by vegetation in restricting denudation. He also suggested that total extraction of silica by vegetation could have constituted an important factor in laterite/ bauxite formation.

Kirke (1973) and Geidans (1973) noted the leaching role of organic acids from vegetation. Loughnan and Sadleir (1984) suggested that an oxidizing environment capable of inhibiting the accumulation of organic matter was a prerequisite for bauxite development. Otherwise intense leaching (required to maintain a low concentration of silica in the groundwater) would lead to acidification of organic matter and lowering of the pH, probably to the point of solution of alumina.

Soil acidity increases the mobility, and hence the potential for loss, of iron and aluminium. Therefore acid soils are generally recognized as being unfavourable to lateritization. McFarlane (1976) noted that although acidic conditions may be present near surface in tropical areas, at depth neutral or alkaline conditions may prevail. She suggested that consumption of humus by abundant microflora in the soil, and the consequent reduction of the concentration of humic acids in solution, is one means by which the pH of tropical soils is kept high. In controlling the pH of weathering solutions, vegetation influences rock weathering. In tropical environments, conditions of low acidity encourage the solubility of silica and therefore the transformation of clay minerals to bauxite. Even where acid conditions do occur, experimental work suggests that some accumulation of lateritic materials can still be expected (Pickering, 1962).

The positive influence of vegetation on the relative accumulation of iron and aluminium in tropical soils has been indicated by Rodin and Basilevich (1967). Although

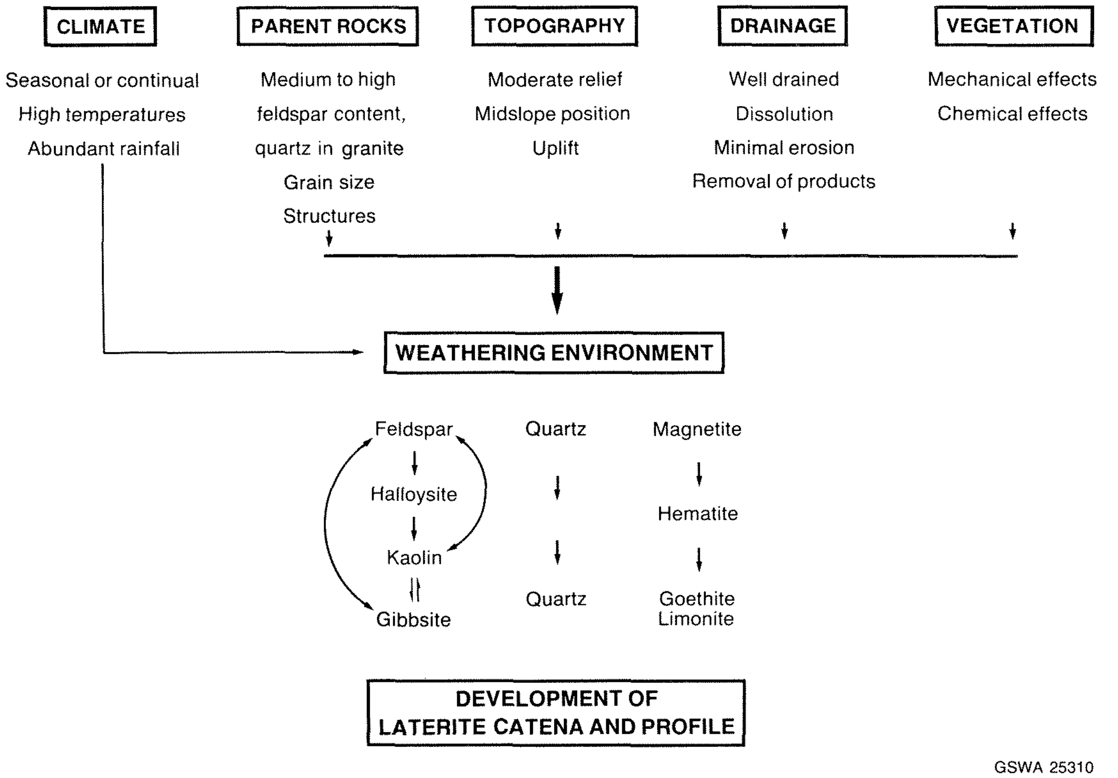


Figure 26. Factors controlling bauxite formation.

aqueous leachates of forest litter readily dissolve hydrated ferric and aluminium oxides to form soluble ferrous and aluminium complex compounds, sorption of the reaction products (which takes place concurrently) has the effect of inhibiting further solution.

Brimhall et al. (1988) considered that tree roots played an important role by increasing permeability in the upper part of laterite profiles, thereby promoting downward translocation of exotic grains containing Al, Fe and other partly introduced constituents such as Zr, Ti, V, Cr and Mo.

Eh–pH conditions

Laterite and bauxite are the residual products of chemical weathering of rocks, by which the removal in solution of Si, Mg, Ca, Na and K leaves concentrations of Al and Fe. Norton (1973) has reviewed the role of groundwater Eh and pH conditions in determining the relative solubility of Al and Fe, and consequently the dominant residual product, laterite (Fe-rich) or bauxite (Al-rich), of such chemical weathering.

Because bauxitization in the Darling Range did not involve significantly changing Al/Fe ratios of present rocks, the groundwater Eh–pH conditions must have been to the right of Norton's (1973) immobility line, and close to his Al–Fe isosolubility curve. This implies a very restricted range of Eh and pH conditions, along a curve from an Eh of about 0.4 mV and a pH of about 4, to an Eh of about -0.4 mV and a pH of 8.

Conclusions

The distribution, composition, thickness and areal extent of the Darling Range bauxite deposits reflect interacting depositional and erosional controls related to climate, parent rocks, drainage, topography, and vegetation (Fig. 26). Partly dependent on these factors, and probably of critical importance, groundwater Eh and pH conditions were locally conducive to bauxite formation (Norton, 1973). The largest, high-grade deposits are preserved in the Jarrahdale–Willowdale–Mount Saddleback region because, at the time of lateritization and bauxite formation in the Late Eocene to Early Oligocene, this area possessed a favourable combination of high rainfall, high temperature, chiefly granitic bedrock, moderate relief, appropriate groundwater Eh–pH conditions, adequate drainage, and dense vegetation. Also, the bauxitic laterite formed here has largely escaped subsequent erosion.

High rainfall and good drainage promote deep chemical weathering and the removal of rock components such as Si, Ca, Na, K and Mg, and permit the alteration of clay minerals to bauxite minerals. High rainfall also dilutes humic and carbonic acids which may inhibit conversion of kaolinite to gibbsite; low gibbsite/kaolinite ratios are characteristic of eastern areas with lower rainfall. High temperatures increase the rate of chemical reactions involving groundwater and bedrock and, with high rainfall, promote luxuriant vegetation.

The Al content of parent rocks is not a critical factor in bauxite formation, but other features such as mineralogy, homogeneity and structural fabric appear to be important. Parent rock mineralogy and chemistry strongly influence the composition (especially with respect to SiO_2, Re.SiO_2, iron oxides and clay) of bauxitic laterite produced at any given locality. The physical properties of a parent rock influence the development of topography and drainage. The distribution of the large, potentially mineable, bauxite deposits indicates that jointed (but otherwise massive), relatively homogeneous granite possessed the most favourable combination of mineralogical, chemical, and physical features for bauxite formation in the Darling Range.

Good drainage, but not rapid runoff, has promoted bauxite formation by providing the large volumes of percolating groundwater necessary for extensive chemical weathering, and by providing a medium for removal of weathering products, such as silica, in solution. The concentration of bauxite on mid-slope situations, as opposed to hill crests or valley floors, illustrates the role of good drainage and large volumes of water moving through depositional sites. Bauxite deposits formed preferentially in areas of moderate relief where drainage was good, but not rapid or dominated by surface runoff; very steep slopes tend to be areas of 'physical' erosion rather than 'chemical' weathering. Poorly drained, stagnant environments are characterized by kaolinization under low pH conditions, and bauxite formation is precluded.

The upper sections of laterite profiles include variable amounts of eolian material, but the source of this material is uncertain, and it is generally difficult or impossible to distinguish exotic eolian constituents from more locally derived alluvial or colluvial material.

Dense vegetation promotes deep lateritic weathering by 'fixing' the soil and providing organic acids for leaching. Abundant vegetation may also increase rainfall and promote penetration of water into the soil.

Chapter 4

Methods of exploration, mining and alumina production

Exploration methods

Previous bauxite exploration in the Darling Range is outlined in Chapter 1. Early exploration methods were governed by the need to define the regional distribution of bauxite mineralization, and consequently included such approaches as the collection of widely spaced surface samples along roads, in gravel quarries, and on accessible laterite ridges. This phase was followed by more systematic duricrust sampling and scout drilling across those areas thought to be most prospective. Some geological mapping was undertaken in late 1963 but, until Alcoa's 1970–72 program of systematic 1:63 360 scale geological mapping across ML 1SA, exploration was largely restricted to drilling.

Current and future exploration can become increasingly cost-efficient by utilizing available knowledge of the factors controlling bauxite deposit distribution (Chapter 3). Such knowledge can assist in the selection of prospective areas, and within these areas can further be used to avoid drilling holes with little or no chance of intersecting economic bauxite mineralization.

Exploration-stage drilling typically employs grid lines spaced at 100 to 200 m intervals. Drill holes are sunk to the clay zone or, where this is thin or absent, to bedrock. Samples are collected at vertical intervals of 0.5 m and analysed for Av.Al_2O_3, Fe_2O_3, Re.SiO_2 and organic carbon. In view of the discovery of a major laterite-hosted gold deposit at Boddington, and subsequent discovery of related base-metal mineralization in bedrocks, future exploration drilling of laterite could also profitably include routine determination of gold and base metals, particularly where laterite overlies mafic rocks, metasediments, or a bedrock lineament.

