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MAJOR MINERAL DEPOSITS OF SOUTHWESTERN WESTERN AUSTRALIA — A FIELD GUIDE

by M. J. Freeman and M. J. Donaldson

SEG 2004
Perth, Western Australia



Geological Survey of Western Australia

SEG 2004 Predictive Mineral Discovery Under Cover

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

Record 2004/17

MAJOR MINERAL DEPOSITS OF SOUTHWESTERN WESTERN AUSTRALIA — A FIELD GUIDE

**by
M. J. Freeman¹ and M. J. Donaldson¹**

¹Geological Survey of Western Australia

Perth 2004

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Major mineral deposits of southwestern Western Australia — a field guide

by

M. J. Freeman¹ and M. J. Donaldson¹

Introduction

This field guide has been prepared for participants in the field excursion '*Mines and Wines of southwestern Western Australia*', held in conjunction with SEG 2004, the Society of Economic Geologists conference held in Perth, Western Australia, in September 2004. Figure 1 shows the route of the excursion, which starts and ends in Perth.

The guide outlines the regional geological setting of southwestern Western Australia, and the detailed geology of three major mineral deposits of the region visited on the excursion:

- the bauxite deposits of the Darling Range, typified by Alcoa World Alumina Australia's Huntly mine;
- Sons of Gwalia Ltd's Archaean pegmatite-hosted Greenbushes tantalum–lithium–tin deposit;
- Iluka Resources Ltd's Pliocene to Holocene titanium–zircon heavy mineral sands deposits in the Capel area.

Brief descriptions of a number of other deposits or mining sites passed, but not visited, on this excursion are also included. The excursion will also visit a number of vineyards and wineries at the northern end of the world-renowned Margaret River wine region, and the guide therefore outlines some of the geological and climatic factors that are important in the production of the region's high-quality red and white table wines.

Regional geology of southwestern Western Australia

Southwestern Western Australia has four main tectonic units: the Archaean Yilgarn Craton, the Mesoproterozoic Albany–Fraser Orogen, the Mesoproterozoic to Neoproterozoic Pinjarra Orogen, and the Palaeozoic to Cainozoic Perth Basin (Fig. 2). These tectonic units are bound by faults, although the younger sedimentary rocks of the Perth Basin also onlap the older basement rocks to a minor extent.

Yilgarn Craton

The Yilgarn Craton comprises Archaean granitic gneiss and linear granite–greenstone terranes that range in age from 3.83 to 2.6 Ga, and contains rare zircon grains dated at 4.4 Ga. The exposed craton covers about 390 000 km², extending about 1000 km north–south and more than 800 km east–west. The greenstone belts are deformed and metamorphosed supracrustal sequences comprising former mafic, ultramafic, and felsic lavas and associated intrusive rocks, as well as sedimentary rocks ranging from conglomerate, sandstone, and shale to chert and banded iron-formation. Metamorphic grades vary from regionally extensive low-greenschist and amphibolite facies (hence 'greenstone belts') to more restricted areas of higher grade, particularly adjacent to major granitic intrusions and in the gneissic terrane of the southwest Yilgarn Craton.

Komatiitic ultramafic rocks host major nickel sulfide deposits (e.g. Kambalda, Mount Keith) that supply about 20% of the world's nickel metal. The Yilgarn Craton's greenstone belts also host major gold deposits, with 20 deposits that have each produced more than 1 million ounces (about 31 t) of gold. The Golden Mile at Kalgoorlie has produced about 2140 t of gold since its discovery in 1893. In the region visited on this excursion, the poorly exposed Archaean Saddleback greenstone belt contains Australia's largest undeveloped gold resource in the 600 t (20 million ounce) Wandoo deposit at Boddington, owned by AngloGold Ashanti Ltd, Newcrest Mining Ltd, and Newmont Mining Corporation.

Granitic rocks of the Yilgarn Craton are predominantly monzogranite, but compositions range from mafic granite to syenite (Cassidy et al., 2002). Massive to porphyritic varieties are most common. Granite gneiss forms elongate zones adjacent to some greenstone belts, and a zone up to 150 km wide at the western margin of the craton.

The Yilgarn Craton is bound to the west by the Darling Fault (Fig. 2) — a long-lived structure that extends for at least 1000 km from the south coast of Western Australia to east of Shark Bay. Janssen et al. (2003) interpreted it as a Precambrian transcurrent shear zone that was reactivated as a Mesozoic extensional structure related to the breakup of Gondwana and the separation of Greater

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Figure 1. Map of southwestern Western Australia, showing towns, roads, topographic features, and excursion localities mentioned in this field guide

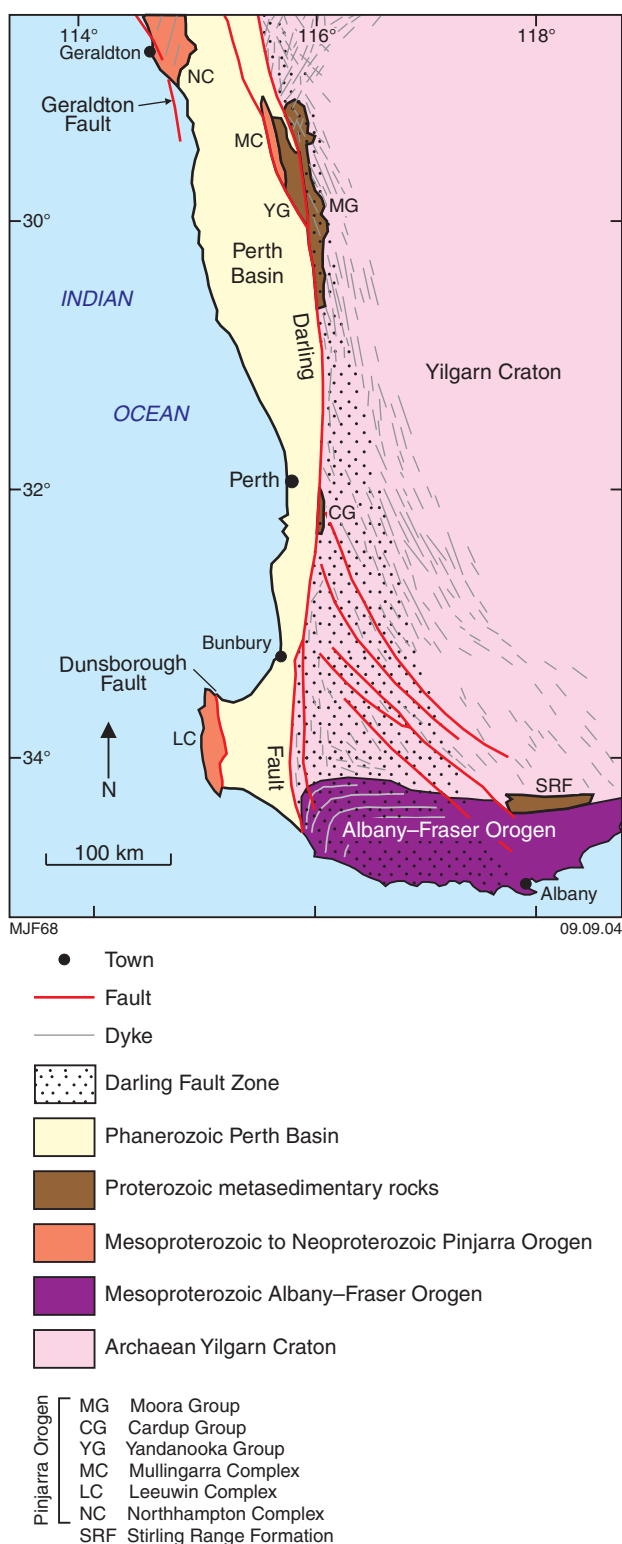


Figure 2. Tectonic units of southwestern Australia (modified from Janssen et al., 2003)

India to the west and Antarctica to the south (Fig. 3). Adjacent to the Darling Fault, in a belt up to 150 km wide, the Archaean rocks are strongly deformed and metamorphosed in the Darling Fault Zone (Fig. 2; Janssen et al., 2003). This is the area of the Yilgarn Craton that will be visited during this field excursion.

Albany–Fraser Orogen

The Mesoproterozoic Albany–Fraser Orogen extends for 1200 km in an east- to northeast-trending belt along the southern coast of Western Australia and around the southeastern margin of the Yilgarn Craton (Fig. 2). The orogen has been interpreted as representing a continental collision at 1300–1100 Ma, and comprises high-grade metamorphic rocks (metasedimentary rocks and mafic to felsic granulites) and granitic intrusives.

This excursion does not visit the Albany–Fraser Orogen, but it is important as the interpreted source of much of the ilmenite–zircon–rutile mineralization that forms the titanium mineral beach-sand deposits in the Perth Basin.

At its western extremity the Albany–Fraser Orogen terminates against the Darling Fault, where predominantly east-striking structures are rotated southward to be parallel to the Darling Fault and Pinjarra Orogen (Fig. 2). A complex history is indicated for the Darling Fault Zone, and Janssen et al. (2003) suggested that the rotation indicated for this area reflects sinistral transcurrent movement at around 550 Ma, associated with the assembly of the Gondwana supercontinent.

Pinjarra Orogen

The Pinjarra Orogen as described in this field guide follows the usage of Fitzsimons (2003) and Janssen et al. (2003). Janssen et al. (2003) discussed the tectonic evolution of the Pinjarra Orogen. The orogen includes (Fig. 2):

- the isolated fault-bound Proterozoic gneissic inliers of the Northampton, Mullingar, and Leeuwin Complexes;
- assumed Proterozoic metasedimentary rocks, including the Cardup, Moora, and Yandanooka Groups adjacent to the Darling Fault near and north of Perth;
- areas of the Yilgarn Craton and Albany–Fraser Orogen adjacent to the Darling Fault that were subjected to repeated tectonic reworking, widespread thermal events, and intrusion of dolerite dyke swarms between 1200 and 550 Ma.

Areas affected by the Pinjarra Orogen to be visited on this field excursion include the Greenbushes deposit and Leeuwin Complex gneisses. The Greenbushes tantalum–lithium–tin deposit is within the Darling Fault Zone, about 50 km east of the Darling Fault, where the Archaean rocks have been affected by isotopic resetting of Rb–Sr ratios in biotite at about 550 Ma (Libby et al., 1999). Outcrops of 550–700 Ma granite gneiss will be visited at Canal Rocks, Bunker Bay, and Sugarloaf Rock at the northern end of the Leeuwin Complex.

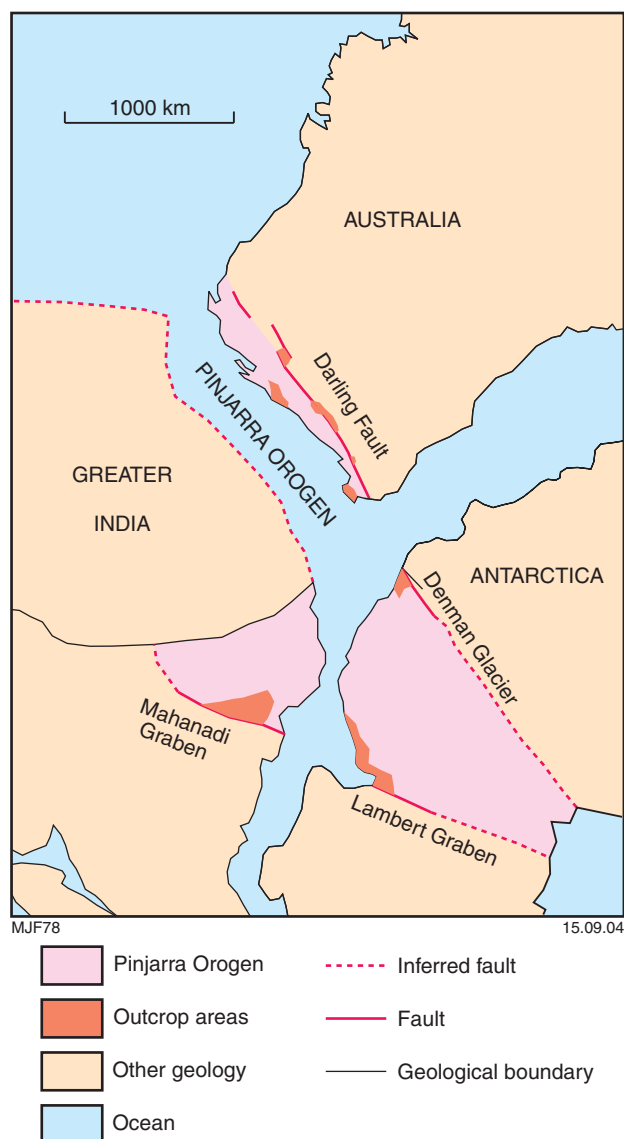


Figure 3. Gondwana reconstruction with parts of Australia, India, and Antarctica, showing inferred extent of the Pinjarra Orogen (modified from Janssen et al., 2003)

Leeuwin Complex

Granite gneisses of the Leeuwin Complex are well exposed in spectacular coastal outcrops between Cape Naturaliste and Cape Leeuwin. On the basis of zircon U–Pb ages, which are similar to ages from heavy-mineral sand deposits of the Perth coastal plain (Sircombe and Freeman, 1999; Cawood and Nemchin, 2000), the Leeuwin Complex gneisses are regarded as a potential source for at least some of these heavy-mineral sand deposits. The actual source could have been related rocks in what is now the Indian subcontinent (Fig. 3).

A detailed summary of the geology of the Leeuwin Complex is given in Janssen et al. (2003) and Collins (2003), and much of the description of these coastal outcrops is taken from those sources. The Geological

Survey of Western Australia (GSWA) produced a 1:250 000 geological map of the region (Lowry, 1967), but this pre-dated modern sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon geochronology. More recent GSWA mapping at 1:50 000 scale (Marnham et al., 2000; Hall and Marnham, 2002) focused on the regolith-landform resources of the area south of Canal Rocks to Cape Leeuwin. Wilde and Nelson (2001) summarized geochronological data available up to 2001.

Leeuwin Complex rocks are predominantly layered granite gneisses, with both two-feldspar–garnet–biotite gneiss and two-feldspar–pyroxene/hornblende–biotite gneiss common, and aegirine–augite syenite gneiss being restricted to the northern part of the complex (Wilde and Murphy, 1990; Murphy, 1992; see summary in Janssen et al., 2003). Mafic granulite and anorthosite are not common, and amphibolite gneiss layers or lenses are typical minor constituents of the felsic gneisses.

Collins (2003) recognized four phases of folding:

- D₁: a prominent gneissic foliation in felsic gneiss, folded around later structures;
- D₂: north-trending folds at several scales, including the 10 km-scale Naturaliste Antiform and the 50 m-scale Sugarloaf Antiform;
- D₃: open east-northeasterly trending folds;
- D₄: open undulatory folds visible along the coast near Bunker Bay.

Geochronological studies of Leeuwin Complex gneisses using SHRIMP U–Pb zircon techniques (e.g. Wilde and Murphy, 1990; Nelson, 1996, 1999, 2002; Collins, 2003) indicate a range of ages from 1178 ± 40 Ma to 522 ± 5 Ma, with most crystallization ages in the range 700 to 760 Ma. Collins (2003) interpreted these data as crystallization of protoliths of the gneisses in the middle Neoproterozoic (c. 750 Ma), with the protoliths at least partly derived from late Mesoproterozoic (c. 1100 Ma, but possibly as old as 1600 Ma) continental crust. This is supported by depleted mantle Nd-model ages (McCulloch, 1987; Fletcher and Libby, 1993). Subsequent granulite- to upper amphibolite-facies metamorphism at about 520 Ma is interpreted from a zircon rim date of 522 ± 5 Ma (Collins, 2003), and other zircon populations recorded by Nelson (2002).

Perth Basin

The Perth Basin comprises a sequence of sedimentary rocks up to 15 km thick that accumulated between Devonian and late Cretaceous times in a north–south-oriented gulf, bound to the east by the Darling Fault. The precursor to India was to the west and Antarctica to the south, and the gulf was open to the Tethyan Ocean to the north. The Perth Basin is dominated by sandstone with less common siltstones, widespread but stratigraphically restricted coal, and rare coarse-grained glaciogene sediments. Preliminary provenance interpretations from zircon geochronology on the sedimentary rocks implies that they were derived from the Albany–Fraser Orogen, the Leeuwin Complex, or potentially from other Pinjarra Orogen rocks that formed the northeastern part of the Indian Plate before its subduction under the Himalayas.

Cainozoic cover sequence

Most of Western Australia has been subjected to long periods of weathering dating back to perhaps Permian times. There is extensive development of lateritic weathering profiles that may be up to 100 m in depth. Laterite profiles are developed over all lithologies, and are characterized by ferruginous duricrust overlying thick clay zones. The laterite profile is discussed in detail in **Bauxite deposits of the Darling Range** below.

Pleistocene to Holocene sand deposits blanket parts of the Perth Basin and Leeuwin Complex, and these will be seen at several locations on this excursion.

Bauxite deposits of the Darling Range

Bauxite is a general term for regolith composed largely of aluminium hydroxides. It is the most important ore of aluminium. Berthier (1821) introduced the term 'bauxite' for terra rosa soils rich in aluminium that overlie limestones at Les Baux in southern France, and Liebrich (1892) extended the term to include aluminous, gibbsite-rich laterite (Hickman et al., 1992). Bauxite deposits of both karstic and lateritic origin occur throughout the world, with lateritic deposits representing 85% of the global resource (Hickman et al., 1992). Western Australia has large deposits of bauxite of lateritic origin in the Darling Range near Perth, and on the Mitchell Plateau in the Kimberley region. This field excursion will visit bauxite mining and processing operations in the Darling Range, about 90 km south of Perth (Fig. 4).

Bauxite mining is an important industry for Western Australia. In 2003 production totalled 11.2 million tonnes of alumina valued at \$3.14 billion, and \$51 million was paid to the State in royalties. The industry directly employed just over 7000 people in 2003.

Regional setting and geomorphology

The term Darling Range is generally applied to the elevated country immediately east of the Darling Scarp. Rather than a 'range', it is better considered as a dissected plateau (Churchward and McArthur, 1980). Most of the plateau is capped with laterite, and the duricrust and related materials of the lateritic profile commonly contain more than 20% Al_2O_3 . This constitutes a widespread and valuable bauxite resource, currently documented as containing more than 3.5 billion tonnes (Hickman et al., 1992).

On the upper slopes and over crests of hills, soils are thin and skeletal, commonly with a covering of sand that overlies the lateritic profile. Valley floors contain thicker alluvium. There are scattered areas of sheeted outcrops or bouldery rock on steeper slopes and higher hills.

State Forest is the dominant land tenure across the plateau, as it was found unattractive for farming activities at the time of colonization because of the rocky and unproductive soils. The native vegetation has adapted to the thin soils overlying the lateritic duricrust. The dominant forest vegetation is eucalypt trees, with jarrah (*Eucalyptus marginata*) and marri (*Corymbia callophylla*) that grow to about 40 m, and with banksia (*Banksia grandis*) and she-oaks (*Allocasuarina fraseriana*) and a range of paperbark trees (*Melaleuca* sp.) that grow to about 20 m. A rich and diverse flora, with many endemic species, dominates the understorey and about 10 000 species of native plants have been documented in the southwest of Western Australia, many in these forests. The presence of this flora is an important consideration in bauxite mining and rehabilitation.

Basement rocks underlying the lateritic profile include Archaean igneous and metamorphic rocks of the Yilgarn Craton. In the area of the Huntly mine (Figs 1 and 4), the Archaean basement comprises granite with rare banded and migmatitic gneiss, paragneiss, and granitic gneiss. Numerous north-northwesterly to northerly striking and easterly striking Proterozoic dolerite dykes intrude the granitic rocks. The foliation and gneissic banding in this part of the Yilgarn Craton trends northerly to north-northwesterly, with steep dips to the east or west. About 30 km east of the Huntly mine area, the north-northwesterly trending Saddleback greenstone belt is fault-bound against the surrounding granitic rocks. The belt is about 30 × 5 km, and consists of weakly metamorphosed felsic to mafic volcanic and pyroclastic rocks, and sedimentary rocks.

Dating of the granitic rocks indicates that they were formed at 2.65 to 2.55 Ga (Myers, 1990). Dolerite dykes immediately east of the Darling Fault and 100 km north of the Huntly mine have been dated at 1214 ± 5 Ma by the $^{207}\text{Pb}/^{206}\text{Pb}$ method (Pidgeon and Cook, 2003).

History of discovery, evaluation, and development

Bauxite was first identified in the region by Simpson (1902). The Electrolytic Zinc Company of Australia had examined the deposits in 1918, although no mining proposals were advanced at that time. GSWA then mapped the extent of gibbsite-bearing laterites in the Darling Range and recognized that they constituted an extensive aluminium resource (Maitland, 1919). In 1957 Western Mining Corporation Ltd (WMC) initiated a reconnaissance exploration program to ascertain the commercial potential of the lateritic profile as a source of aluminium. This work was then continued by Western Aluminium No Liability (WANL) on titles granted to a joint venture between WMC, Broken Hill South Ltd, and North Broken Hill Ltd. Regional evaluation included sampling at about 400 m spacings along road cuttings and around the edges of breakaways. The laterite was found to contain extensive areas of material averaging more than 30% available Al_2O_3 ($\text{Av. Al}_2\text{O}_3$)* and with low reactive silica (Re. SiO_2)†.

In 1961 a Special Mining Lease (ML1SA) was granted to WANL to facilitate evaluation of the bauxite. This mining lease was restricted to Crown Land (mostly State Forest) and excluded private property. Scout drilling identified mineable deposits in the Jarrahdale–Dwellingup

* Available Al_2O_3 ($\text{Av. Al}_2\text{O}_3$) is that portion of the total aluminium in the ore that is 'available' to the Bayer refining process. In the Darling Range deposits this is largely in the form of gibbsite.

† Reactive silica (Re. SiO_2) is silica combined in clay minerals which reacts with caustic soda during the digestion stage of the Bayer process, causing alumina and caustic soda losses (Hickman et al., 1992).



Figure 4. Map showing the extent of the Darling Range bauxite deposits, mining plant areas, and State Agreement mining leases

region, culminating in the delineation of 37 Mt containing 33% $\text{Av. Al}_2\text{O}_3$. Bulk sample testing demonstrated that the bauxite could be treated economically. In late 1961 the Aluminium Company of America (Alcoa) joined WANL, contributing aluminium mining, smelting, and marketing expertise, and development funds to accelerate the evaluation.

Grid drilling, first at 370×185 m centres and then at 45×45 m centres was undertaken to block out the ore at Jarrahdale. Mining commenced in 1962, with the ore being transported to Kwinana by train for conversion to

alumina. In 1977 WANL became Alcoa. After the Jarrahdale mining was established, Alcoa developed two new mines at Huntly and Willowdale (Fig. 4), and alumina refineries at Pinjarra and Wagerup. The Jarrahdale mine was closed in 2001 and the Kwinana refinery now processes ore from Huntly. The mines are currently owned by Alcoa World Alumina Australia.

Initially, reconnaissance drilling was carried out widely in the Darling Range on a 240×120 m grid, which was then closed down progressively in selected areas to 60×60 m.

Evaluation of the various drilling grids indicated that the wide-spaced drilling results provided a reliable guide to the bauxite resources, allowing quick compilation of regional resource figures.

Other companies followed WANL's successes. Bauxite Holdings NL explored the Saddleback area in 1962, identifying thick resources. In 1979, Worsley Alumina Pty Ltd (WAPL) was created to develop this area in a joint venture between Reynolds Australia Alumina Ltd, the Shell Company of Australia Ltd, Broken Hill Proprietary Ltd, and Kobe Alumina Associates Pty Ltd on State Agreement Mining Lease 258SA. The WAPL lease includes private property and allows for mining on farmland. WAPL commenced mining in 1970 and transport ore by a 51 km conveyor belt to an alumina refinery at Worsley, near Collie.

Geology of the bauxite resource

General distribution

Laterite is well developed and thickest over a 200 km-long region extending south from the Avon River, which cuts through the ranges east-northeast of Perth (Fig. 4). It occupies gently sloping upland areas between 200 and 300 m in altitude. Higher peaks consist of basement inliers protruding through the laterite. At altitudes below about 200 m, the topography is dominated by incised watercourses where the laterite has mostly been stripped or never formed.

Nature of the bauxite occurrences

Figure 5 shows an idealized lateritic profile that, in the Darling Range, averages about 20 m in thickness. Not all zones are necessarily present at a particular locality, either through removal by erosion or due to local conditions at the time of laterite development. The nature of the profile is critically dependent on the precursor rock, as well as the physico-chemical conditions prevailing during formation.

Overlying the laterite is a 0.2 to 4 m-thick (average 0.5 m) loose overburden of soil and transported clay- to sand-sized sediment. The uppermost 15 cm is the relatively fertile horizon supporting plant growth and seed germination, and during mining is stockpiled for rehabilitation. This horizon also contains tree roots and rootlets and organic carbon that are detrimental if fed to the alumina processing plants.

Bauxite is mined from the upper part of the lateritic profile, which is subdivided into two distinct layers (Fig. 5):

- An **upper lateritic residuum** comprises a lateritic gravel of uncemented ferruginous pisoliths at the top, underlain by lateritic duricrust consisting of ferricrete, which in turn is underlain by a friable fragmental unit with poorly cemented nodular and granular gibbsitic material; the duricrust and friable fragmental unit constitute the bauxite ore.
- A **basal clay-rich layer** comprises a mottled zone of iron-enriched red mottles in a kaolinitic matrix at the

top, underlain by a plasmic (clay) zone dominated by kaolin and quartz, in turn underlain by saprolith which grades into unweathered bedrock.

Lateritic gravel consists of loose, ferruginous pisoliths that have a concretionary fabric with a core of quartz sand or a ferricrete fragment. In the mining operation this material is removed with the overlying subsoils and is not processed as ore. It is not always present, but can be up to 2 m thick.

Duricrust (Fig. 6a) is the strongly cemented ferricrete or ironstone caprock. It consists of pisolitic or angular ferricrete fragments cemented into a massive rock by subsequent ferruginization, but locally it may retain characteristics of the original basement rocks, such as textures that reflect porphyritic granite or porphyritic dolerite parent rocks. Over granitic bedrock, the duricrust is commonly 1–3 m thick, but over mafic volcanic rocks of the Saddleback area it is typically about 5 m thick. It is locally absent in lower rainfall parts of the Darling Range. The duricrust can generally be ripped without blasting, but areas containing angular fragments of hard, very dark, maghemite-bearing ferricrete require drilling and blasting. Magnetic susceptibility is measured on grade-control drillhole samples to predict areas of this maghemite-bearing material.

The **friable fragmental unit** of the lateritic residuum is considered by Alcoa to consist of an upper nodular bauxite zone and a lower granular bauxite zone. Basement rock types are commonly reflected in the nature of the fragmental unit; for example, dolerite dykes are recognizable as vertical darker and redder zones enriched in iron oxide compared to adjacent granite-sourced laterite. The **nodular bauxite zone** (Fig. 6b) contains nodules ranging from about 2 to 10 cm, and locally may contain 'floaters' of duricrust up to about 1 m across. Nodules are dominantly gibbsite and quartz, and are stained brown by iron oxyhydroxides. The **granular bauxite zone** (Fig. 6c) is dominated by pisolites of gibbsite and quartz and generally has less iron staining than the nodular zone. The combined thickness of the friable fragmental unit is up to about 2 m near the tops of hills, reaches up to 10 m in mid-slope areas, and is up to 20 m in the Saddleback area.

The **mottled zone** forms the top of the **basal clay layer**, and the top of the mottled zone forms the floor in the mine pits. It contains mottles and irregular patches richer in iron oxyhydroxides in a matrix of paler kaolinitic material. The mottles are up to 40 cm across, and the zone ranges in thickness from 1 to 5 m, but can be locally absent. Relationships between the mottles and the matrix indicate a complex genesis, with progressive bleaching and ferruginization suggesting multiple cycles of laterite development. The mottled zone grades downward into a pale-coloured **plasmic zone**, composed essentially of kaolinite and quartz, and marked by the absence of iron staining and mottles. This zone contains no relict bedrock fabrics and it grades progressively downward into **saprolith**, which is clay-rich weathered bedrock that retains relict bedrock fabrics. The saprolith grades downwards into fresh bedrock. The basal clay layer is typically 20–30 m thick, but is much thinner where the basement rock is dolerite.