Ore development

Exploration-stage drilling is adequate to identify general areas containing economic bauxite mineralization, but the precise definition of mineable orebodies requires more detailed drilling and assessment. In the ore development phase all areas containing at least 20% Av.Al_2O_3 are drilled at 60 to 100 m intervals. Samples collected at 0.5 m intervals down the holes are analysed for Av.Al_2O_3, Re.SiO_2, Fe_2O_3 and organic carbon. The information obtained is sufficient to provide reliable ore boundaries, together with data on the approximate three-dimensional geometry and contained tonnage of individual deposits. Orebodies are identified using 25% and 27.5% Av.Al_2O_3 cut-offs with a minimum vertical ore section of 2.0 m, and those selected for mining are then drilled at intervals of 15 to 25 m. At this stage, Alcoa uses tractor-mounted 'Edson' rotary vacuum drill rigs (Fig. 27).

Detailed geological mapping ensures that all potential ore is included in the area to be mined, and plans and cross sections are drawn at 1:1000 scale. Pits are designed to utilize as much of the available ore as possible (cut-off usually 27.5% Av.Al_2O_3), whilst accommodating limitations imposed by safety requirements and mining equipment capabilities.

Ore-grade information, necessary for the refineries, is generally based on one composite sample from each 15 by 15 m block of ore. Grade control and monitoring are computerized. The goal at each mine site is to have at least 3 years' supply of refineable bauxitic ore ahead of mining, in order to respond to changing quality parameters and production rates set by the refinery. Refinery costs are approximately twelve times those incurred at mine site, and therefore ore sent to the refinery has to meet exacting grade specifications.

Ore is commonly mined from several pits in order to achieve the 'head grades' required at each refinery. This dispersal of mining activities is the consequence of the chemical and mineralogical variability of the ore being mined combined with such environmental constraints as dieback control and acceptable noise levels.

Because bauxite mining takes place in forested areas and within major water catchments, all operations have to be accommodated within an overall landuse planning framework, involving agreement with the Department of Conservation and Land Management (CALM) and the Water Authority of Western Australia (WAWA).

Mining and post-mining rehabilitation have to be approved annually on a rolling five-year basis, and there are environmental research reviews every three years. The Western Australian Government liaises closely with the companies and monitors their activities.

Mining methods

Mining methods employed at the various mine sites are similar with respect to overburden removal, drilling and blasting, and loading of broken bauxite into trucks (Fig. 28). Crushing and transportation of the crushed bauxite to the refinery differ between sites.

Figure 27. Tractor-mounted Edson vacuum drill in operation (Alcoa).

Overburden consists of 0.5–2.0 m of loose, thin humus and unconsolidated gravel. Its removal involves scrapers and bulldozers with attendant front-end loaders and off-highway trucks. The overburden is trucked either to temporary storage piles or is spread on the ripped floors of mined-out areas.

Blasting of the duricrust layer is carried out on a 3.5 m spacing, with hole depths averaging 3.0 m and using ammonium nitrate–fuel oil explosive. Large boulders are either reblasted or are stockpiled for subsequent burial during pit rehabilitation.

The broken duricrust, together with the underlying friable fragmental material, is transferred by front-end loaders into off-highway trucks of 35 or 50t capacity for haulage to the crushing plant.

Four mine sites (Del Park, Huntly, Willowdale and Mount Saddleback) employ mobile crushers and overland belt-conveying systems (Figs 29, 30). Jarrahdale ore is delivered to a fixed crushing plant (Fig. 31). The mobile crushers reduce the ore to fragments less than 200 mm in diameter, and pass this material onto the overland conveyors; the Jarrahdale crusher reduces the ore to 25 mm or less.

Processing

The 100 year-old Bayer process, with some adaptations, continues to be the most efficient way of producing alumina from bauxite. The basis of the process is the variation in solubility of hydrated alumina in sodium aluminate solutions with changes in concentrations of

Figure 28. Front-end loader and haulage truck in action at a mine face (Alcoa).

caustic soda (NaOH) and temperature. This solubility variation permits efficient extraction of alumina from bauxite at elevated temperatures, together with good yields of precipitated alumina on cooling. Figure 32 shows a flow sheet for an alumina refinery that employs autogenous grinding mills (e.g. Pinjarra, Wagerup, Worsley).

The crushed bauxite supplied to the Kwinana refinery is milled in open-circuit rod mills and then pumped directly to the digesters. Ore from the other mine sites, crushed to less than 200 mm, is milled in semi-autogenous mills to 35-mesh particle size. The resulting bauxite slurry is then blended in storage tanks before digestion.

The slurry is digested with caustic liquor at a temperature of 143°C and a pressure of 242 kPa. Caustic soda concentrations vary with the predicted $Re.SiO_2$ content of the ore feed, but 150–190 g/L is common. The hot slurry is held for about 30 minutes to allow for dissolution of the gibbsite, and complete desilication of the process liquor.

The process liquor's desilication is a crucial stage in the Bayer process. The ore contains kaolinite which supplies $Re.SiO_2$ to the liquor. This form of silica reacts with caustic soda and the extracted alumina to form an insoluble desilication product. Because one tonne of SiO_2 reacts with 0.8 t of sodium hydroxide, potential losses of caustic soda (an expensive reagent) and alumina make it imperative that the ore does not contain more than 2% $Re.SiO_2$.

Conversely, satisfactory desilication of the process liquor depends on an adequate $Re.SiO_2$ level in the ore being digested to get the auto-catalytic reaction started. Usually, $Re.SiO_2$ levels must be at least 1%. Ores with less than 1% $Re.SiO_2$ are poorly digested and the silica content of the alumina product exceeds the exacting specifications required by aluminium smelters. Ideally bauxite feed should have a $Re.SiO_2$ range of between 1.1 and 1.5%.

Following digestion, the slurry is 'flash' cooled, in discrete steps, back to atmospheric pressure. The flash steam from each stage is used to preheat incoming caustic liquor and bauxite slurries. Darling Range bauxite produces a residue consisting of two distinct particle size ranges; a coarse fraction rich in silica, and a fine fraction (red mud) rich in iron oxide. The coarse fraction is gravity settled in sand-traps from which it is continuously removed and washed to recover caustic soda.

The sand-trap overflow feeds large settling tanks where, with the aid of coagulants, the mud is separated and pumped through a series of washing stages for recovery of entrained alumina-rich liquor.

Figure 29. Mining operations at Del Park South, showing a Dosco Continuous Miner loading ore onto an overland conveyor; mobile crusher and overburden stockpiles in background.

The supersaturated sodium aluminate liquor (green liquor) overflowing the thickeners is passed through a filtration stage to remove all traces of suspended residue, and then 'flash' cooled still further. The purpose of this final 'flash' cooling is to assist both heat recovery and preparation of the liquor for precipitation of alumina trihydrate.

Controlled precipitation (or 'decomposition') is achieved by mixing the green liquor with medium-sized alumina trihydrate seeds in large agitation tanks. Under these conditions steady growth occurs on the seed, producing a tough crystal and no generation of new, unwanted nucleii. Following precipitation, the hydrate is classified hydraulically, the coarsest material being collected for calcination, and the remainder being recycled as seed.

During the calcination stage the water of hydration is driven off and a phase change occurs in the alumina. Alumina is produced by calcining hydrate at 1100°C in alumina fluid-bed calciners. The degree of calcination is controlled to produce a non-absorbent alumina with handling characteristics satisfactory to aluminium smelters. The main physical properties affecting handling characteristics are surface area, particle size and angle of repose.

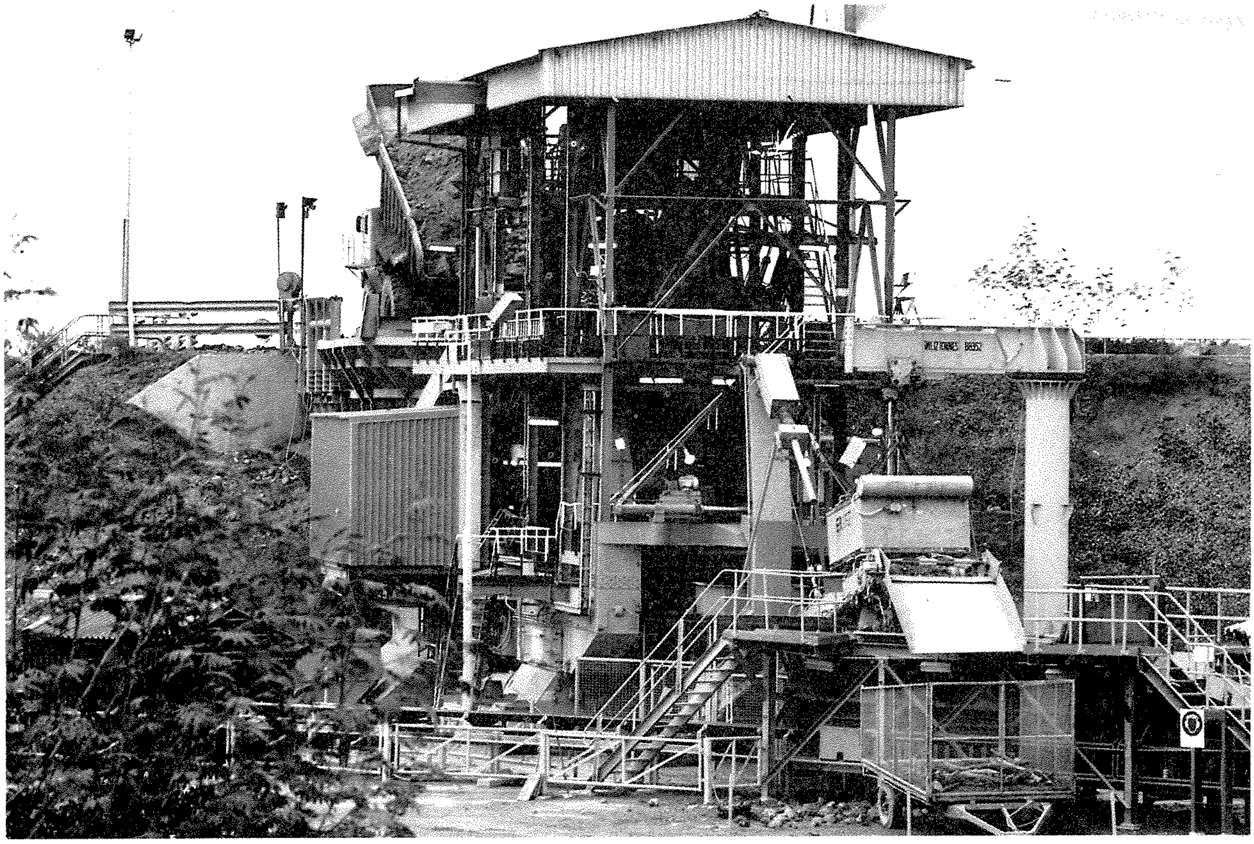


Figure 30. Mobile crusher receiving another truckload of ore, Huntly.