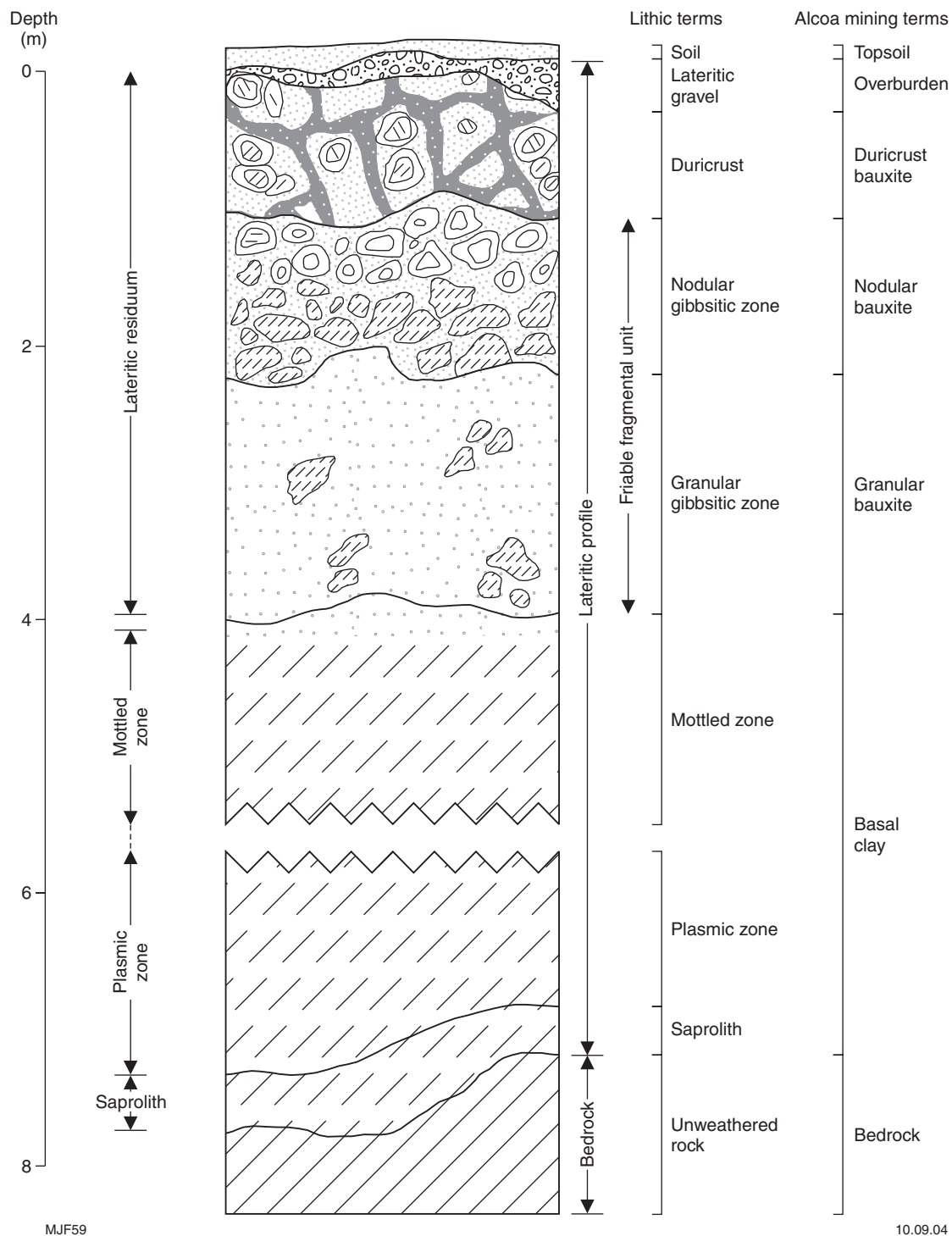


Figure 5. Generalized lateritic profile for Darling Range bauxite deposits (after Hickman et al., 1992)

Dolerite remnants form unweathered spherical to subspherical corestones up to several metres across within the lateritic profile.

Mineralogy and chemistry

Grubb (1966) investigated the overall mineralogy of the laterite from former mines in the Jarrahdale district, and Sadleir and Gilkes (1976) detailed the mineralogy, particularly in relation to the parent material, of the laterite in a railway cutting at Jarrahdale. Figure 7 shows mineral variation through a lateritic profile developed over granitic bedrock in the western Darling Range.

The lateritic residuum is dominated by gibbsite (>50%, decreasing downwards) and goethite (10–30%), with quartz (5–20%, high over granites and very low over mafic rocks), hematite (2–10%), maghemite (2% but rarely rising to 50%), kaolinite (1%) and locally minor boehmite (1%). There are trace quantities of corundum, rutile, anatase, muscovite, and magnetite. Quartz and kaolinite are dominant in the basal clay layer, with goethite proportion decreasing downward in the mottled zone. Accessory muscovite, feldspar, and refractory minerals are derived from the basement rocks.

The chemical composition of bauxite is dominated by Al_2O_3 and SiO_2 and varies with bedrock (see Table 1 and Fig. 8). Aluminium is strongly enriched in the upper part of the laterite profile in comparison to the bedrock (Fig. 8b), and available alumina increases sharply above the basal clay unit. Gibbsite, boehmite, and corundum are the main aluminium-bearing minerals. Only the aluminium in gibbsite is extracted in the Bayer process at the Western Australian refineries, and total Al_2O_3 is therefore commonly 3–8% higher than $\text{Av. Al}_2\text{O}_3$. Iron is strongly concentrated in lateritic duricrust and the friable fragmental unit, and is higher over dolerite bedrock than granitic bedrock (Fig. 8c).

Silica concentrations in the laterite profile are more related to bedrock chemistry than iron concentration. Quartz is retained through the profile, although grains at surface commonly show some degree of corrosion. Reactive silica (Re. SiO_2), derived by conversion of primary aluminosilicates to clays, decreases markedly above the basal clay layer, and a large proportion of original bedrock silica is removed from the upper part of the profile by groundwater.

The conversion of bedrock to laterite proceeds by gross leaching of the alkali and alkali-earth elements, and the alteration of aluminosilicates to clay immediately above fresh rock. Gibbsite formation at the expense of kaolinite results in silica loss in the upper part of the profile, resulting in enhanced Al_2O_3 and Fe_2O_3 content in that zone. Sadleir and Gilkes (1976) inferred that some iron is removed in solution whereas the immobile aluminium remains.

Age

The age of formation of the Darling Range laterite deposits is poorly constrained, but from studies elsewhere in Australia, they are believed to have formed between the

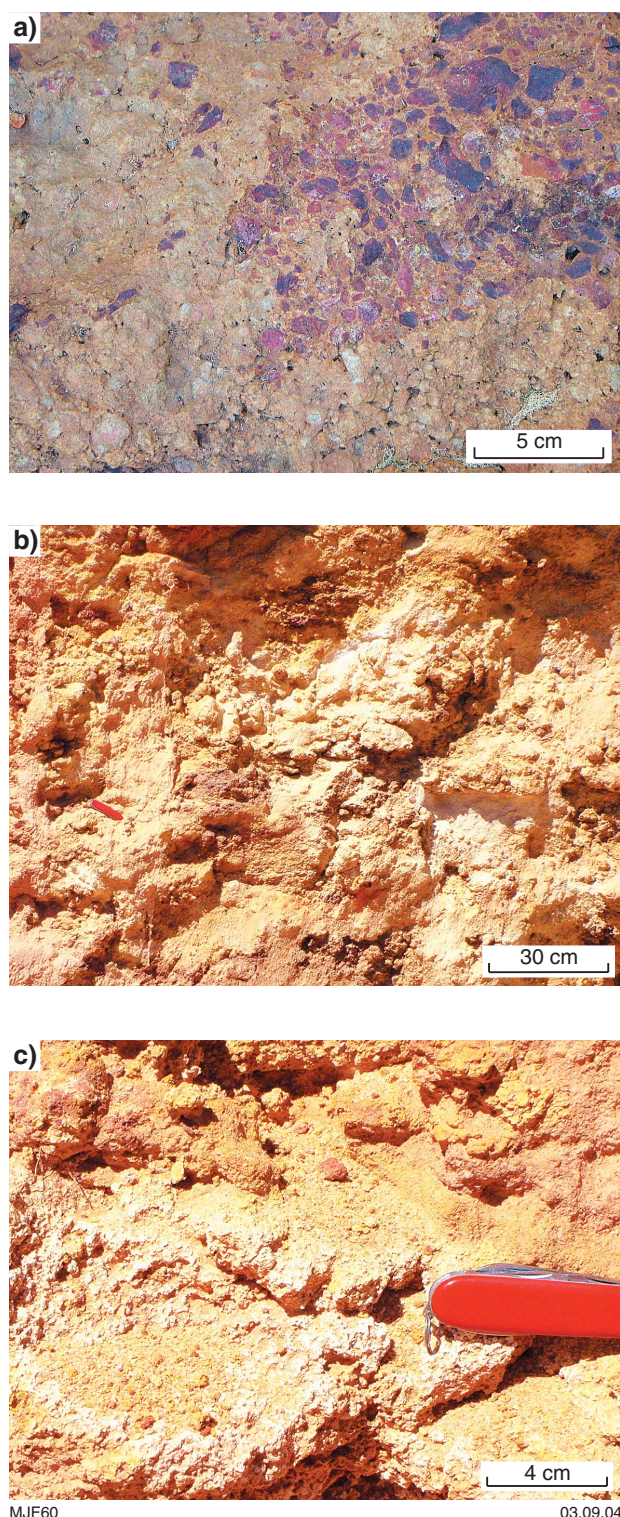


Figure 6. Photographs of bauxite at Huntly mine site: a) duricrust with angular clasts of maghemite in gibbsitic ferricrete; b) nodular bauxite zone of friable fragmental unit; c) granular bauxite zone of friable fragmental unit

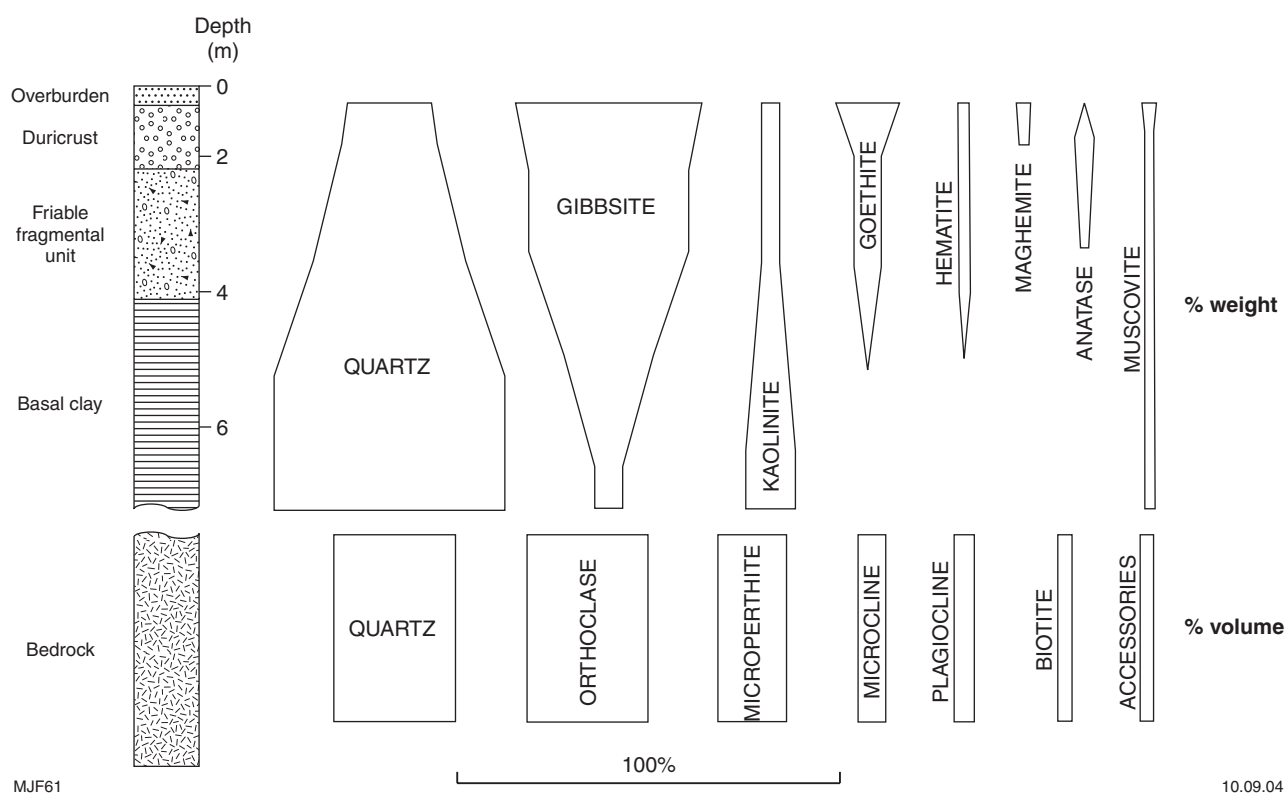


Figure 7. Mineralogy of Darling Range bauxite overlying granitic basement (after Hickman et al., 1992)

Table 1. Chemical composition of bauxite and ferruginous laterite in the Darling Range (after Hickman et al., 1992)

	<i>Darling Range Bauxite derived from granite</i>	<i>Mount Saddleback Ferruginous laterite derived from dolerite</i>	<i>High-iron, low-quartz bauxite derived from mafic rock</i>
Percentage			
Total Al ₂ O ₃	40.5	16.6	35–45
Av.Al ₂ O ₃	37.5	11.5	28–35
Total SiO ₂	21.8	9.8	2–3
Re.SiO ₂	0.3	0.4	1 – 2.5
Fe ₂ O ₃	10.0	52.4	22–32
TiO ₂	1.2	2.3	2–3
Loss on ignition	23.6	17.1	22–27

NOTES: Available Al₂O₃ (Av.Al₂O₃) is that portion of the total aluminium in the ore that is 'available' to the Bayer refining process. In the Darling Range deposits this is largely in the form of gibbsite. Reactive silica (Re.SiO₂) is silica combined in clay minerals which reacts with caustic soda during the digestion stage of the Bayer process, causing alumina and caustic soda losses (Hickman et al., 1992).

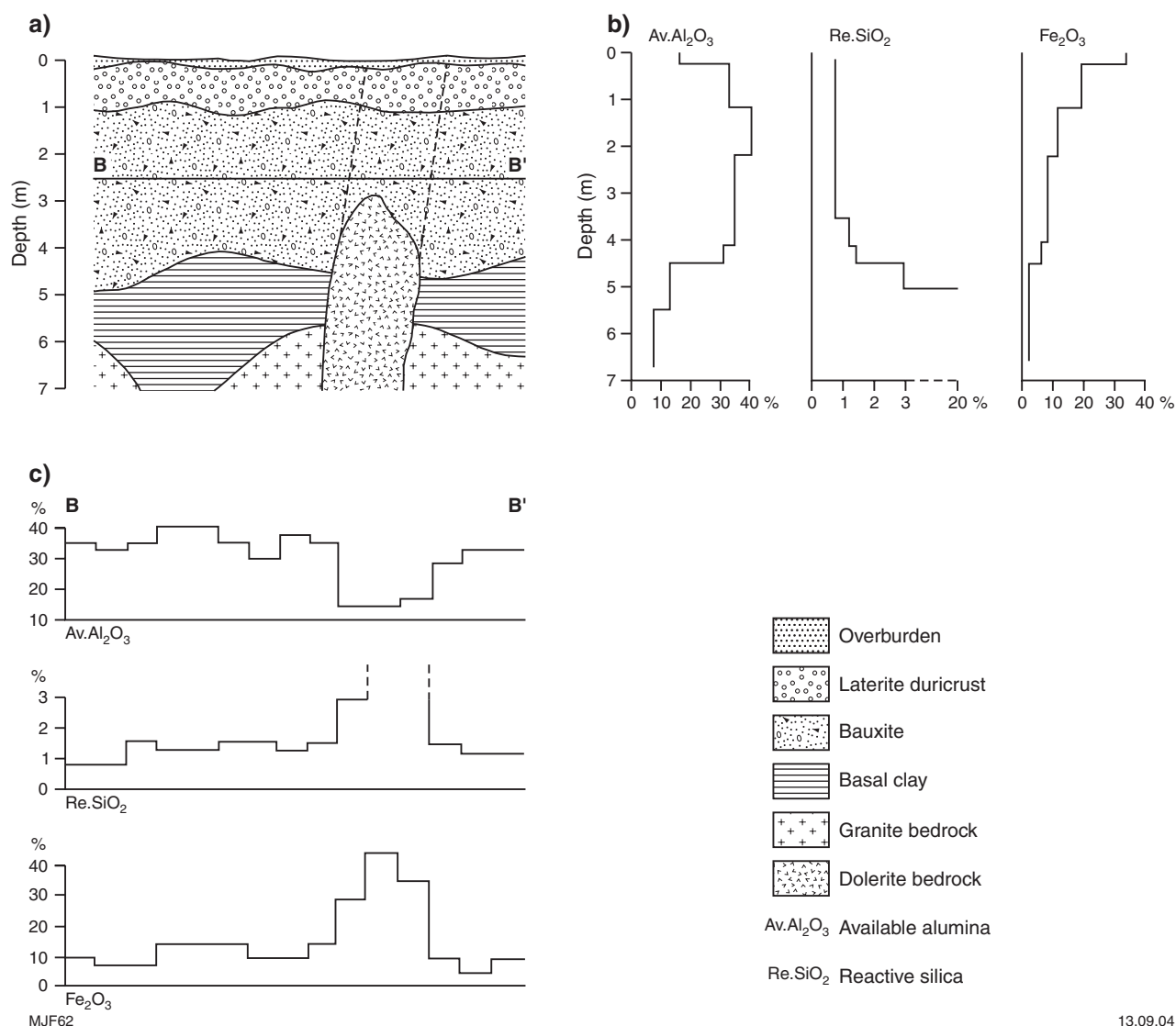


Figure 8. Chemical composition of a bauxite profile: a) cross section through lateritic profile above granite bedrock intruded by dolerite dyke; b) compositional profile with depth; c) lateral compositional variation across granite-dolerite bedrock (after Hickman et al., 1992)

latest Cretaceous and late Tertiary (Senior and Mabbutt, 1979; Senior and Senior, 1972).

Tenure and State Agreement

Alcoa World Alumina Australia holds State Agreement mining lease ML1SA over the bauxite resources (Fig. 4). This is a special tenure created by an Act of Parliament to grant authority for Alcoa to hold the title and mine bauxite, while committing the company to perform to specified standards in its mining and downstream processing. The Act has, therefore, removed the operations from the Western Australian Mining Act. It imparts a higher degree of certainty for the company to invest knowing that it will not be subject to Government policy changes that may have detrimental impacts on future resource access or the economics of the operations. State Agreements, since this first one, have been used by Governments to provide

certainty to the private sector to invest in major developments that impinged on a number of statutes.

Resources, mining, and other operations

Bauxite ore

Aluminium-rich laterite becomes bauxite ore when certain criteria are met, including:

- $\text{Av. Al}_2\text{O}_3 > 27.5\%$;
- $\text{Re. SiO}_2 < 2.5\%$;
- minimum thickness 2 m;
- minimum mining block mass 20 000 t;
- area is outside conservation areas, such as nature reserves or old growth forest;
- area is outside other environmentally sensitive areas, including reservoir buffers and distance from housing.

These conditions are met over an area of about 5000 km² near the western limit of the Darling Range, where mineable pods range from several hectares to more than 100 ha.

Ore thickness is typically 2–7 m and the base is commonly parallel to the land surface. The top of the ore (the top of the duricrust) is commonly highly undulose, with a 2–5 m wavelength and an amplitude up to 1 m. Hollows are filled with lateritic gravel or soil overburden.

Bauxite formed from granitic bedrock is relatively homogenous in composition and mineralogy, but the many dolerite dykes and scattered gabbroic bodies and pegmatitic veins result in bauxite with highly variable chemistry and mineralogy, necessitating careful mine planning to minimize variations in plant feed. The inverse relationship between Fe₂O₃ and Al₂O₃ in the bauxite also requires attention in the mining process to reduce feed composition variations. Considerable effort goes into homogenizing the feed to the alumina plant by mining several pods simultaneously, and blending ore in stockpiles at the plant. Ore pods range in size from as small as 20 000 t to more than 10 Mt.

Resources, reserves, and production

The total quantity of bauxite in the Darling Range is very large. Alcoa's bauxite resources and reserves available for mining currently total 2190 Mt at 32.5% Av.Al₂O₃ (27.5% cut-off), estimated as 1600 Mt inferred resources, 190 Mt indicated resources, 150 Mt measured resources, 60 Mt probable reserves, and 190 Mt proved reserves (Senini, P., Alcoa World Alumina Australia, 2004, written comm.).

At January 2003, proved–probable reserves at Worsley were 326 Mt of ore at 30.7% aluminium, within measured–indicated–inferred resources of 560 Mt of ore at 31.5% aluminium (Resource Information Unit, 2004).

Western Australian alumina production in 2003 totalled 11.2 Mt (Table 2), with a reported value of \$3.1 billion, for an average of \$288/tonne. This is 20% of world production, and nearly 70% of Australia's total alumina production. Since mining commenced in 1963 the industry has produced 182 Mt of alumina from the Darling Range.

Table 2. Bauxite mined and alumina produced during 2003 from the three Darling Range bauxite mines

Mine	Ore mined (Mt)	Alumina produced (Mt)	Company
Huntly	22	5.58	Alcoa World Alumina Australia
Willowdale	8	2.34	Alcoa World Alumina Australia
Worsley	11.2	3.30	Worsley Alumina Pty Ltd

SOURCE: P. Senini, Alcoa World Alumina Australia (2004, written comm.)
J. Jarvis, Worsley Alumina (2004, written comm.)

Pre-mining procedures

Initial exploration drillhole spacings of 120 × 120 m are closed down progressively to an ultimate 15 × 15 m for pit design. Comparison of resources estimated from the different grid spacings, and reconciliation with plant feed after mining, demonstrates that the broad-scale drilling is a reliable predictor of the final reserves, although not adequate for day-to-day grade-control purposes. Tractor-mounted vacuum drilling rigs are used for all resource–reserve drilling. Drillholes are 50 mm in diameter and drilling is undertaken on an intermittent campaign basis, about 5 years ahead of mining. In a typical year's program, up to 40 000 holes are drilled to an average depth of 6.5 m. Drill samples are taken at each 0.5 m and submitted for chemical analysis. Geological logging is not conducted on a routine basis and drilling is stopped 1 m below the depth at which the bit strikes clay.

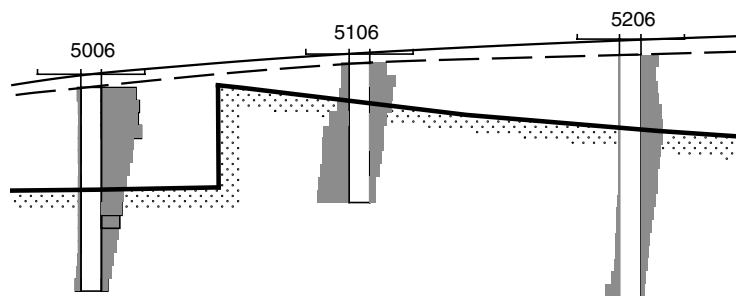
Samples are analysed for Av.Al₂O₃, Re.SiO₂, Fe₂O₃, SO₄²⁻, C, oxalate, and magnetic susceptibility. Chemical determinations are made using the Fourier Transmission Infra Red (FTIR) technique in Alcoa's own laboratory where this analytical method has been developed and refined specifically for Alcoa's needs. Results are plotted in plan and on sections and mining is planned by geological control in 20 000 t blocks, with a minimum dimension of 30 m for any mining activities. Figure 9 shows stacked cross sections of part of a deposit, with cumulative downhole histograms of Av.Al₂O₃ and Re.SiO₂ values averaged from the top of the duricrust to the base of each drillhole sample, and the planned floor level and a batter slope.

Pre-mining environmental issues

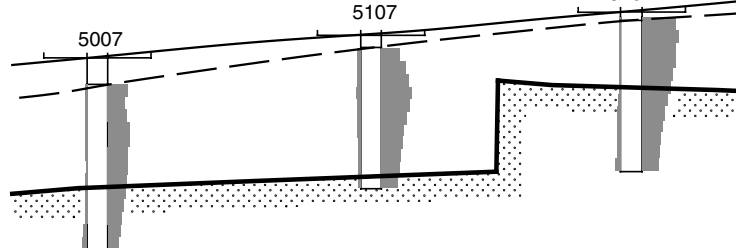
Much of the Darling Range forest is infected with *Phytophthora cinnamomi*, which is a fungal disease that severely affects native vegetation. Since its introduction into Western Australia in the early 1900s, it has become widespread in the forest, killing jarrah trees and a large number of understorey plants. The fungus infects roots, depriving plants of essential water and leading to progressive death, termed dieback, through water deprivation. Conservation of the native vegetation requires dieback-free material to be isolated from infected materials. Before mining, mapping of the extent of dieback infections is completed and the infection boundary is marked on the ground. Stringent precautions are in place to ensure there is no transport of infected soil or rock into disease-free areas, and no vehicles are permitted to leave an infected area without being cleaned.

Contractors, under the supervision of the Forest Products Commission, extract marketable timber from areas to be mined. Products include saw logs, posts, and firewood. Some timber debris and logs are stored along pit edges, to be used after mining to provide habitat for fauna in rehabilitated areas. Before 2004 the remaining nonmerchantable timber was cleared and burnt. However, changes to procedures currently being implemented will result in much of this material being collected and used in a silicon smelter operated by Simcoa at Kemerton, just northeast of Bunbury. This vegetation usage will displace the use of higher quality timber that was previously cut

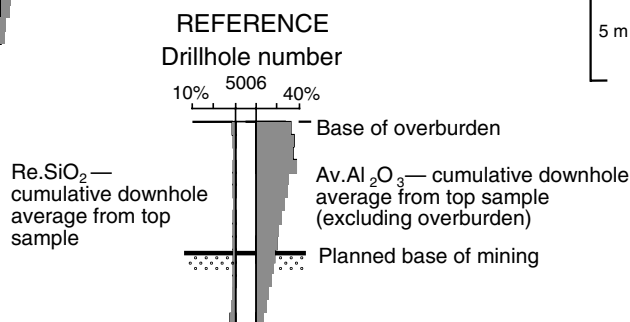
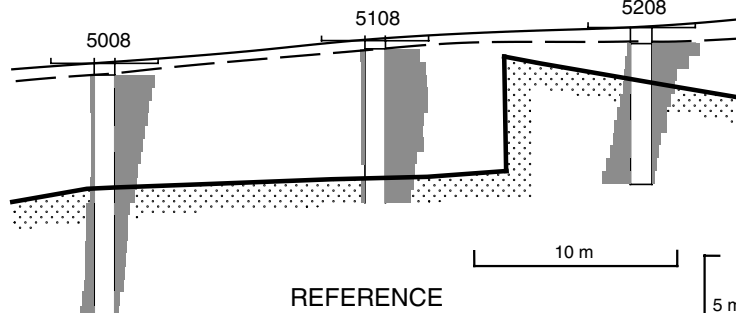
NORTHERN SECTION



CENTRAL SECTION



SOUTHERN SECTION



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Figure 9. Stacked cross sections of pre-mining grade-control drillholes through the bauxite deposit at Huntly. Profiles show Av.Al₂O₃ and Re.SiO₂ grades as cumulative averages downhole from the base of overburden. Drillholes are on a 15 m × 15 m grid (source: Alcoa World Alumina Australia)

for the smelter, reducing the environmental impact of two mining-related operations.

Topsoil and then overburden are removed separately, firstly using scrapers and then the hollows in the top of the duricrust are cleaned out with backhoes. The cleaned-out surface is then smoothed with bauxite ore as a preliminary to blast-hole drilling.

Alcoa's mines are in water supply catchments, so it is essential to prevent pollution in the catchment. Run-off from bauxite mining areas has a high sediment load caused by soil and subsoil disturbance during mining operations. Effective sediment control and erosion-prevention programs are used to prevent this sediment from polluting streams, damaging stream ecosystems, and contaminating sources of potable water.

Alcoa compiles an annual Clearing Advice application and submits it to the Mining Operations Group, comprising representatives of the Department of Industry and Resources, the Department of Conservation and Land Management, and the Water Corporation, for approval before commencing clearing operations.

Mining

Mining commences with ripping of duricrust with Komatsu 575 dozers. Where necessary, duricrust is drilled and blasted with ANFO, with blast-holes on a 3.5 m square grid, typically to depths of 3 m. Hydraulic excavators then load the bauxite into trucks for transport to crushers. Before 2004 the fleet consisted of 13 Komatsu 85–105 t trucks, but this fleet is being replaced with eight 205 t Komatsu trucks.

Bauxite is mined concurrently from several pits and fed into crushers to blend feed of varying quality. The trucking distance of ore to the crushers is up to 10 km. Two mobile jaw-crushers operate side-by-side at Huntly. These are capable of ‘walking’ between set-ups, which may be between 5 and 10 years. After crushing to –150 mm, ore is transported by conveyor belt to the Pinjarra refinery (Fig. 4). The conveyor is extended each time the crushing locality is changed. A move is planned for late 2004 to a new site at McCoys. Conveyor feed is sampled continuously to maintain the quality of plant feed.

Rehabilitation

After mining is completed in an area, large rocks are buried, vertical pit-faces are battered down, and the pit floor is smoothed to blend the mined area into the surrounding landscape. Pit-floor ripping is conducted in areas of heavy compaction, and to improve the depth of soil fracture, before returning topsoil. After soil return, a dozer rips the entire surface along contours to a depth of 1.5 m. This reduces runoff by increasing the water storage capacity in surface and subsurface soils.

The long-term objective of Alcoa’s mine rehabilitation is to establish a self-sustaining jarrah–marri forest ecosystem to enhance or maintain nature conservation, timber production, water harvesting, recreation, and other forest values. The forest naturally has a diverse understorey of shrubs and herbaceous plants, and to restore this all seed used is collected from the area around the mine so that the provenance of the rehabilitated flora is correct. The seed mix contains four tree and more than 50 understorey species, selected in order to reproduce the diversity and density of plants similar to the pre-mining condition. Most plants germinate from scattered seeds, but where necessary, planting of recalcitrants (plants that do not readily germinate from seed) is carried out in winter months.

An interagency committee, with representatives from mining, development, conservation, and environmental agencies, oversees the setting of rehabilitation standards that Alcoa is required to adopt. Alcoa has received international awards for its excellence in rehabilitation in returning native ecosystems after mining.

Figure 10 shows an area of mining and infrastructure at Huntly and the same area four years later when vegetation has re-established.