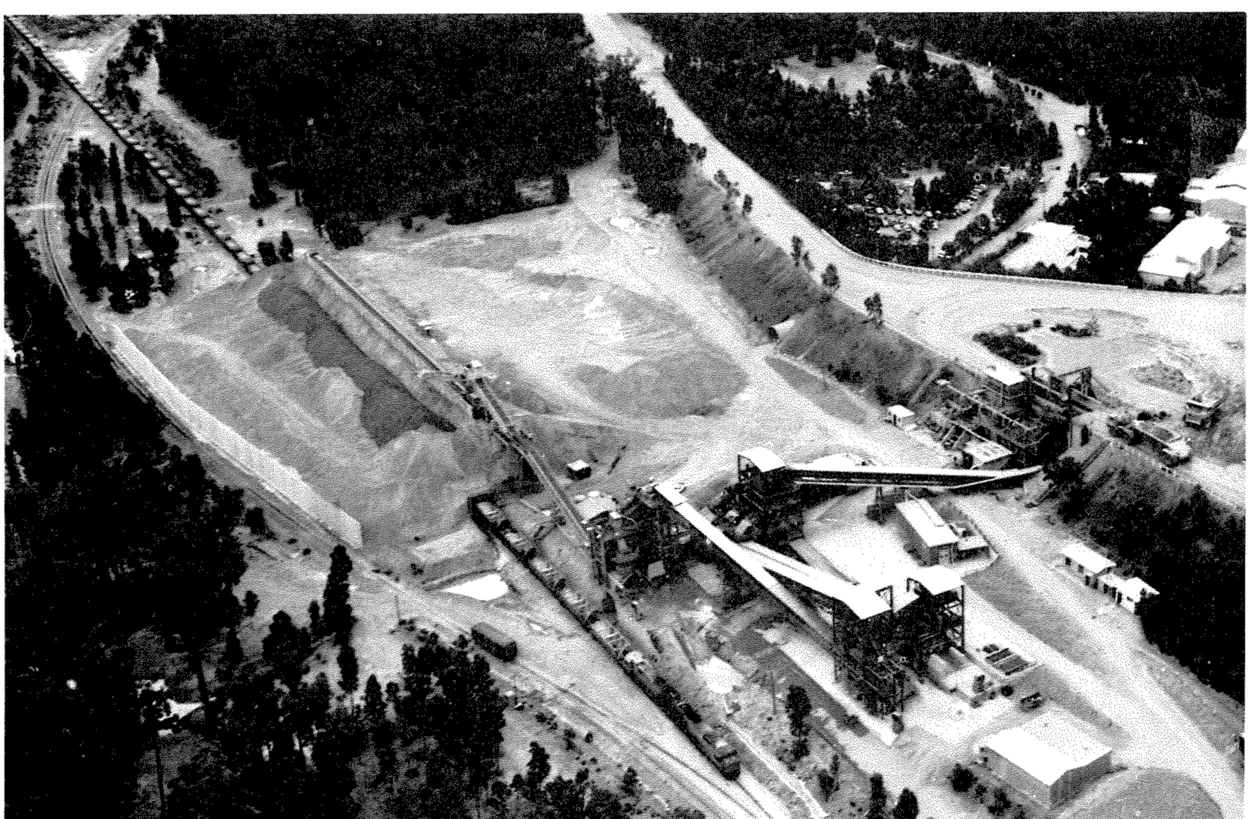


Figure 31. Fixed crusher and train loading facility, Jarrahdale.

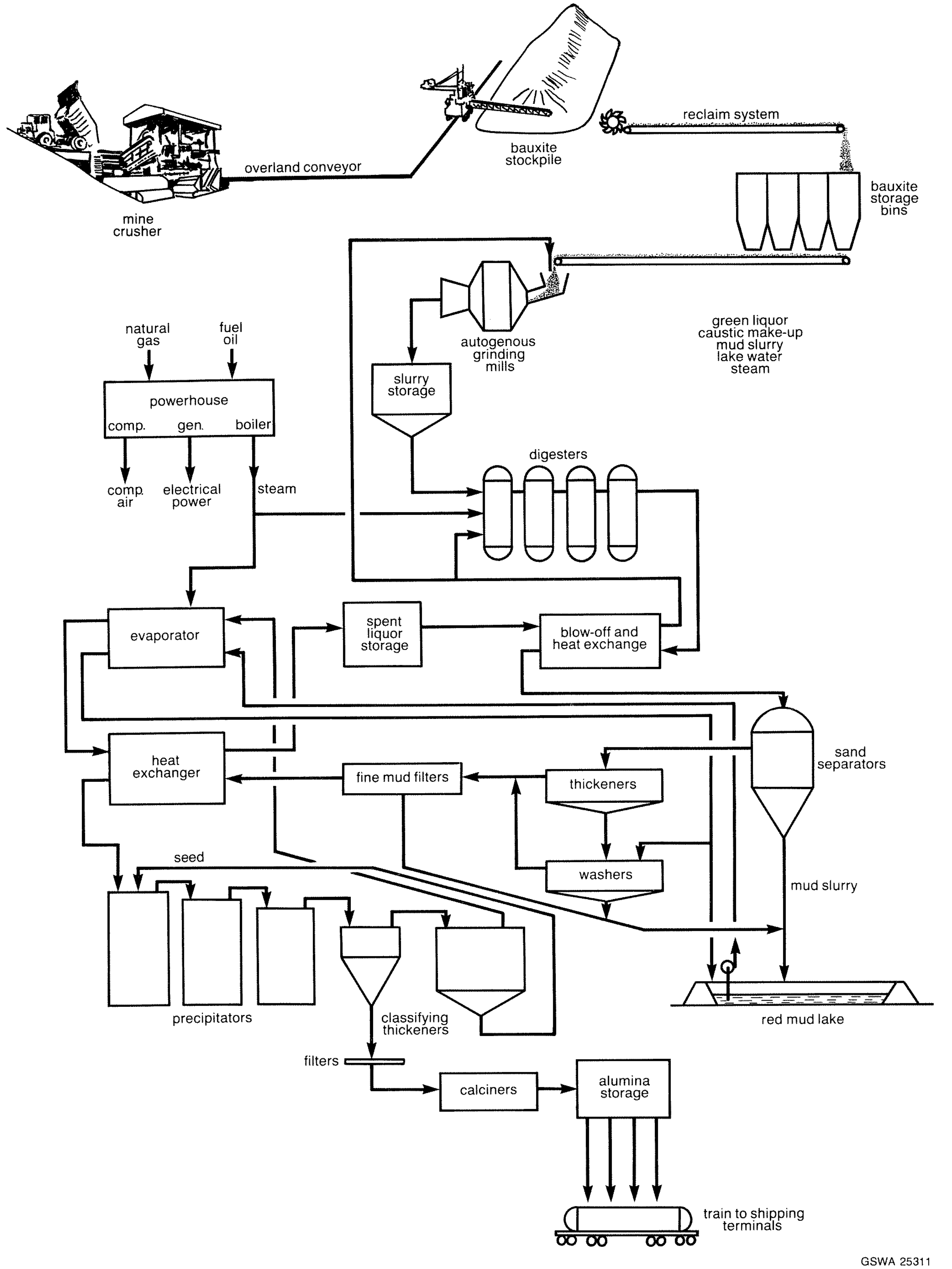


Figure 32. Alumina refinery flowsheet (Alcoa).

Following classification and removal of the precipitated alumina trihydrate, the spent liquor is returned for further bauxite digestion.

To minimize caustic soda and sodium aluminate losses, considerable attention is paid to maximizing underflow densities and wash-water rates during the residue-washing stage. After being washed essentially free of liquor, the residue is pumped to disposal areas.

The typical Av.Al_2O_3 grade (30–35%) of Darling Range bauxite is low by world standards. Approximately 3 to 4 kg of bauxite are required to produce 1 kg of alumina. One obvious consequence of this is the considerable magnitude of the materials-handling operation in transporting ore to the refinery, and the exacting nature of the subsequent blending, stockpiling, and digesting of the ore.

Residue treatment and disposal are likewise massive operations in comparison with alumina refineries elsewhere. For each 1 kg of alumina, approximately 2 to 3 kg of residue are produced.

Darling Range bauxite, like most shallow deposits, has a relatively high organic content. This organic material is derived from decomposed vegetation and roots, and includes many substances such as humus, lignin, cellulose, and protein. Under the alkaline oxidative conditions existing in the Bayer process, these complex organic compounds break down through a series of stages to simple compounds such as the sodium salts of succinic, acetic, and oxalic acids, and to carbon dioxide.

Predominant among the salts is sodium oxalate, which tends to reach saturation in the plant liquor and co-precipitates with alumina trihydrate causing the generation of excessive amounts of contaminated fine hydrate.

Carbon dioxide reacts with the caustic soda in the liquor to form sodium carbonate causing increased losses of caustic soda and the need for more lime to be added to the liquor to regenerate caustic soda.