Figure 10. Photographs of mining area at Huntly: a) mobile crushing plant and other mine infrastructure in front of cleared partially mined area, with North Dandalup reservoir beyond; b) same site four years later following rehabilitation of all the cleared areas and restoration of the landforms (photos courtesy of Alcoa World Alumina Australia)

Greenbushes tantalum–lithium–tin deposit

The Greenbushes pegmatite, about 270 km south of Perth, contains one of the world's major tantalum deposits, and the world's largest lithium deposit. Originally mined for its tin content, the deposit has a continuous mining history extending over 116 years. Tantalum became the main ore component only in the 1970s following an increase in demand and price for the metal, and a collapse in the international tin price.

The Greenbushes mineral field has historical production of more than 2150 t of tantalite (Ta_2O_5), and more than 54 000 t of Li_2O (in spodumene), as well as significant quantities of tin and high-purity kaolin.

Exploration and development history

Tin (cassiterite) was first reported at Greenbushes in 1884 in a GSWA report (Hardman, 1884; see Blockley, 1980). Mining of alluvial deposits and deeply weathered 'soft rock' ore commenced in 1888. D. W. Stinton, a kangaroo hunter, took up the first 400 acre (100 ha) mining lease at Greenbushes and was the founder of the Bunbury Tin Mining Company. Stibiotantalite was identified in 1893, and tantalite in 1900 (Hatcher and Clynick, 1990), but there was no market for these minerals before 1944.

Spodumene was first identified by GSWA in 1949. Pegmatite was recognized as the primary source of cassiterite as early as 1893, but alluvial deposits and lateritic caprock masked its extent.

Greenbushes Ltd took control of all mining tenements on the mineral field and relocated the South West Highway away from the pegmatite body in the early 1970s, following significant tantalum price rises. Exploration and mining in the weathered zone, which extends to about 50 m depth, increased with further price rises in the period 1975–1980, and the Greenbushes deposit was demonstrated to be a major tantalum deposit by world standards. In 1977 a deep drilling program was instituted to test the deposit to a vertical depth of 550 m (Hatcher and Clynick, 1990).

The Greenbushes operations, Greenbushes Tin, and Lithium Australia were acquired by Gwalia Consolidated Ltd in 1990. In 1998 a sister company, Sons of Gwalia Ltd, merged with Gwalia Consolidated and the Greenbushes operation is now part of Sons of Gwalia's Mineral Division.

Sons of Gwalia also produces tantalum concentrate from its Wodgina mine in the Pilbara region in northern Western Australia. The combined production of tantalum concentrates by the company represents about 65% of total world tantalum production. Sons of Gwalia Ltd was placed into voluntary administration in August 2004.

Geological setting

The Greenbushes pegmatite is part of an Archaean pegmatite swarm (Fig. 11) that intruded granitic, sedimentary, and mafic igneous rocks at about 2650 Ma (de Laeter and Blockley, 1972). The pegmatites are spatially associated with the major Donnybrook–Bridgetown shear zone (Partington, 1986a), and other pegmatites close to this shear zone have much younger Sm–Nd and Rb–Sr ages of 1100 Ma (Mullalyup) and 680 Ma (Ferndale; Partington 1986b). Syntectonic intrusion or post-intrusion remobilization of the Donnybrook–Bridgetown shear zone is indicated by mylonite and boudinage development along the pegmatite contacts. The country rocks and pegmatites have been metamorphosed to amphibolite facies.

The geological history of this part of the Darling Fault Zone is poorly constrained by modern SHRIMP U–Pb zircon dating, and complementary dating of metamorphic effects related to the Pinjarra Orogen by Libby and de Laeter (1998) and Libby et al. (1999) confirmed widespread Rb–Sr biotite ages between 1000 and 400 Ma (see summary in Janssen et al., 2003).

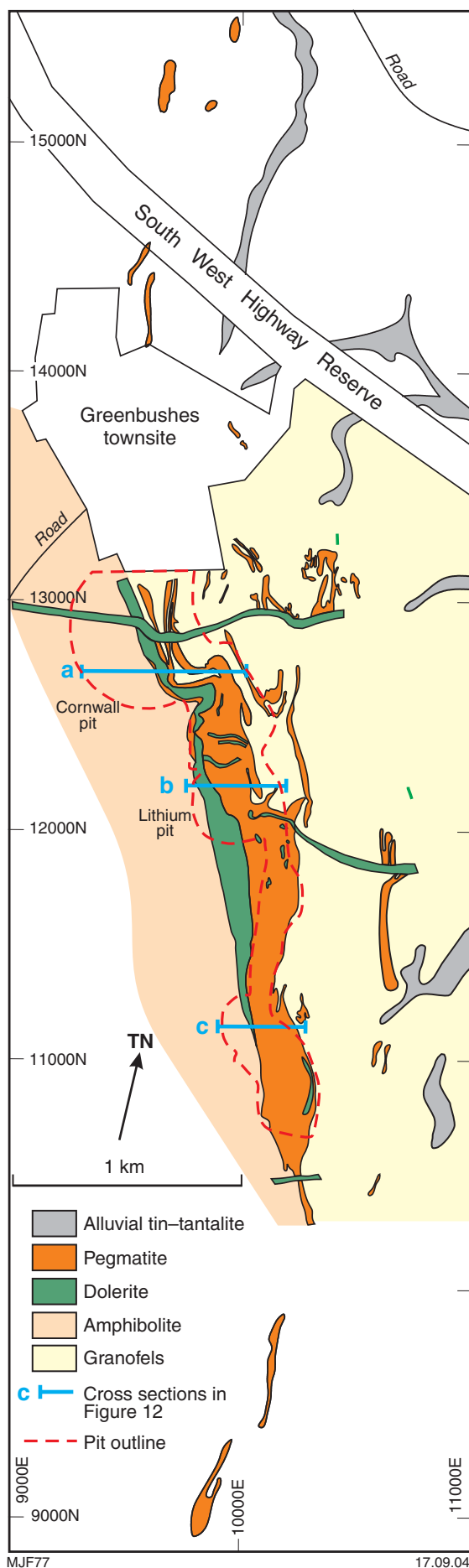
Geology of the Greenbushes deposit

The Greenbushes pegmatite deposit comprises one major body about 3300 m long and up to 250 m wide, and numerous discontinuous (at surface), and very much smaller, bodies in a swarm that extends over a 7 km² area (Fig. 11). The pegmatites generally dip west at 30–70° and have sharp contacts with the country rocks. The pegmatites characteristically have a gneissic texture, with common mineral banding, but relict igneous texture is rarely preserved (Hatcher and Clynick, 1990). There is no evidence of a parental granite body close to the pegmatite or to at least 500 m depth in the drilling to date.

Compositional and mineralogical zoning

The main pegmatite has a compositional layering rather than a concentric zonation, with considerable variation in layering along strike. In the Cornwall openpit at the northern end of the main pegmatite, the pegmatite comprises several discrete layers separated by country rocks (Fig. 12a):

- an upper **Potassic Zone** characterized by quartz–microcline–perthite(–muscovite);
- a central **Albite Zone** containing quartz–albite (–muscovite–tourmaline–apatite) in a body that bifurcates with depth;
- a lower **Mixed Zone** containing quartz–albite–K-feldspar–spodumene(–tourmaline–apatite–mica).



The Lithium openpit, 500 m to the south, contains the same broad compositional layers, but with a wide quartz–spodumene(–muscovite–albite–microcline–perthite) **Lithium Zone** developed within the Albite Zone (Fig. 12b).

Farther south in the main body the upper Potassic Zone is absent, and a Mixed Zone is present on both the top and bottom of the pegmatite, with a central Lithium Zone (Fig. 12c).

Globally, tantalum ore grades are typically 0.15 – 0.02% (150–200 g/t) Ta_2O_5 with high-grade zones exceeding 0.05% (500 g/t). Tin grades average about 0.05% (500 g/t) Sn. Within lithium ore zones, grades are typically 3.5 – 4.5% Li_2O , and globally the pegmatite averages around 1.5% Li_2O . The Greenbushes pegmatite is classed as a lithium pegmatite. Metal grades vary widely in the different pegmatite zones, as shown in Figures 12 and 13.

Ore mineralogy

Ore minerals identified from the Greenbushes deposit are listed in Table 3. The main tantalum ore mineral is tantalite, which forms rectangular prisms less than 0.5 mm in diameter, and fine (<65 μm) inclusions in cassiterite (Hatcher and Clynick, 1990). Tantalite is more specifically columbo-tantalite because it contains niobium (formerly called columbium), which is itself part of the mineral series ferrotantalite–manganotantalite.

The main lithium ore mineral is spodumene, which is commonly about 70 mm, but has been noted as crystals more than 1 mm in size. Spodumene is a monoclinic pyroxene, and is typically colourless to white, but it also has several colour forms including green (hiddenite) with minor iron and chromium, and pink (kunzite) containing minor manganese. Other lithium-bearing minerals identified at Greenbushes are also listed in Table 3. Cassiterite is the only tin ore mineral and ranges from 1 to 60 mm across.

Mining and processing operations

In recent mining history, two separate openpit mines have been operated at Greenbushes (Fig. 11): the Cornwall pit immediately south of the townsite accessed the main tantalum ore body until it closed in 2003; and the Spodumene pit 300 m to the south, which is the source of lithium. Since the Cornwall pit phase was completed, mining has been concentrated in a major cutback of the pegmatite south of the Cornwall pit. This cutback is centred on the massive Central Lode Pegmatite zones to provide both tantalum and lithium ore. Metal distribution through the pegmatite is superimposed on pit outlines in

Figure 11. Geological plan showing the distribution of pegmatite and main mining areas at Greenbushes (modified from Hatcher and Glynnick, 1990, and Sons of Gwalia Ltd, 2004, written comm.)

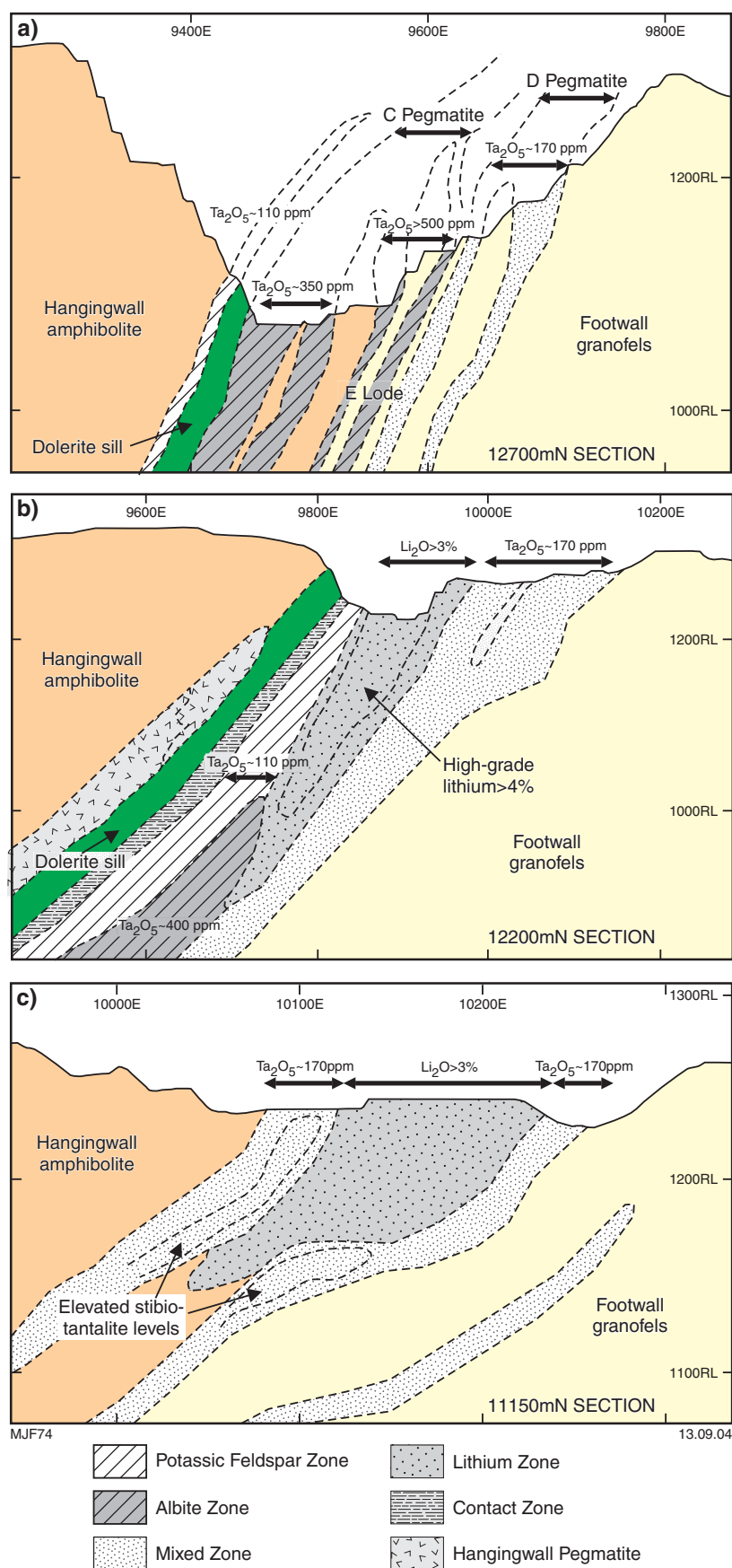


Figure 12. Cross sections through the Greenbushes pegmatite deposit showing ore zonation: a) Cornwall openpit at 12700 mN; b) Central Lode Stage 3 at 12200 mN; c) Central Lode Stage 1 at 11150 mN (after Sons of Gwalia Ltd, 2004, written comm.)