The accumulated build-up of total organic carbon in liquor streams at the Kwinana and Wagerup alumina refineries has reached serious levels. A liquor-burning plant has been commissioned at Kwinana to counter the organic carbon levels. Once the success of the measure has been demonstrated it is likely that liquor-burning plants will be added to Wagerup's refinery circuit. The Willowdale five-year mining plan has been modified to bypass bauxite which has extractable organic carbon levels greater than 2%.

Chapter 5

Mining and the environment

Introduction

Bauxite exploration and mining take place in a region characterized by finely balanced ecosystems. These ecosystems are still poorly understood, and the adverse effects of any developmental work (mining, damming of valleys for water, clearing for agriculture, roads, or timber production) are relatively slow in revealing themselves. Consequently, all earth-moving and clearing activities have to be carefully controlled and managed. To this end, the companies work in close co-operation with State government departments and tertiary institutions. Relevant research programs are funded and staffed with scientific personnel. Every effort is made to minimize the impact of bauxite exploration and mining on the environment, and to rehabilitate areas immediately mining operations have been completed. The following sections cover selected aspects related to the environment.

Conservation

In 1972, the Environmental Protection Authority (EPA) established a Conservation Through Reserves Committee which subsequently divided the State into twelve regions or systems. These were defined on the basis of broad associations of landform, vegetation, landuse and tenure.

Systems 1 to 6 cover the South West; in the Darling Range, System 6 encompasses the greater part of the area containing bauxite mineralization.

The South West is managed by the Department of Conservation and Land Management as three regions: northern, central and southern. Each region is made up of a mosaic of forest blocks which have preferred landuses (e.g. timber production, water protection, nature conservation). These blocks in turn formed the basis of EPA 'Red Book' recommendation areas.

In May 1982, the Darling Range Study Group released its report on landuse planning in the region. It set out guidelines to be followed in managing the region's natural resources (water, timber, vegetation, bauxite) and identified major environmental constraints (salinity, dieback, conservation). The report recommended the development of regional framework plans as the principal means of coordinating resource management.

Numerous large conservation reserves (totalling about 25–30% of the lateritic area covered by Plate 1) have now been established in the Darling Range (Fig. 33), and from many of these future bauxite exploration and mining will be precluded. These nature conservation areas are based on botanical and ecological studies. Population density of the rarer species, and the range of mobile species, minimum size, variety of habitats, and the extent of dieback infection have been the principal criteria employed.

Jarrah dieback

Healthy jarrah–marri forest (Fig. 34) is under attack from a fungal disease. The disease and the diseased areas of the forests are both embraced by the term 'jarrah dieback'. The disease was accidently introduced 60 years ago and is caused by the pathogen *Phytophthora cinnamomi* Rands, a fungus which attacks the root systems of the jarrah, marri, and various understorey species. Jarrah, *Eucalyptus marginata*, dies after most of the understorey has been eliminated by the disease (Fig. 35). Marri, *Eucalyptus calophylla*, has its vigour reduced but is able to survive and to recolonize jarrah dieback areas (Shea, 1975).

Because the disease can be carried in soil adhering to vehicle tyres, and earth-moving machinery, all machinery and vehicle movements in State forest must comply with forest hygiene regulations.

Exploration for bauxite within State forest has been controlled by dieback hygiene prescriptions in force since 1969. In addition, nearly 50% of the 1.9 Mha of State forest were placed under quarantine in 1979. This exclusion measure severely restricts the movement of vehicles in the central, eastern, and southern regions of the Darling Range.

Maps based on low-level aerial photography are used to differentiate healthy forest from diseased areas, and from areas in which the presence of the disease is suspected. Under rigidly enforced conditions CALM has allowed selective logging to occur in the quarantined or Disease Risk Areas (DRA). Bauxite exploration and mining operations in the DRA will be subject to the same rigorously applied controls; for example, access is prohibited except along designated formed roads.

To that end a series of detailed prescriptions is being developed to cover all phases of ore development and mining. These will be applied at Urbrae (north of Huntly) before entering the DRA (Fig. 18).

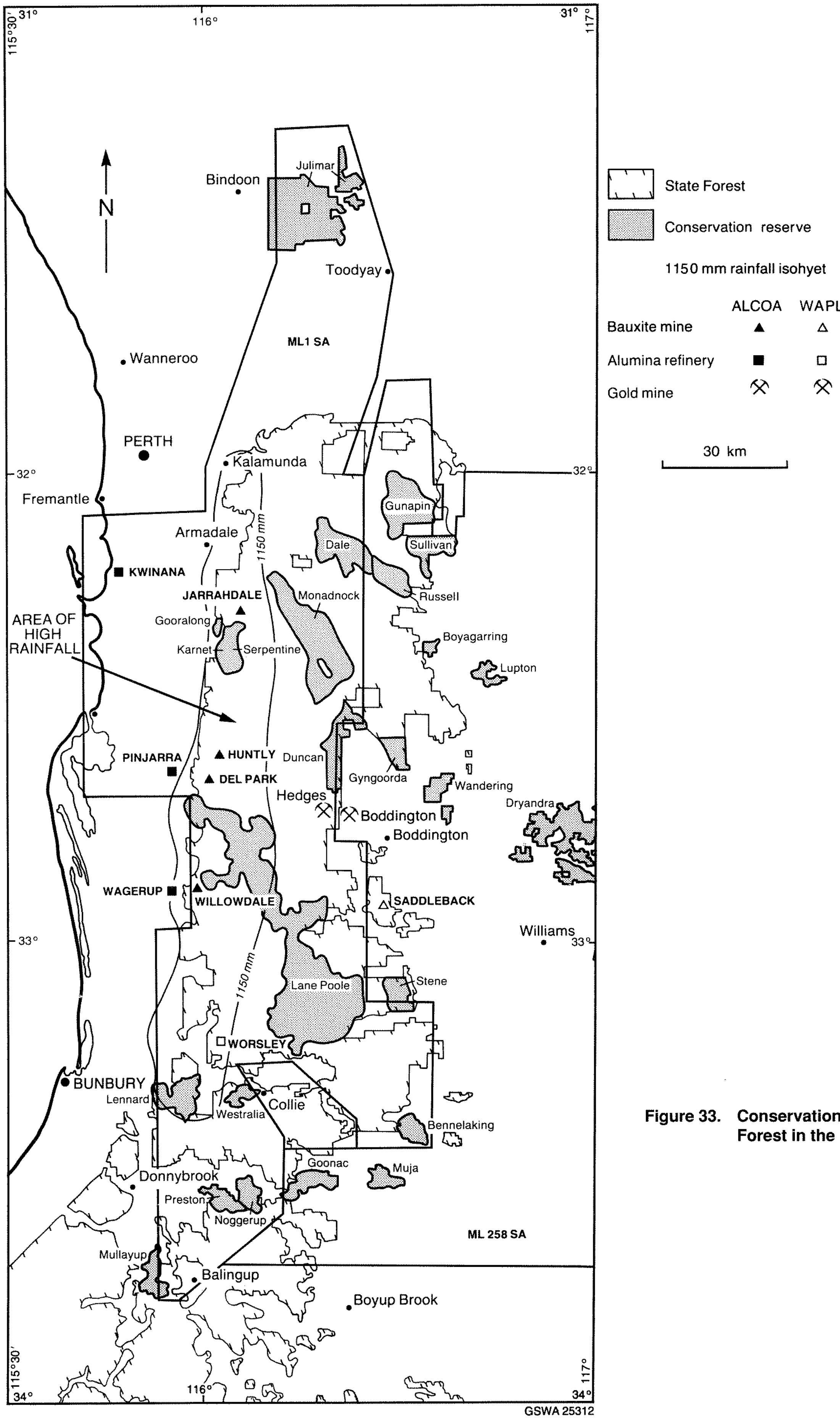


Figure 33. Conservation areas and State Forest in the Darling Range.

Figure 34. Typical healthy jarrah–marri forest (CALM).

Figure 35. Forest affected by dieback disease (CALM).

Division of the lateritic terrain into general geomorphic categories, together with geological investigations, could increase the chances of finding practical tools for the management of State forests (Smurthwaite and Shearer, 1983). A regional survey covering more than 400 sites has demonstrated that 14 indicator species could be used to identify naturally disease-prone sites from naturally protectable ones (Shearer, pers. comm.).

Salinity

High-salinity levels do not occur in streams draining the high-rainfall areas currently being mined by Alcoa. Farther east there is potential for increased salinity as forest clearing brings about changes in hydrology. After the EPA approved the Wagerup Environmental Review and Management Program (ERMP), Alcoa gave a public undertaking not to mine east of the 1150 mm rainfall isohyet until the combined State and company research program had established safe mining and rehabilitation procedures.

Sites in lower rainfall zones (characterized by thick pallid zones, sluggish drainage and impeded movement of water through the soil profile) have had thousands of years to accumulate meteorological salt. Deep-rooted, indigenous vegetation minimizes the flow of water through the soil profile. Removal of this vegetation (by clearing for mining, agriculture, or through dieback) raises the watertable, thus remobilizing the groundwater, and salt is flushed from the soil profile into streams. The potential risk to metropolitan water reservoirs (e.g. South Dandalup reservoir) is immense.

Sites in the high-rainfall zone (Fig. 33) generally have little salt in the laterite profile because the salt has been leached by heavy and regular rain. Hence, forest clearing or dieback effects provide substantial increases in groundwater discharge without deterioration of water quality.

Existing stream monitoring and drilling data demonstrate a marked gradient in salt storage from west to east, with the greatest accumulations occurring in the eastern low-rainfall zone.

The mechanisms of soil and water movement in natural and disturbed hillslopes are constantly being evaluated. Data are being processed and collated by various research groups, and computer-based models have been set up to predict the probable outcome of any particular ground-disturbing activity. Extrapolation of results obtained from one site to another is risky because of the variable nature of lateritic terrain: many relationships are site-specific.

A 25-year trial mining program has been under consideration since 1975 to monitor mining simulation trials conducted in lower rainfall sites. The exact location of these trial mining sites has yet to be finalized. Precise measurements of groundwater qualities and quantities (together with assessment of rehabilitation techniques) will determine whether Alcoa can access bauxite from zones with less than 1150 mm rainfall. The program is estimated to cost $25 million (Carbon, 1984).

Residue disposal

Disposal of waste residues is a large and costly operation, and environmental considerations play a major part in determining how this is carried out. From an economic point of view the disposal area should be adjacent to the refinery. However, competing uses for land and the unavailability of suitable topographical and subsoil features often necessitate the use of more remote locations.

The Kwinana residue ponds, or red mud lakes, are situated in a market garden area, and dust blowing from the lakes is a nuisance to local vegetable growers. Breaks in the clay membranes lining the ponds have allowed caustic solutions to enter the groundwater. The pollution plume is being closely monitored, and measures are being taken to combat it and to prevent further emissions. The problems encountered at Kwinana illustrate the need for both careful environmental consideration and planning of waste disposal.

The disposal ponds for the other two alumina refineries are within the borders of the refineries. The ponds and stormwater lakes form part of an integrated plant-drainage system. This arrangement ensures that contaminants do not affect adjacent streams, swamps and groundwater.

Post-mining rehabilitation

Bauxite mining necessitates complete removal of vegetation and topsoil in areas of pits, haulage roads and residue disposal areas. Rehabilitation of mine sites is aimed at regeneration of a stable forest ecosystem capable of maintaining or enhancing conservation, water, timber and recreation values. Specific goals include restoring flora and fauna similar to that of the native forest, preventing long-term adverse effects on water supplies, controlling dieback and fire hazards, and in some localities establishing recreational areas. A good general account of rehabilitation methods is provided by Bartle and Slessar (1989).

Since bauxite mining commenced in 1963, approaches to, and methods of achieving, rehabilitation have evolved in response to information obtained by monitoring the results of various techniques, and to environmental conditions required by land users outside the mining industry.

Rehabilitation of mined-out areas commences with the battering down of vertical mine faces to make the pit's morphology blend with that of the adjacent forest. Banks of laterite boulders and gravel are constructed low in the landscape in order to minimize scouring caused by heavy rain and overland flow. The banks are constructed to trap surface water and introduce it through seepage back into the profile, or to remove it rapidly from the vicinity of the rehabilitated area.

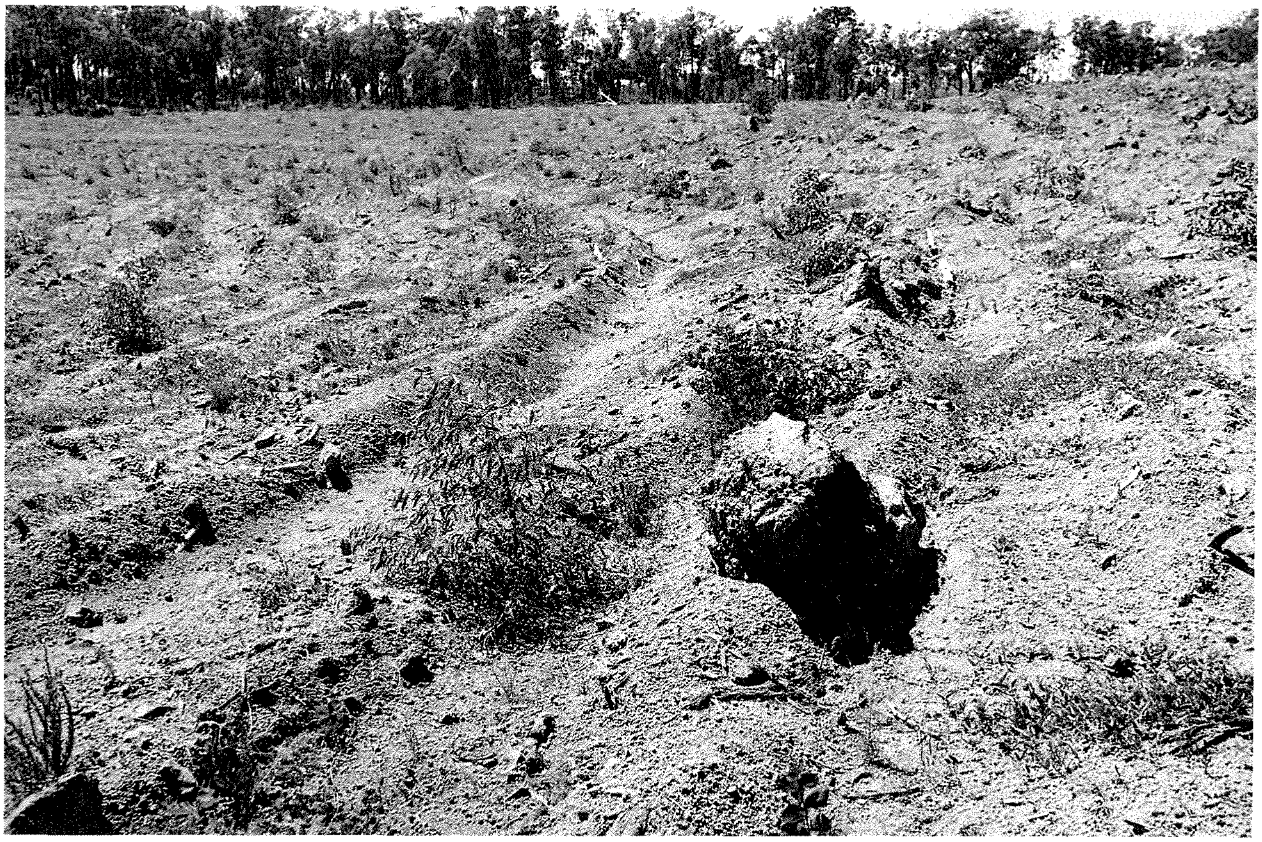


Figure 36. Typical rehabilitated area, with vegetation aged about 10 months (Bartle and Slessar, 1989).

About 0.5 m of topsoil is spread over the mine floor and the compacted surface is ripped to a depth of 1.5 to 2 m to ensure that new trees achieve maximum root penetration, and that drainage is adequate (Dell et al., 1983).

Early problems of soil surface instability and retarded tree growth reflected inadequate site preparation, species selection, revegetation techniques and nutrition. The most successful species used in the early planting program were fast-growing eucalypts from NSW, Tasmania and Victoria. They were selected for their commercial timber potential and resistance to jarrah dieback.

Seedlings of native species from nearby forest areas are now planted to ensure that the composition of the forest in mined areas is not radically altered. The ripping process leaves a shallow depression along the rip line. To avoid erosion, associated with rapid runoff, and to promote water penetration and storage, the rip lines follow contours; this also produces curved lines of trees and avoids any impression of a plantation (Fig. 36).

Trees are planted after winter rains, and a mix of species is used to simulate a natural forest and to minimize losses should a particular species prove not to be viable. Undergrowth seed is broadcast by hand or by helicopter. This addition complements the native seeds already present in the returned topsoil, while the mature acacias and ground creepers lower ground temperatures and generally improve growing conditions for the young trees. Since 1980 jarrah has constituted about 10% of the seed mixture, and excellent regrowth has been achieved; other eucalypts commonly used are marri, wandoo, blackbutt and butterbark (Fig. 37).

Fertilization applied to the eucalypts consists of 15 kg nitrogen plus 25 kg phosphorus per ha, and superphosphate applied at a rate of 50 kg per ha stimulates growth of seeded legume species. Koch (1987) has shown that inclusion of legume species provides early surface vegetation contributing to organic matter accumulation and generation of a nitrogen pool comparable with that of the native forest.

Rehabilitated areas have attracted back some 85% of the animal species of the original forest. Studies have shown that there is a rapid reintroduction of invertebrates and small animals by providing small logs and ample litter to afford them protective cover. Only birds which require hollow branches as nesting sites have yet to recolonize the rehabilitated areas.

The only management practice routinely required for replanted pits is protection from fire; controlled burning should commence after about 15 years when the trees are