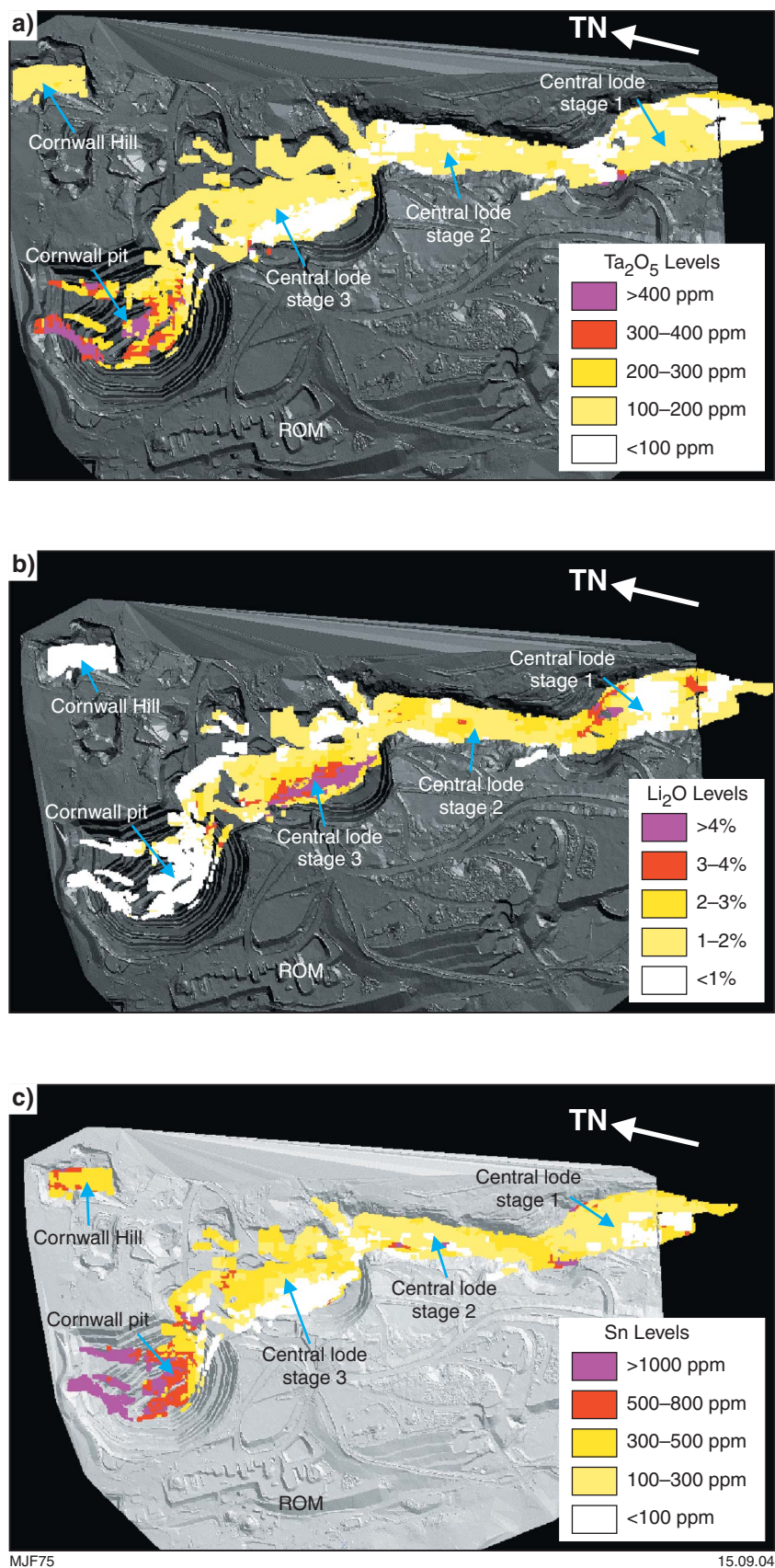


Figure 13. Metal grade distribution in the Greenbushes openpits: a) tantalum; b) lithium; c) tin (after Sons of Gwalia Ltd, 2004, written comm.)

Table 3. Economic minerals, Greenbushes tantalum mine

<i>Minerals</i>	<i>Chemical formula</i>
Tantalum	
Columbo-tantalite	(Fe,Mn)(Nb,Ta) ₂ O ₆
Stibio-tantalite	(Nb,Ta)SbO ₄
Microcline	((Na,Ca) ₂ Ta ₂ O ₆ ·(O,OH,F))
Ta-ilmenite	Fe ²⁺ (Ta,Ti)O ₃
Ta-rutile (struverite)	(Ti,Ta,Fe ³⁺) ₃ O ₆
Wodginite	(Ta,Nb,Sn,Mn,Fe) ₁₆ O ₃₂
Ixiolite	(Ta,Fe,Sn,Nb,Mn) ₄ O ₈
Tapiolite	(Fe,Mn)(Ta,Nb) ₂ O ₆
Holtite	Al ₆ (Ta,Sb,Li)[(Si,As)O ₄] ₃ (BO ₃)(O,OH) ₃
Lithium	
Spodumene	LiAlSiO ₆
Lithiophilite	Li(Mn ²⁺ ,Fe ²⁺)PO ₄
Amblygonite	(Li,Na)AlPO ₄ (F,OH)
Holmquistite	Li(Mg,Fe ²⁺) ₃ Al ₂ Si ₈ O ₂₂ (OH) ₂
Lepidolite	K(Li,Al) ₃ (Si,Al) ₄ O ₁₀ (OH) ₂
Tin	
Cassiterite	SnO ₂

SOURCE: Sons of Gwalia Ltd (2004, written comm.)

Figure 13. An underground mine was developed in 2001 using a 5.5 × 5.5 m decline from the base of the Cornwall pit to access a large high-grade tantalum deposit. This operation used 40 t dump trucks and 15 t capacity loaders, with ore faces drilled out by twin boom jumbo drills. The underground mine was designed to produce 600 kt of tantalum ore per year, but is currently (September 2004) on care and maintenance pending better market conditions.

Openpit mining is by drill and blast techniques, with 5 and 10 m benches drilled on an approximate 3.5 × 4 m grid. Hydraulic excavators load broken ore onto 85 t dump trucks, which is taken to a Run of Mine (ROM) pad where it is stockpiled according to mineralogical characteristics and grade. Tantalum and lithium ores are stockpiled separately. Ore is fed to a primary jaw crusher by a front-end loader, with further secondary and tertiary crushing by cone crushers.

The tantalum primary processing plant was constructed in 1992 and expanded in 2001 to process 35 t of final product per day from 10 500 t of ore. The process involves grinding in ball mills, and concentration of tin and tantalum minerals by Russell Jigs, Derrick Screens, spirals, and shaking tables. The primary concentrate is transported to the secondary processing plant by kibble where it is screened and tantalite and tin–tantalum minerals are separated by rapid magnetic separation. The tantalum concentrate is then roasted to remove arsenic and antimony to produce a final product of tantalite concentrate at a rate of more than 500 000 lbs/year at more than 30% Ta₂O₅. Arsenic is removed from the tin–tantalum concentrate by flotation, and this concentrate is then smelted in a primary electric arc furnace to produce crude tin and tantalum slags. Tin is refined in kettles to produce a final product of tin ingots at more than 98% Sn. Tantalum slags are further smelted in a secondary electric arc furnace to produce a granulated tantalum glass containing more than 20% Ta₂O₅.

Crushed spodumene ore is delivered to the lithium processing plant by front-end loader where it is milled in a ball mill to assist liberation and achieve required particle size for gravity separation in spirals or the heavy media separation (HMS) plant. Magnetic contaminants are removed from gravity concentrates by magnetic separation. Four final products include fine, concentrate, glass grade, and universal categories to service different markets.

In the 12 months to the end of June 2004, Greenbushes produced 1 119 504 lbs of Ta₂O₅ in concentrate, 553 t of tin, and 126 534 t of lithium–spodumene concentrate. Sons of Gwalia's other tantalum mine, Wodgina in the Pilbara region of Western Australia, produced 1 172 507 lbs of Ta₂O₅ in concentrate in the same period, thereby just beating Greenbushes to the title of world's largest producer (Sons of Gwalia, 2004).

Titanium mineral deposits of the Swan Coastal Plain

Western Australia is a dominant supplier to world markets of titanium minerals and zircon produced from fossil beach deposits ('mineral sands'). In 2002–03 the industry produced about 2.2 Mt of heavy minerals (mainly titanium minerals and zircon), with a value of \$847 million, down from \$855 million in 2002. It is the sixth-most valuable sector of the State's mining industry, with additional economic benefits derived from the downstream processing of titanium minerals to produce white pigments. The titanium minerals mining industry directly employs about 2000 people.

Two regions on the Swan Coastal Plain dominate production: the Bunbury–Capel region, about 200 km south of Perth, and the Eneabba region, about 240 km north of Perth. This field guide covers the deposits south of Perth, with excursion stops at Capel, Yoganup, and Minninup (Figs 1 and 14).

Titanium minerals and zircon represent the most valuable minerals recovered in heavy-mineral concentrates produced from mining the fossil beach deposits, but a variety of other minerals with specific gravity greater than about 2.85 may also be recovered in mining operations. These minerals include monazite, xenotime, garnet, kyanite, tourmaline, hornblende, sphene, apatite, magnetite, and various hydrated iron oxides. Most have no market, but substantial quantities of garnet are produced from modern coastal deposits about 450 km north of Perth, and monazite and xenotime are marketed intermittently.

The titanium minerals industry has in recent years moved away from previously used terminology of 'mineral sands', 'beach sands', or 'heavy mineral sands' to describe its products and activities. The preferred name is now titanium minerals industry, in recognition of the greater value of titanium (and zircon) minerals compared with silica sand, and to avoid association with environmental issues related to mining beach sand. The term titanium minerals industry is used in this guide, although in some deposits the value of zircon has recently surpassed the value of titanium minerals.

Baxter (1977) and Harrison (1990) give detailed descriptions of the industry, and much of the background in this field guide is based on these works.

Regional geological setting and geomorphology

The Swan Coastal Plain (Fig. 14) extends north from the Whicher Scarp, about 250 km south of Perth, for about 650 km. It is 12–35 km wide and is bound on the east by the Darling Scarp in the south and the Gingin Scarp in the north. These three scarps are dominantly erosional now, but the Darling Scarp was initiated as a structural feature related to the Darling Fault.

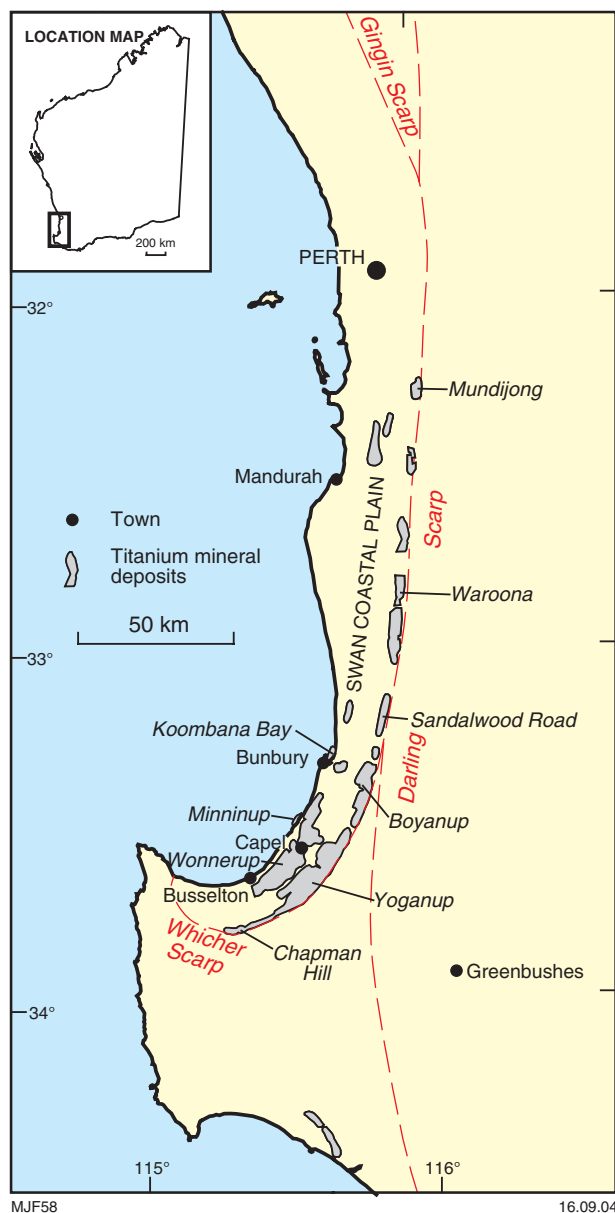


Figure 14. Map showing the distribution of titanium mineral deposits on the Swan Coastal Plain

The nearshore parts of the Swan Coastal Plain contain three phases of sand dunes that are recognized geomorphologically, progressing easterly from the coast, as:

- Quindalup Dunes: modern, nearshore, unconsolidated dunes consisting of quartz and limesand;
- Spearwood Dunes: higher, slightly older and more rounded dunes, where the limesand is cemented to form limestone (calcareous eolianite or calcarenite);
- Bassendean Dunes: the most inland dunes; lower, highly degraded and well rounded; mostly yellow quartz sand from which the lime component is interpreted to have been dissolved.

East of the Bassendean Dunes to the bounding scarps is the Pinjarra Plain, underlain by silty and clayey sediments assigned to the Guildford Formation, consisting of fine terrigenous sediments derived from the scarp material. At the base of the scarps and extending out under the Guildford Formation is a quartz sand unit, the Yoganup Formation, that represents former elevated beach deposits. Ferricrete is commonly deposited on or within the sands. Along much of the Darling Scarp the Yoganup Formation rests on crystalline basement rocks; coastal erosion had progressed inland from the original fault scarp by up to 2 km before deposition of the sand wedge.

The Quindalup Dunes consist of the Safety Bay Sands, and the Spearwood Dunes consist of the Tamala Formation. North and south of the Swan Coastal Plain the Tamala Formation consists of thick calcareous eolianite deposits that in places form high coastal cliffs, and extend offshore as islands and shoals representing the eroded remnants of submerged dunes that formed at lower sea levels than the present.

The Swan Coastal Plain is largely underlain by the Phanerozoic Perth Basin — a deep, linear trough of Silurian to Quaternary sediments (Cockbain, 1990; Crostella and Backhouse, 2000). East of the Darling Fault, as described in more detail elsewhere in this guide, is the Archaean Yilgarn Craton; south of the Whicher Scarp and east of the Gingin Scarp are weakly indurated Mesozoic sediments of the Perth Basin.

SHRIMP U–Pb ages for zircons from titanium mineral deposits in the Swan Coastal Plain are dominated by populations of 1100–1300 Ma or 500–600 Ma (Sircombe and Freeman, 1999), which are similar to populations determined by Cawood and Nemchin (2000) from Perth Basin sediments. This is interpreted to demonstrate that the titanium mineral deposits formed by further concentration of heavy minerals already concentrated in Cretaceous sediments of the Perth Basin. These ages also suggest that most of the sediment in the Perth Basin was originally derived from the Albany–Fraser Orogen or Leeuwin Complex, or similar pan-African rocks inferred to formerly exist to the west (Collins, 2003). Outcrops of some of these potential source rocks in the Leeuwin Complex will be visited during this field trip.

History of discovery, exploration, mining, and processing

Following World War II, GSWA participated in a nationwide search for monazite as a source of radioactive elements. The first reported mining of the beach deposits, between 1949 and 1950, was at Cheyne Bay on the south coast, about 400 km southeast of Perth.

Exploration on the Swan Coastal Plain commenced in the 1950s and deposits at South Capel were pegged and mined by Western Titanium NL starting in 1954. Cable (1956) Ltd and Perron Bros Pty Ltd commenced mining of deposits at Koombana Bay, on the northern outskirts of Bunbury, in 1956. Cable Sands is still actively mining in the area. Westralian Oil NL identified deposits at

Yoganup and Capel North, and commenced mining in 1959. Westralian Oil later became Westralian Sands Ltd. The Western Titanium leases later went through various ownership changes before eventually becoming owned by RGC Mineral Sands. Westralian Sands and RGC merged in 1997 to form Iluka Resources Ltd, who is now the world's second-largest producer of these minerals.

In the early 1980s, a farmer digging a well at Boyanup, 20 km southeast of Bunbury, intersected black sands at a shallow depth (Richards, G., Iluka Resources Ltd, 2004, written comm.). Westralian Sands recognized the regional implications of the find and applied for exploration licences along the full length of the Darling and Whicher Scarps. Subsequent exploration identified a number of deposits over 300 km of strike length, including the large and high-grade Boyanup deposit.

In the Eneabba area, 240 km north of Perth, there was a pegging rush in the early 1970s (Lissiman and Oxenford, 1975). Several mines were commenced, all later coming under the ownership of Iluka Resources. Mining is still being carried out in the two regions, focused around Bunbury in the south and Eneabba in the north.

In the 1960s the Becher process of upgrading ilmenite to synthetic rutile was developed in Perth, and applied to commercial production. This led progressively to the introduction of more plants to the stage where Western Australia now dominates the world market for synthetic rutile and pigment feedstock.

Western Australian titanium minerals production figures and values for calendar year 2003 are given in Table 4, with total historical production figures to December 2003.

Geology of the titanium mineral deposits

The Swan Coastal Plain titanium mineral deposits are Pliocene to Holocene beach or nearshore dune deposits at three broad altitudes, related to former higher sea-level stillstands and to the present coastline:

- The **Yoganup strandline** is at the base of the Darling and Whicher Scarps at heights of 15–76 m.
- The **Capel strandline** is within the Spearwood Dune system at heights up to 15 m.
- The **Quindalup strandline** is on modern beaches and dunes at heights up to 6 m. It is likely that lower stillstands have left strandline deposits offshore following the rise in sea level after the last and earlier glacial maxima.

The Yoganup strandline is stratigraphically equivalent to the Yoganup Formation (Masters, 1990). Initially identified as a wedge of sand at the base of the Darling and Whicher Scarps, it is now recognized as a sheet extending across the Swan Coastal Plain below the Guildford Formation, thinning towards the coast (Johnston, T., Iluka Resources Ltd, 2004, written comm.). Many titanium mineral deposits are within this unit, from Chapman Hill south of Busselton to Mundijong 200 km to the north (Fig. 14).

Table 4. Western Australian titanium minerals production for the calendar year 2003 and total historical production to December 2003

<i>Mineral/commodity</i>	<i>2003 production (t)</i>	<i>2003 value (A\$M)</i>	<i>Total production to December 2003 (t)</i>	<i>Value (A\$M)</i>
Ilmenite	862 391	110.5	37 182 391	2 330.50
Upgraded ilmenite	556 253	315.5	7 186 253	3 675.50
Leucoxene	46 736	17.3	695 736	231.3 0
Zircon	396 805	229.9	9 306 805	2 769.90
Rutile	123 675	80.3	2 633 775	1 400.30
Monazite	—	—	232 000	95.30
Xenotime	—	—	5 640	1.96
Garnet	127 975	n/a	1 236 975	^(a) 88.00
Kyanite	—	—	6 400	0.35
Staurolite	2 129	0.3	5 269	10.78

NOTES: Values quoted using 2003 market values

(a) Total value to December 2002 only

n/a not available

SOURCE: Department of Industry and Resources, Western Australia

The Capel strandline is within the Tamala Formation, which is commonly typified as a limestone-dominated unit with dunes up to about 100 m high. However, the dunes are much lower where there are titanium mineral deposits, and the palaeo-environment reflects a beach and nearshore depositional setting. Adjacent dune sands are commonly mineralized, and the economic deposits are tabular.

Mineralization in the Quindalup Dunes is confined to the shore between Bunbury and Busselton, and is stratigraphically within the Safety Bay Sands. This mineralization has been mined at only three sites: Minninup, Wonnerup, and Koombana Bay (Fig. 14).

The ages of the deposits are poorly constrained because of the lack of methods to date the sediments reliably. Mallet (1982) determined a late Pliocene age for planktonic foraminifera in units equivalent to the Capel strandline, and Kendrick (1981) found a molluscan fauna indicating a Pliocene age in beds correlated with the Capel strandline. Miocene lignite was immediately overlain by high-grade mineralization in the 21 m strand at the Yoganup North (Boyanup) deposit (Johnston, T., Iluka Resources Ltd, 2004, written comm.). Playford et al. (1976) considered the Yoganup strandline to pre-date the Capel strandline. The Quindalup strandline is modern, and titanium minerals are re-accumulating now at Minninup, only a decade after mining finished. This locality will be visited on this field trip (Figs 1 and 14).

Figure 14 shows the very large widths of the deposits in the Capel district, in both the Yoganup and the Capel strandlines, in contrast with the deposits further along strike. In a study of the modern environment at Minninup beach, Prof. Lindsay Collins, of Curtin University of Technology in Perth, noted that the combination of swells and waves from prevailing northwesterly winds, and swells from the west-southwest related to the roaring forties, generates ideal conditions for concentrating heavy mineral grains. Initial mining of these deposits commenced in Koombana Bay, a J-shaped bay on the north side of Bunbury Basalt outcrops at Bunbury — a

classic coastal setting for the concentration of high-density minerals. The formation of the major deposits in both the Capel and Yoganup strandlines in this same geomorphic setting (Fig. 14) is probably due to these same factors.

Characteristics of the deposits

The concentration of economic minerals in the strandlines ranges from a background of less than 1% to almost pure black sands, approaching 100%, over thicknesses of 1–20 m (rarely 30 m), widths from 5 to 400 m, and lengths up to 10 km. The concentrations of the various ore minerals vary along strike, as documented by Masters (1990) for the Yoganup Formation (Table 5).

The mineable thickness is up to about 8 m in the Capel strandline, and about 10 m in the Yoganup strandline. The deposits dip westward, commonly showing stepwise displacement downward, progressing from one wave-cut platform base down a low coastal scarp to another wave-cut platform.

Table 5. Variation in heavy mineral content, Yoganup Formation (after Masters, 1990)

<i>Ore mineral</i>	<i>South of Bunbury</i>		<i>North of Bunbury</i>	
	Percentage			
Ilmenite	(a)82.9	(b)86.9	(a)81.0	(b)90.0
Altered ilmenite	1.4	—	3.5	—
Leucoxene	2.4	1.2	4.8	2.5
Zircon	10.9	11.1	6.9	7.2
Monazite	0.5	0.5	0.3	0.3
Other minerals	2.2	—	3.5	—

NOTES: (a) Figures in the left-hand column are the present concentrations, inferred to be after postdepositional weathering has converted some ilmenite to altered ilmenite and leucoxene

(b) Figures in the right-hand column were recalculated to approximate the inferred depositional concentrations (Masters, 1990)

The basement for the deposits is weakly indurated Mesozoic sedimentary rock, commonly the Yarragadee Formation or the Leederville Formation. Both these units are thinly to thickly interbedded sands, silty sands or clayey sands. Several of the orebodies show that coastal erosion had generated wave-cut platforms and low coastal cliffs before deposition of the heavy mineral sands. Any one strandline may contain a number of former beach deposits over widths of up to 400 m and vertical ranges of several tens of metres. Within each of the strand intervals the companies recognize a number of units based on altitude, and the separate units may have distinctive mineralogy. Figure 15 shows the distribution of deposits at Yoganup, and cross sections showing geology and grade distribution.

At the base of the orebodies there may be a thin basal conglomerate consisting of pebbles, cobbles, and boulders of well-rounded quartz sandstone to orthoquartzite in a sand matrix. Immediately above the conglomerate the titanium mineral deposits are well bedded on a 1–20 cm scale, with bedding ranging from planar to trough cross-bedded, and from horizontal to gently dipping offshore. Adjacent beds can display marked variation in the concentrations of the ore minerals. Collins and Baxter (1984) mapped and described the orebody at the Yoganup Extended deposit about 15 km southeast of Bunbury. They identified five mappable units within the Yoganup Formation, distinguished by the thickness, attitude, and interrelationships of the individual beds and laminae. They documented complex interplays of bed-forms, attitudes, and mineral assemblages consistent with a wave-dominated shoreline depositional environment.

Upslope, the deposits are truncated against Mesozoic basement. Downslope, the mineral concentrations decrease progressively away from the high-energy shoreline over several tens to hundreds of metres. The limit to mining downslope is governed by an economic cut-off grade.

Overburden on the mineralization is up to 20 m thick, and commonly of yellow to white, fine- to coarse-grained quartz sand or clays of the Guildford Formation.

Controls on ore deposition

The classic location for deposition of high-density minerals is in bays downwind and downswell of headlands, in J-shaped bays. The size and scale of the headlands and adjacent bays can vary markedly. Three smaller-scale cases include:

- a deposit at Sandalwood Road (Fig. 14), where Cable Sands finished mining in 2003, is located north, and presumably in the lee, of a prominent outcrop of vein quartz;
- the Yoganup Extended deposit, adjacent to an outcrop of Bunbury Basalt just off the Whicher Scarp;
- the Yoganup West and the high-grade part of the Tutunup West deposits that are also controlled by similar basalt palaeo-headlands.

However, not all mineralization is related simply to these coastal features. A medium-scale J-shaped bay at Koombana Bay at Bunbury has a headland formed by resistant Bunbury Basalt. On the largest scale, all the

deposits south of Bunbury could be considered to be related to the headland at Cape Naturaliste, about 50 km west of the site (Fig. 14).

Exploration and mining of the deposits

Exploration and evaluation

Exploration typically commences with interpretation of likely strandline zones through careful study of aerial photographs. The Swan Coastal Plain is mostly held as private property, and the Mining Act 1978 requires tenement holders to obtain the agreement of landowners before exploring on such land. Therefore, companies commonly initiate exploration drilling by obtaining the consent of local Government Councils to drill along road verges. Only when encouraging intersections are obtained in this phase will negotiations be commenced with the land owners. Grid drilling varies between companies, but typically commences with drillholes at about 40–100 m centres, on lines from 800 m to 4 km apart dependent mainly on land-access factors. As exploration advances the spacings are progressively closed to drillhole spacings of 10–20 m along lines that may be 40 m apart. Samples are collected at 1 m intervals down holes. In new areas the samples are panned and logged during drilling, and only intervals with visible mineralization are submitted for analysis. Initial determinations are only of total high-density minerals ($SG > 2.85$). Mineralogical analyses are commonly only routinely completed on samples from defined deposits. In later phases of infill drilling, the rig may not be geologically supervised and samples will be taken from specified depths for analysis.

The initial analysis of ore samples is a simple gravity separation providing a percentage of heavy minerals. Chemical and mineralogical determinations follow, commonly in company-owned laboratories, to precisely define mineral constituents important in marketing of the product. Of particular interest is the TiO_2 content of the ilmenite, and a number of different grades are marketed, under such names as HiTi. Trace-element contents of the ilmenite also affect marketability. For example, high U_3O_8 and ThO_2 content of the ilmenite can be restrictive in pigments, and deposits with levels below about 80 ppm are at a premium. The presence of some transition metals affects the reactivity of the ilmenite, and chromium and manganese concentrations are important in this regard.

Tenure and royalties

The Mining Act 1978 specifies a number of tenement types that may be held in support of exploration and mining in Western Australia. A Prospecting Licence is an exploration title that is held for up to four years (renewable for two more) covering an area of up to 200 ha. An Exploration Licence is an exploration title covering between about 3 to 200 km² for a five-year period, renewable for four years (under review at the time of writing). Mining Leases are titles for productive mining covering up to 1000 ha for a period of 21 years, renewable.

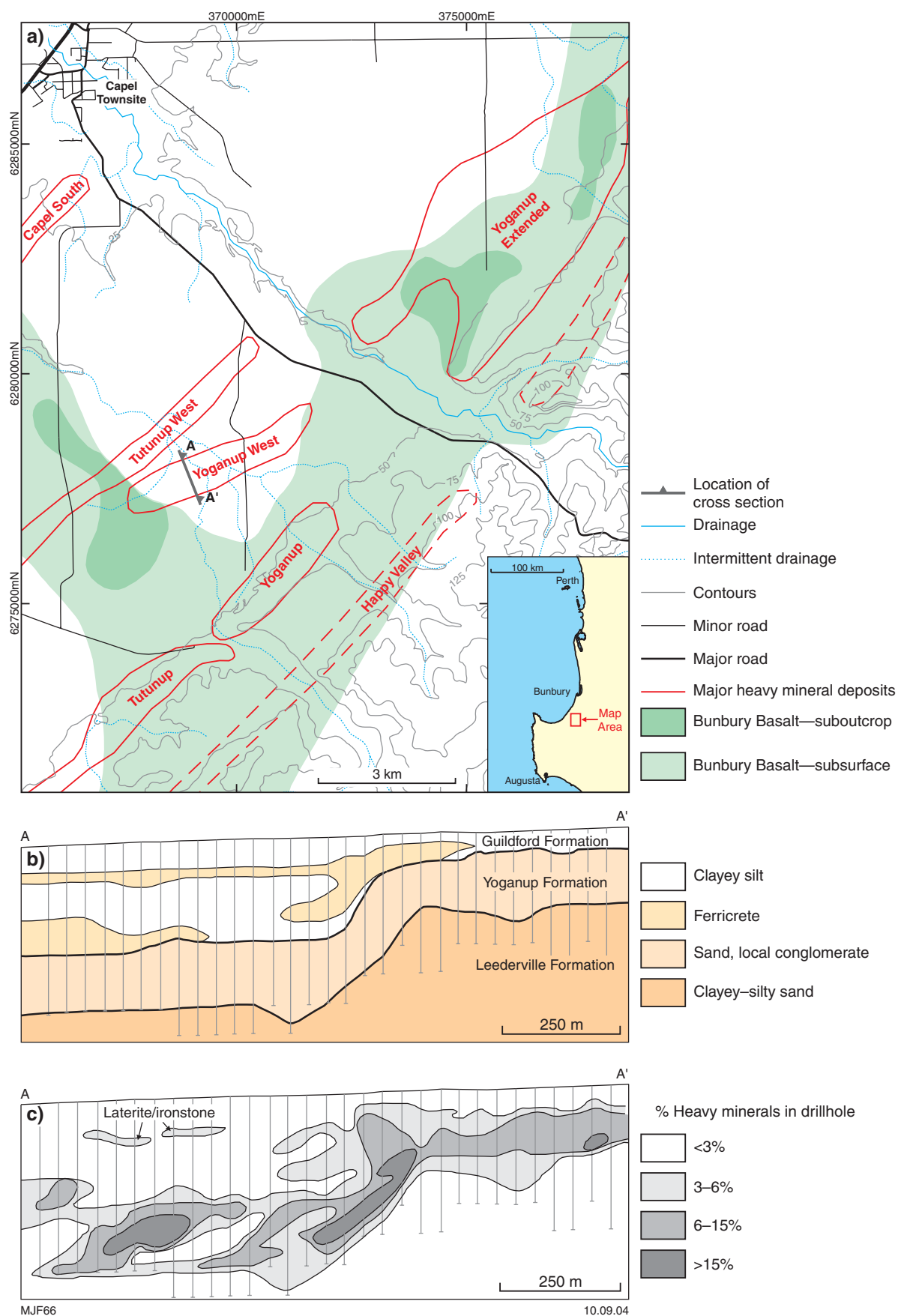


Figure 15. Yoganup titanium mineral mining area: a) map of titanium mineral deposits and subsurface basalt occurrences; b) geological cross section through Yoganup West strandline; c) cross section through Yoganup West strandline showing total heavy mineral concentrations in drillholes (after Iluka Resources Ltd, 2004, written comm.)