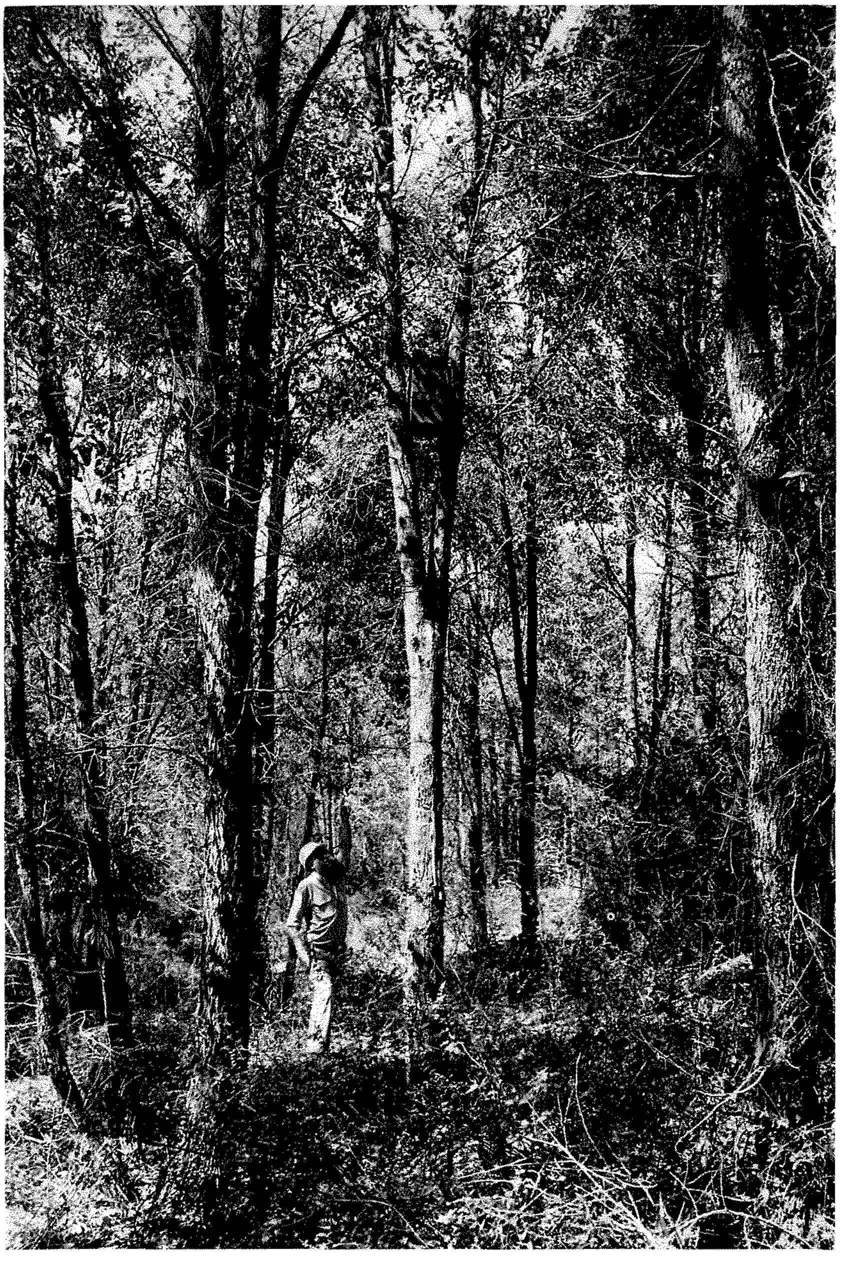


Figure 37. Rehabilitated area after 10 years (Bartle and Slessar, 1989).

mature enough to withstand fire (severe burns); some tree thinning may also be appropriate at this stage.

Post-mining rehabilitation is a major part of the environmental management and monitoring programs of both Alcoa and Worsley. By mid-1989, 71 % (4567 ha) of the total area so far cleared to permit bauxite mining operations (6445 ha) had been rehabilitated, and pit rehabilitation was generally occurring within two or three years of pit clearing. Research by company staff, and outside bodies such as Government departments and tertiary institutions, is continually assessing the success of current rehabilitation techniques, and examining ways of improving results.

References

ALLEY, N. F., 1970, Duricrust — an Australian dilemma: Paper presented to 1970 Meeting of Association of Canadian Geographers.

ANAND, R. R., GILKES, R. J., ARMITAGE, T. M., and HILLYER, J. W., 1985, Feldspar weathering in laterite saprolite: Clays and Clay Mineralogy, v. 33, p. 31–34.

ANAND, R. R., and GILKES, R. J., 1987, The association of corundum and maghemite in Darling Range laterites, Western Australia: Australian Journal of Soil Research, v. 35, p. 303–311.

AUSTRALIAN BUREAU OF AGRICULTURAL and RESOURCE ECONOMICS, 1991, Quarterly mineral statistics; March quarter.

AUSTRALASIAN INSTITUTE OF MINING AND METALLURGY., and AUSTRALIAN INDUSTRY MINING COUNCIL, 1989, Australasian Code for Reporting of identified mineral resources and ore reserves: Australasian Institute of Mining and Metallurgy, and Australian Mining Industry Council.

BAKER, G. F. U., 1971, Bauxite deposits of the Darling Range, Western Australia: Twelfth Pacific Science Congress, Canberra 1971 (unpublished).

BAKER, G. F. U., 1972, Origin of Darling Range bauxites, Western Australia: Economic Geology, v. 67, p. 981–982.

BAKER, G. F. U., 1975, Darling Range bauxite deposits, W.A., *in* Economic Geology of Australia and Papua New Guinea, Volume 1. Metals, *edited by* C. L. KNIGHT: Australasian Institute of Mining and Metallurgy, Monograph 5, p. 980–986.

BALL, P. J., and GILKES, R. J., 1985, The Mt. Saddleback bauxite deposit, South Western Australia, *in* Proceedings of Third International Conference on Lateritization Processes, Tokyo: Japanese National Committee of IGCP and Mining and Metallurgy Institute of Japan, 14 pp.

BALL, P. J., and GILKES, R. J., 1987, The Mt. Saddleback bauxite deposit, South Western Australia: Chemical Geology, v. 60, p. 215–225.

BARDOSSY, G., 1979, Growing significance of bauxites: Episodes (IUGS newsletter) No. 2, p. 22–25.

BARDOSSY, G., and ALEVA, G. J. J., 1990, Lateritic bauxites: Developments in Economic Geology, No. 27. Elsevier, Amsterdam.

BARTLE, J., and SLESSAR, G. C., 1989, Mining and rehabilitation, *in* The Jarrah Forest, *edited by* B. DELL et al: Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 357–377.

BERTHIER, P., 1821, Analyse de l'alumine hydratée des Baux: Ann. Mines, v. 6, p. 531–534.

BLIGHT, D. F., COMPSTON, W., and WILDE, S. A., 1981, The Logue Brook Granite-age and significance of deformation zones along the Darling Scarp: Western Australia Geological Survey, Annual Report for 1980, p. 72–80.

BOWLER, J. M., 1982, Aridity in the late Tertiary and Quarternary of Australia, *in* Evolution of flora and fauna of arid Australia, *edited by* W. R. BARKER and P. J. M. GREENSLADE: Peacock Publications, Adelaide, p. 35–45.

BRETAN, P. G., 1985, Deformation processes within mylonite zones associated with some fundamental faults: University of London, Ph. D. thesis (unpublished).

BRIMHALL, G. H., LEWIS, C. J., AGUE, J. J., DIETRICH, W. E., HAMPEL, J., TEAGUE, T., and RIX, P., 1988, Metal enrichment in bauxites by deposition of chemically mature aeolian dust: Nature, v. 333, p. 819–824.

BUREAU OF MINERAL RESOURCES, 1989, Australia's identified mineral resources, 1988: Australian Mineral Industry Quarterly, v. 41, p. 33–39.

BUTT, C. R. M., 1976, Bauxite deposits of the Darling Range, *in* Surficial mineral deposits and exploration geochemistry, Yilgarn Block, Western Australia, *edited by* R. E. SMITH, C. R. M. BUTT, and E. BETTENAY: 25th International Geological Congress, Sydney, N. S. W., 1976, Excursion Guide, No. 41 C.

BUTT, C. R. M., 1979, Some aspects of geochemical exploration in lateritic terrains in Australia, *in* Lateritization Processes, Proceedings of the International Seminar on Lateritization Processes, Trivandrum, India, 1979, p. 369–380.

CARBON, B.A., 1984, Environmental aspects of bauxite mining in Western Australia, *in* Bauxite: Proceedings of the 1984 Bauxite Symposium, Los Angeles, California, 1984, *edited by* L. JACOB Jr: American Institute of Mining, Metallurgical and Petroleum Engineers, p. 672–680.

CHURCHILL, D. M., 1973, The ecological significance of tropical mangroves in the early Tertiary floras of southern Australia: Geological Society of Australia, Special Publication 4, p. 79–86.

CHURCHWARD, H. M., and McARTHUR, W. M., 1980, Landforms and Soils of the Darling System, Western Australia, *in* Atlas of Natural Resources, Darling System, Western Australia: Department of Conservation and Environment, p. 25–33.

CLARKE, E. de C., 1919, The bauxites of the Darling Range — Southwest Division: Western Australia Department of Mines, Annual Report for 1918, p. 80–83.

COMPSTON, W., WILLIAMS, I. S., and McCULLOCH, M. T., 1986, Contrasting zircon U–Pb and model Sm–Nd ages for the Archaean Logue Brook Granite: Australian Journal of Earth Sciences, v. 33, p. 193–200.

DARLING RANGE STUDY GROUP, 1982, Land use in the Darling Range: A report to the Premier of Western Australia.

DAVY, R., 1977, Petrography and chemistry of selected rocks from the Saddleback greenstone belt: Western Australia Geological Survey, Record 1977/12.

DAVY, R., 1979a, Geochemical exploration Saddleback Greenstone Belt: Western Australia Geological Survey, Record 1979/8.

DAVY, R., 1979b, A study of laterite profiles in relation to bedrock in the Darling Range near Perth, W.A: Western Australia Geological Survey, Report 8.

DAVY, R., and EL-ANSARY, M., 1986, Geochemical patterns in the laterite profile at the Boddington gold deposit, Western Australia: Journal of Geochemical Exploration, v. 26, p. 119–144.

DELL, B., BARTLE, J. R., and TRACEY, W. H., 1983, Root occupation and root channels of jarrah forest subsoils: Australian Journal of Botany, v. 31, p. 615–627.

de SWARDT, A. M. J., 1964, Lateritization and landscape development in parts of Equatorial Africa: Zeitschrift für Geomorphologie (NS), v. 8, p. 313–333.

EVANS, H. J., 1975, Weipa bauxite deposit, Q, *in* Economic Geology of Australia and Papua New Guinea, Volume 1. Metals, *edited by* C. L. KNIGHT: Australasian Institute of Mining and Metallurgy, Monograph 5, p. 959–964.

FLETCHER, I. R., WILDE, S. A., LIBBY, W. G., and ROSMAN, K. J. R., 1983, Sm–Nd model ages across the margins of the Archaean Yilgarn Block, Western Australia — II, The southwest transect into the Proterozoic Albany–Fraser Province; Geological Society of Australia Journal, v. 30, p. 333–340.

FLETCHER, I. R., WILDE, S. A., and ROSMAN, K. J. R., 1985, Sm–Nd model ages across the margins of the Archaean Yilgarn Block, Western Australia — III, The western margin: Australian Journal of Earth Sciences, v. 32, p. 73–82.

GEIDANS, L., 1973, Bauxitic laterites of the South Western part of Western Australia: Australasian Institute of Mining and Metallurgy Conference Proceedings, 1973, p. 173–182.

GILKES, R. J., 1988, Mineralogy of Darling Range bauxite: Minerals and Energy Research Institute of Western Australia, Report No. 38 (unpublished).

GILKES, R. J., SCHOLZ, G., and DIMMOCK, G. M., 1973, Lateritic deep weathering of granite: Journal of Soil Science, v. 24, p. 523–536.

GILKES, R. J., and SUDDHIPRAKARN, A., 1981, Mineralogical and chemical aspects of lateritization in southwestern Australia: Proceedings of International Seminar on Lateritization Processes, Trivandrum, India 1979, p. 33–44.

GLASSFORD, D. K., and KILLIGREW, L. P., 1976, Evidence for Quarternary westward extension of the Australian desert into south-western Australia: Search, v. 9, p. 394–396.

GRUBB, P. L. C., 1964, Bauxite from Jarrahdale, Western Australia: CSIRO Mineragraphic Investigations Report No. 884.

GRUBB, P. L. C., 1966, Some aspects of lateritization in Western Australia: Journal Royal Society of Western Australia, v. 49, p. 117–125.

GRUBB, P. L. C., 1971, Mineralogical anomalies in the Darling Ranges bauxites at Jarrahdale, Western Australia: Economic Geology, v. 66, p. 1005–1016.

GRUBB, P. L. C., 1973, High-level and low-level bauxitization: a criterion for classification: Mineral Science Engineering, v. 5, p. 219–231.

HOS, D., 1975, Preliminary investigation of the palynology of the Upper Eocene Werrillup Formation, Western Australia: Journal Royal Society of Western Australia, v. 58, p. 1–14.

JOKLIK, G. F., JACKSON, W. D., and ZANI, J. A., 1975, Kimberley bauxite deposits, W. A., *in* Economic Geology of Australia and Papua New Guinea, Volume 1, Metals, *edited by* C. L. KNIGHT: Australasian Institute of Mining and Metallurgy, Monograph 5, p. 968–980.

KEMP, E. M., 1978, Tertiary climatic evolution and vegetation history in the south-east Indian ocean region: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 24, p. 169–208.

KIRKE, E. A., 1973, Alumina from Darling Range bauxite: Proceedings Australasian Institute of Mining and Metallurgy Conference, Western Australia, May 1973, p. 553–564.

KIRKE, E. A., and MURRAY, A. M., 1979, Bauxite — mining and processing *in* Mining in Western Australia, *edited by* R. T. PRIDER: University of Western Australia, p. 219–228.

KNIGHT, N. D., 1988, Aluminium, *in* Australian Mineral Industry Annual Review for 1986: Australian Bureau of Mineral Resources, p. 41–48.

KOCH, J. M., 1987, Nitrogen accumulation in a rehabilitated bauxite mined area in the Darling Range of Western Australia: Australian Forestry Research, V. 17, p. 59–72.

LIEBRICH, A., 1892, Beitrag zur Kenntnis der Bauxitez vom Vogelsberg: Ber. Oberhess. Ges. Natur. Heilk., Giessen, Naturw. Abt. 28, p. 57–98.

LOUGHNAN, F. C., and SADLEIR, S. B., 1984, Geology of established bauxite-producing areas in Australia, *in* Bauxite, Proceedings of the 1984 Bauxite Symposium, Los Angeles, California, 1984, *edited by* L. JACOB: Society of Mining Engineers of American Institute of Mining, Metallurgical and Petroleum Engineers Inc., New York, p. 436–451.

MABBUTT, J. A., 1980, Weathering history and landform development, *in* Conceptual models in exploration geochemistry, *edited by* C. R. M. BUTT and R. E. SMITH: Journal of Geochemical Exploration, v. 12, p. 96–67.

MacLAREN, M., 1906, On the origin of certain laterites: Geological Magazine, v. 43, p. 536–547.

MAITLAND, A. G., 1907, Recent advances in the knowledge of the geology of Western Australia: Western Australia Geological Survey, Bulletin 26, p. 63.

MAITLAND, A. G., 1919, The bauxite deposits (aluminous laterite) of Western Australia, *in* The Mining Handbook of Western Australia: Western Australia Geological Survey Memoir 1, part 2, section 8, p. 32–33.

MATHESON, R. S., 1944, Bauxite investigations: Department of Mines, Western Australia, Annual Report 1942, p. 55.

McFARLANE, M. J., 1971, Lateritization and landscape development in Kyagwe, Uganda: Quarterly Journal of the Geological Society of London, v. 126, p. 501–539.

McFARLANE, M. J., 1976, Laterite and landscape: Academic Press Inc. (London) Ltd., 151 p.

MILLOT, G., 1970, Geology of clays: Chapman and Hall, London.

MONTI, R., 1987, The Boddington laterite gold deposit, Western Australia: a product of supergene enrichment processes, *in* Recent advances on understanding Precambrian gold deposits, *edited by* S. E. HO and D. I. GROVES: Geology Department and University Extension, University of W.A. Publication 11, p. 355–368.

MULCAHY, M. J., 1960, Laterites and lateritic soils in south Western Australia: Journal of Soil Science, v. 11, p. 206–226.

MURRAY, A. M., 1979, Bauxite, *in* Mining in Western Australia, *edited by* R. T. PRIDER: University of Western Australia Press, Perth, p. 101–110.

MYERS, J. S., 1990, Western Gneiss Terrane, *in* Geology and Mineral Resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 13–31.

NIEUWLAND, D. A., and COMPSTON, W., 1981, Crustal evolution in the Yilgarn Block near Perth, W.A. *in* Archaean Geology, *edited by* J. E. GLOVER and D. I. GROVES: International Archaean Symposium, 2nd, Perth, W.A., 1980, Proceedings; Geological Society of Australia, Special Publication, 7, p. 159–171.

NORTON, S. A., 1973, Laterite and bauxite formation: Economic Geology, v. 68, p. 353–361.

OWEN, H. B., and HARGREAVES, M. R., 1975, Mount Saddleback bauxite area, Western Australia, *in* Economic Geology of Australia and Papua New Guinea, Volume 1, Metals, *edited by* C. L. KNIGHT: Australasian Institute of Mining and Metallurgy, Monograph 5, p. 987–991.

PALLISTER, J. W., 1952, Erosion levels and laterite in Buganda Province, Uganda: Comptes Rendues, XIX[e] Congres geologique international, Alger, v. 21, p. 193–199.

PARKER, T. W. H., and SADLEIR, S. B., 1984, Recent investigations of the Mitchell Plateau bauxite deposit, Western Australia, *in* Bauxite *edited by* J. LEONARD Jr: American Institute of Mining Metallurgy and Petroleum Engineering; Bauxite Symposium, Los Angeles, 1984, Proceedings, p. 500–524.

PATTERSON, S. H., 1967, Bauxite reserves and potential aluminium resources of the World: United States Geological Survey, Bulletin 1228.

PATTERSON, S. H., KURTZ, H. F., OLSON, J. C., and NEELEY, C. L., 1986, World bauxite deposits, geology and resources of aluminium: United States Geological Survey Professional Paper 1076-B, 151 p.

PICKERING, R. J., 1962, Some leaching experiments on three quartz-free silicate rocks and their contribution to an understanding of lateritization: Economic Geology, v. 57, p. 1155–1206.

PLAYFORD, P. E., 1954, Observations on laterite in Western Australia: Australian Journal of Science, v. 117, p. 11–14.

PLAYFORD, P. E., 1959, Jurassic stratigraphy of the Geraldton district, Western Australia: Journal Royal Society of Western Australia, v. 42, p. 101–124.

PRESCOTT, J. A., 1931, The soils of Australia in relation to the vegetation and climate: Australian Council for Scientific and Industrial Research, Bulletin 52, p. 45–51.

PRIDER, R. T., 1966, The lateritized surface of Western Australia: Australian Journal of Science, v. 28, p. 443–451.

RODIN L. E., and BASILEVICH, N. T., 1967, Production and mineral cycling in terrestrial vegetation, Oliver and Boyd, Edinburgh.

SADLEIR, S. B., and GILKES, R. J., 1976, Development of bauxite in relation to parent bedrock near Jarrahdale, W.A: Journal of Geological Society of Australia, v. 23, p. 333–344.

SAINT-SMITH, E. C., 1912, A geological reconnaissance of a portion of the southwest division of Western Australia: Western Australia Geological Survey, Bulletin 44, p. 10.

SCHELLMANN, W., 1975, Formation of, and prospecting for tropical bauxite above silicate rocks: Mining Magazine, July 1975, p. 33–39.

SHEA, S. R., 1975, Environmental factors in the Northern Jarrah Forest in relation to pathogenicity and survival of *Phytophthora cinnamomi*: Western Australia Forests Department, Bulletin 85.

SIMPSON, E. S., 1902, Notes from the departmental laboratory: Western Australia Geological Survey, Bulletin 6, p. 8–26.

SIMPSON, E. S., 1912, Laterite in Western Australia: Geological Magazine, v. 9, p. 399–406.

SIMPSON, E. S., 1951, Gibbsite, *in* Minerals of Western Australia, Volume 2: Government Printer of Western Australia, p. 366–390.

SIMPSON, E. S., and GIBSON, C. G., 1907, The distribution and occurrence of the baser metals in Western Australia: Western Australia Geological Survey, Bulletin 30, p. 104–105.

SOMM, A. F., 1975, Gove bauxite deposits, N. T., *in* Economic Geology of Australia and Papua New Guinea, Volume 1, Metals, *edited by* C. L. KNIGHT: Australasian Institute of Mining and Metallurgy, Monograph 5, p. 964–968.

SMURTHWAITE, A. J., and SHEARER, B. L., 1983, Laterite geology and Jarrah Dieback — mapping methods and preliminary findings: Western Australia Geological Survey, Environmental Geology Report EV22 (unpublished).

STEPHENS, C. G., 1961, Laterite in the type locality, Angadipuram, Kerala, India: Journal of Soil Science, v. 12, p. 214–217.

TERRILL, S. E., 1948, Notes on laterite in the Darling Range near Perth, Western Australia: Journal of the Royal Society of Western Australia, v. 34, p. 105–113.

TERRILL, S. E., 1956, Laterite and materials of similar appearance in South-Western Australia; Presidential Address, July 1954: Journal of the Royal Society of Western Australia, v. 40, p. 4–14.

TOMICH, S. A., 1964, Bauxite in the Darling Range, Western Australia: Australasian Institute of Mining and Metallurgy Proceedings, v. 212, p. 125–135.

TRENDALL, A. F., 1962, The formation of apparent peneplains by a process of combined lateritization and surface wash: Zeitschrift Fur Geomorphologie (Annals of Geomorphology), v. 6, p. 183–197.

TURTON, A. G., MARSH, N. L., McKENZIE, R. M., and MULCAHY, M. J., 1962, The chemistry and mineralogy of lateritic soils in the southwest of Western Australia: Commonwealth Scientific and Industrial Research Organization, Soils, Special Publication 20.

VALETON, I., 1972, Bauxites, *in* Developments in Soil Science I: Elsevier, Amsterdam, p. 87–128.

van de GRAAF, W. J. E., CROWE, R. W. A., BUNTING, J. A., and JACKSON, M. J., 1977, Relict early Cainozoic drainages in Western Australia: Zeitschrift Fur Geomorphologie (Annals of Geomorphology) v. 21, p. 379–400.

WESTERN AUSTRALIAN GOVERNMENT CHEMICAL LABORATORIES, 1938, Annual Report 1937, p. 4.

WILDE, S. A., 1976a, The Saddleback Group — a newly discovered Archaean greenstone belt in the southwestern Yilgarn Block: Western Australia Geological Survey, Annual Report 1975, p. 92–95.

WILDE, S. A., 1976b, Explanatory notes on the Precambrian of the Pinjarra 1:250 000 Geological Sheet: Western Australia Geological Survey, Record 1976/15 (unpublished).

WILDE, S. A., 1980, The Jimperding Metamorphic Belt in the Toodyay area, and the Balingup Metamorphic Belt and associated granitic rocks of the southwestern Yilgarn Block: International Archaean Symposium, 2nd, Perth, 1980, Excursion Guide: Geological Society of Australia.

WILDE, S. A., and LOW, G. H., 1978, Perth, Western Australia: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 36 p.

WILDE, S. A., and LOW, G. H., 1980, Pinjarra, Western Australia: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 31 p.

WILDE, S. A., and PIDGEON, R. T., 1986, Geology and geochronology of the Saddleback Greenstone Belt in the Archaean Yilgarn Block, southwestern Australia: Australian Journal of Earth Science, v. 33, p. 491–501.

WILDE, S. A., and WALKER, I. W., 1982, Collie, Western Australia: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 39 p.

WILDE, S. A., and WALKER, I. W., 1984, Pemberton–Irwin Inlet, Western Australia: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 37 p.

WOODWARD, H. P., 1908, Notes on the geology of the Greenbushes Tinfield (with special reference to the deep leads): Western Australia Geological Survey, Bulletin 32, Part 1, p. 16–19, 30–33.

WOOLNOUGH, W. G., 1918a, The physiographic significance of laterite in Western Australia: Geological Magazine, v. 5, p. 385–393.

WOOLNOUGH, W. G., 1918b, The Darling Peneplain of Western Australia: Royal Society of New South Wales Journal and Proceedings, v. 3, 1918, p. 385–396.

WOOLNOUGH, W. G., 1927, The chemical criteria of peneplanation (Part 1), and The duricrust of Australia (Part 2). Presidential Address: Royal Society of New South Wales Journal and Proceedings, v. 61, p. 17–53.

Appendix I

Terminology

Alumina: the pure anhydrous oxide (Al_2O_3) of aluminium; available alumina ($Av.Al_2O_3$) is that portion of the total aluminium in the ore that is 'available' to the Bayer refining process.

Aluminium versus Aluminum: the word aluminium is used throughout except when reference is made to the Aluminum Company of America.

Bauxite: the term used for heterogeneous weathering products that are rich in alumina but low in alkalis, alkaline earths, and silica; bauxite is composed of aluminium oxides and hydroxides (e.g. gibbsite, boehmite and diaspore) with minor quartz, iron hydroxides, and clay minerals.

Bauxitic laterite: the term is applied to well-developed lateritic areas in which ore-grade material is likely to occur.

Duricrust: the term used for a hard crust or layer in the upper part of the laterite profile: it corresponds to the field term, hard cap or caprock.

Laterite: defined as red or brown residual soil or rock which is the result of intense weathering in situ of crystalline bedrock, and in which occur concentrations of (in particular) aluminium and iron hydroxides, quartz, and clay minerals.

Ore (bauxite): an economically mineable concentration of available alumina acceptable to the refinery.

Reactive silica ($Re.SiO_2$): silica, combined in clay minerals, which reacts (or combines) with caustic soda during the digestion stage of the Bayer process, causing alumina and caustic soda losses.

Appendix II

Abbreviations

General abbreviations, not in common usage

AHD	Australian Height Datum
Av.Al_2O_3	Available alumina
DRA	Disease risk area
EOC	Extractable organic carbon
EL	Exploration Licence (WA Mining Act 1978–1986)
EPA	Environmental Protection Authority
ERMP	Environmental review and management program
GSWA	Geological Survey of Western Australia
kPa	Kilopascals
LME	London Metal Exchange
LOI	Loss on ignition
M	Million
mg/L	milligrams per litre
ppm	Parts per million
MC	Mineral Claim (WA Mining Act 1904)
ML	Mining Lease (WA Mining Act 1978–1986)
ML 1SA	Alcoa's special mineral lease (issued under 1904 Mining Act)
ML 258SA	WAPL's special mining lease (1978 Mining Act)
MPA	Management Priority Area
pa	per annum
Re.SiO_2	Reactive silica
t	tonne
TOC	Total organic carbon
TR	Temporary Reserve (WA Mining Act 1904)
WAWA	Water Authority of Western Australia

Company names

Alcoa US	Aluminum Company of America Limited
Alcoa	Alcoa of Australia Limited
Alvam	Aluminium subsidiary of VAM
BHP	Broken Hill Proprietary Limited
Bridge Oil	Bridge Oil Limited
CSR	Colonial Sugar Refinery Limited
Dampier	Dampier Mining Company Limited
Hanwright	Hancock, Wright and Campana
MPB	Mitchell Plateau Bauxite
PMC	Project Mining Corporation
Pacminex	Pacific Minerals Exploration
Reynolds	Reynolds Metal Limited
VAM	Vam Limited
WANL	Western Aluminium No Liability Propriety Limited
WAPL	Worsley Alumina Propriety Limited
WMC	Western Mining Corporation Limited

Index

C

D

E

F

G

H

I

J

K

L

M

N

O

P

Q

R

S

T

U

V

W

Y

Z

EXPLANATION

The regional distribution of ore-grade bauxitic laterite is expressed in terms of the percentage of any given area (generally drilling sectors ranging from 3.2 to 12.8 km^2) occupied by bauxite ore (see definition). Two categories of ore-grade are shown: 'demonstrated', based on closely spaced drilling, and 'inferred', based on limited drilling and/or geological interpretation.

BAUXITIC LATERITE DISTRIBUTION

Bauxite is restricted to areas of laterite, and these are coloured according to ore content and category

ORE DISTRIBUTION

ORE CONTENT AREA %	DEMONSTRATED	INFERRED
⩾ 50		
30–49		
20–29		
< 20		

Ore content: percentage of area containing ore

Demonstrated ore: based on systematic or grid pattern drilling

Inferred ore: based on scout or irregularly spaced drilling and/or geological interpretation

ORE DEFINITION

COMPANY	AVERAGE Al_2O_3 CUT-OFF (%)	THICKNESS (m)	DRILLING GRID (m)
Alcoa of Australia Ltd	⩾ 27.5	2.5	120 x 120
Worsley Alumina Pty Ltd	⩾ 25.0	2.0	100 x 100
Pacminex Pty Ltd	⩾ 26.0	2.0	—

COMPANY DRILLING

Alcoa of Australia Ltd

Worsley Alumina Pty Ltd

Pacminex Pty Ltd

MINING AREAS

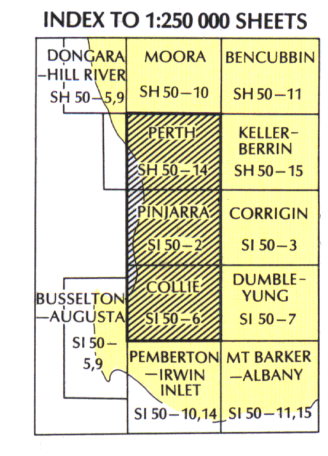
Alcoa of Australia Ltd, 25-year envelope (1987–2011)

Worsley Alumina Pty Ltd, 10-year envelope (1987–1996)

Pacminex Pty Ltd, proposed initial mine-site (1974)

LOCATION DIAGRAM

INDEX TO 1:250 000 SHEETS



Evaluation and compilation by A.J. Smurthwaite, I.M. Brown, and G.G. Meddings.
Laterite outlines modified after Wilde and Low, 1978, 1980, and Wilde and Walker, 1982.
Cartography by the Surveys and Mapping Division, Department of Mines, Western Australia.
Topographic base from the Department of Conservation and Land Management.
Published by and available from the Geological Survey of Western Australia, Department of Mines, 100 Plain Street, East Perth, 6004.
Printed by the State Print, Department of Services, Perth, WA.

HON. GORDON HILL, J.P., M.L.A.
MINISTER FOR MINES
D.R. KELLY, DIRECTOR GENERAL OF MINES

P.E. PLAYFORD
DIRECTOR, GEOLOGICAL SURVEY
OF WESTERN AUSTRALIA

Scale 1:500 000

10 0 10 20 30 40 50
KILOMETRES

DISTRIBUTION OF BAUXITIC LATERITE DARLING RANGE, WESTERN AUSTRALIA