An idiosyncrasy of Western Australian land tenure is that land disposed before 1899 included mineral rights, whereas in later allocations all minerals were the property of the Crown (i.e. the State). Therefore, mining on some land on the Swan Coastal Plain does not require a mining lease, and is removed from requirements of the Mining Act.

Mining attracts royalties payable to the State Government, levied usually at a rate dependent on the value of the output. For ilmenite, the rate is 1.5% of the realized value. However, in order to encourage downstream processing of minerals, in the 1970s the Government struck a rate of royalty of \$1.50 per tonne on ilmenite upgraded in the State. The fact that the State has now become a prime producer of synthetic rutile in the world clearly shows the wisdom of Government's use of the royalty regime in order to magnify the wealth-creation derived from its mineral endowment within the State. In the 1970s much of the ilmenite was not even marketable and the industry was highly dependent on the zircon and rutile production to maintain operations.

Mining, processing, and rehabilitation

Mining techniques employed depend on the level of the deposit in relation to the water table. Most mining currently uses scrapers and bulldozers or, if the grades are high, hydraulic excavators and trucks. Cable Sands (WA) Pty Ltd until recently operated a suction-cutter dredge at the Jangardup mine, on the south coast 120 km south of Bunbury, and this was also used in mining the Minninup deposit.

The ore is passed through a trommel to remove oversize material (>50 mm), break up clay lumps, and wash out the clay fraction, which may be thickened and sent to solar drying ponds. The sand fraction is then passed through a series of spiral concentrators to separate the heavy minerals from quartz sand that is returned to the pit.

The large area required for solar drying ponds is a major cost and also a social issue, increasing the area of land affected by mining and raising costs. Research to increase the clay density in the slime waters is ongoing, with an intent to develop a codisposal process where the fines are returned to the former pit intermixed with sand tailings.

The high-density concentrate is transported by trucks to the dry plant in Bunbury (Cable Sands) or Capel (Iluka Resources). In these plants saleable products are separated by a variety of techniques using differences in magnetic and electrostatic properties.

Research conducted in the 1970s at the Chemistry Centre of Western Australia (now part of the Department of Industry and Resources) by Dr John Becher developed a process for efficiently removing the iron oxide from the ilmenite lattice and producing synthetic rutile (referred to as upgraded ilmenite in departmental statistical reports). A commercial-scale industrial plant was built at South Capel with a capacity of about 2 t/h, and after this was shown to be a technical and commercial success, five more

were built. The last was built at North Capel by Iluka Resources at a capital cost of \$130 M, and commissioned in 1997. The first plant has now been decommissioned, but the remainder continue in commercial operation. In these plants, ilmenite and pulverized coal are fed into a rotating, inclined kiln in which the temperature is raised to more than 1000°C. The carbon reduces the iron oxide to metallic iron, and the titanium oxide – iron product is then oxidized and the iron oxide dissolved in sulphuric acid, leaving the raw titanium dioxide. The ideal feed for this process is ilmenite in which part of the iron oxide has been naturally removed, elevating the TiO₂ content from the stoichiometric 53% TiO₂ up to levels of more than 65% TiO₂.

Mine rehabilitation depends on land-use planning for any particular site. Broad-area farming is the predominant subsequent land use, and mined areas are routinely returned to this activity. Iluka Resources is also establishing a rural–urban subdivision at Boyanup over the former Yoganup North mine site. At Waroona a mine is proposed to also include urban developments, where value-adding for the benefit of the community will be accomplished by revising the landforms and pre-designing levels for roads and drainage to provide an optimum setting for the residential areas, all costs effectively being borne by the mining operation. Figure 16 shows the Yoganup North mine site before and after rehabilitation; the area of future residential development is at the southwestern end of this site. At Minninup rehabilitation involved reconstruction of coastal dunes to restore the beach to its pre-mining configuration, and replanting with native coastal vegetation (Fig. 17). This locality will be visited on the field excursion.

Environmental and social issues and economic aspects of mining

The titanium minerals industry operates in areas where there is much competition from alternative land uses. For example, conservation areas may prevent mining, urban subdivisions have encroached on some deposits, industrial plants and commercial estates have been developed on the strandlines, and most recently there has been marked growth in the planting of vineyards for wine production.

In parts of the Swan Coastal Plain, mining in areas of pristine native vegetation has generated much community opposition. In 2002 Cable Sands proposed mining in the Ludlow pine forest that has scattered remnant specimens of tuart eucalypt trees, a species known for tall imposing forest trees. There is strong community attachment to the tuarts, and even though Cable Sands was able to offer significant conservation offsets that resulted in the Minister for the Environment approving the mining, community action has continued to oppose mining in this area. This is despite the fact that companies had surrendered the strike-extension of the deposit in an area of high-quality native vegetation that allowed the Ludlow National Park to be created in the 1980s.

In order to mine in areas where there are pre-existing developments, the net value of the deposit must pay for the removal, and possibly the postmining replacement, of

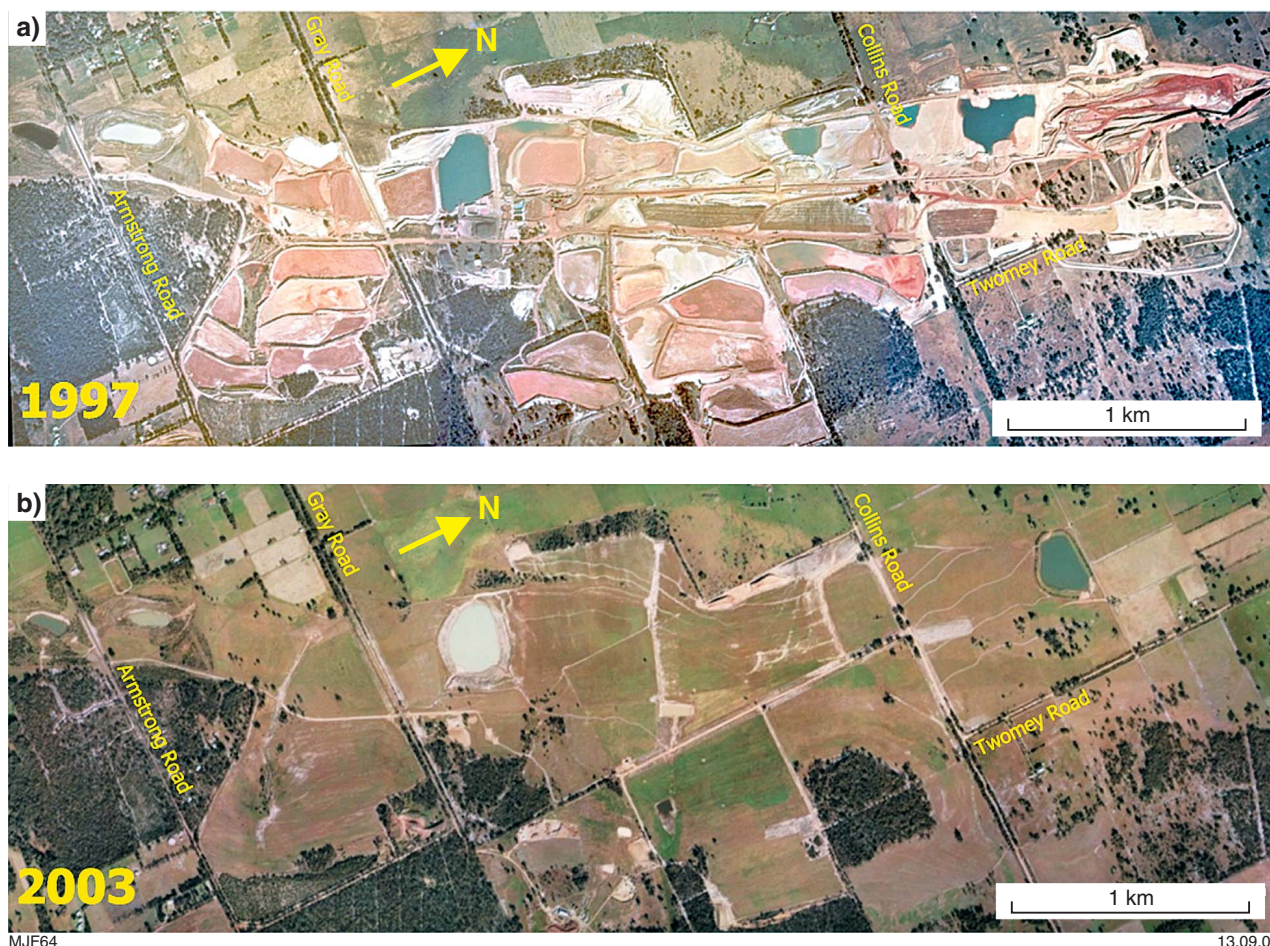


Figure 16. Aerial photographs of Yoganup North mine: a) during mining in 1997; b) in 2003 after rehabilitation (photos courtesy of Iluka Resources Ltd)

the developments. Titanium minerals deposits generally do not have the same dollar value as many base or precious-metal deposits, and mining is unlikely to be profitable if it entails removal of high-value buildings, commercial or industrial facilities, or even intensive agriculture such as vineyards. Examples include both of Alcoa's alumina plants at Pinjarra and Wagerup, the township of Waroona, and vineyards south of Yarloop.

The Department of Industry and Resources, and its predecessors, have facilitated the incorporation of maps showing the location of deposits into a range of State Government land-use planning initiatives in order to protect the deposits until after mining. However, although being quite successful in protecting a number of deposits from being sterilized or fragmented, this process results

in community concerns that real estate developments are being disenfranchised in relation to the mining industry. It creates an interesting application of geology to community-based land-use planning processes. The important economic perspective for Government is that the sterilization of a deposit results not just in the loss of profit by the mining company, but in the total loss of the gross value of the deposit, which may be five to twenty-five times the profit.



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Figure 17. Photographs of the former Minninup titanium minerals mine, south of Bunbury (looking south): a) dune form reconstruction and shaping post-mining in 1990; b) view in 1999 following dune restoration and regeneration of native vegetation

Margaret River wine region

The Margaret River wine region encompasses the area between Cape Naturaliste in the north and Cape Leeuwin in the south, an area locally termed ‘The Capes’. This area is about 100 km north to south and about 20 km east to west (Fig. 18), and contains more than 100 individual vineyards and wineries. Most are within 5 km of the Indian Ocean, which accounts for the strong maritime influence on the climate. The region has about 3000 ha (~7000 acres) of vineyards, which represents only about 2% of Australia’s total area under vines. However, it produces a much larger proportion of the countries so-called ‘super premium’ wines, and Margaret River wines are highly sought after around the world for their delicacy and depth of flavour. In particular, the Cabernet Sauvignon produced by Cullen, Moss Wood, and Vasse Felix (to name just a few!), and the Chardonnays of Leeuwin Estate, Devil’s Lair, Pierro, and Cape Mentelle are consistently recognized as among the very best of Australian wines, and comparable to the best in the world.

The region is characterized by many small, family-owned vineyards and boutique wineries that produce only a few thousand cases of wine each year. Even the largest producers, Cape Mentelle, Leeuwin Estate, and Vasse Felix, each produce only around 50 000 cases per year. In contrast, Lindemans, one of the giants of the Australian wine industry, produces more than 10 million cases of wine per year, including several million cases of its Bin 65 Chardonnay alone, from the Murray River area in northern Victoria, and Penfolds produces more than one million cases per year from the Barossa Valley region of South Australia (Halliday, 1998). To keep this in perspective, the entire Australian wine production of about 500 000 litres per year is surpassed by a single Californian wine maker, Gallo.

Geology

The Capes area is underlain by granitic gneisses and minor mafic granulite and anorthosite of the Leeuwin Complex. The geology of this Proterozoic complex is described in some detail under **Regional geology of southwestern Western Australia** above. To the east the Leeuwin Complex is bound by the Dunsborough Fault, which parallels the coastline about 10 km inland (Figs 2 and 18). With minor exceptions where some younger units overlap the Leeuwin Complex across the fault, the Dunsborough Fault marks the western limit of the southern Perth Basin — a Phanerozoic sedimentary basin more than 10 km thick consisting of Silurian to Cretaceous rocks, which formed in a rift defined by the Darling and Dunsborough Faults (Fig. 2). East of the Darling Fault is the 3.8 – 2.6 Ga Archaean Yilgarn Craton, consisting of granite gneiss and granite–greenstone terranes.

The Leeuwin Complex rocks are unconformably overlain by unconsolidated sand deposits and calcarenite eolianite (‘coastal limestone’) of Pliocene–Holocene age.

Descriptions of these deposits and their stratigraphic relationships are discussed in **Geology of the titanium mineral deposits** above. There are numerous caves developed in the calcarenite of the Tamala Formation along the Naturaliste Ridge — a distinct topographic feature running the length of the Capes within a few kilometres of the coast. The caves bottom on basement gneisses, with the Tamala Formation exceeding 150 m in thickness. The sand and limestone deposits are restricted to a few kilometres of the coast (Fig. 18).

Leeuwin Complex gneisses, Phanerozoic sedimentary rocks, and Yilgarn Craton rocks have all been subjected to prolonged periods of weathering since at least the Cretaceous, resulting in the widespread development of a deep laterite profile, commonly capped by a duricrust of ferricrete. The distribution of ferruginous gravel is shown in Figure 18, taken from detailed GSWA mapping of the area (Marnham et al., 2000; Hall and Marnham, 2002; Leonard, 1991). These gravels are described as ‘cemented ferruginous pisolitic duricrust forming cappings in hillcrests, locally concealed by residual quartz sand’ (Hall and Marnham, 2002). Soils developed over laterite are particularly prized by winemakers.

Almost all the major wineries and vineyards of the Margaret River region are west of the Dunsborough Fault, and east of the sand and limestone deposits of the Naturaliste Ridge, and are therefore largely underlain by Leeuwin Complex granitic gneiss (Figure 18).

Soils

The predominant soil type of the vineyards is gravelly or gritty sandy loam developed from the gneissic bedrock or lateritic cover (Gladstones, 1992; Halliday, 1998), but the complex distribution of Holocene sand deposits, bedrock outcrop, and laterite, mainly related to local drainage and topography, provides a variety of soil types throughout the region.

It has long been recognized by winemakers (and wine drinkers) that geology plays an important role in wine-grape growing and the quality of the wine produced from those vines. The terra rosa soil developed over limestone (e.g. at Coonawarra and Padthaway in South Australia) is a good example of geological influence, but more commonly it is the physical nature of the soils rather than the underlying bedrock that has the largest impact on wine quality. Gladstones (1992) discussed the relative importance of soil’s physical and chemical properties, its mineralogical components, and topography on wine quality.

The most important characteristic of soils necessary for the production of quality wines is good drainage, and this can be achieved in soils derived from a variety of rock types. Terra rosa, derived from limestone, is typically well

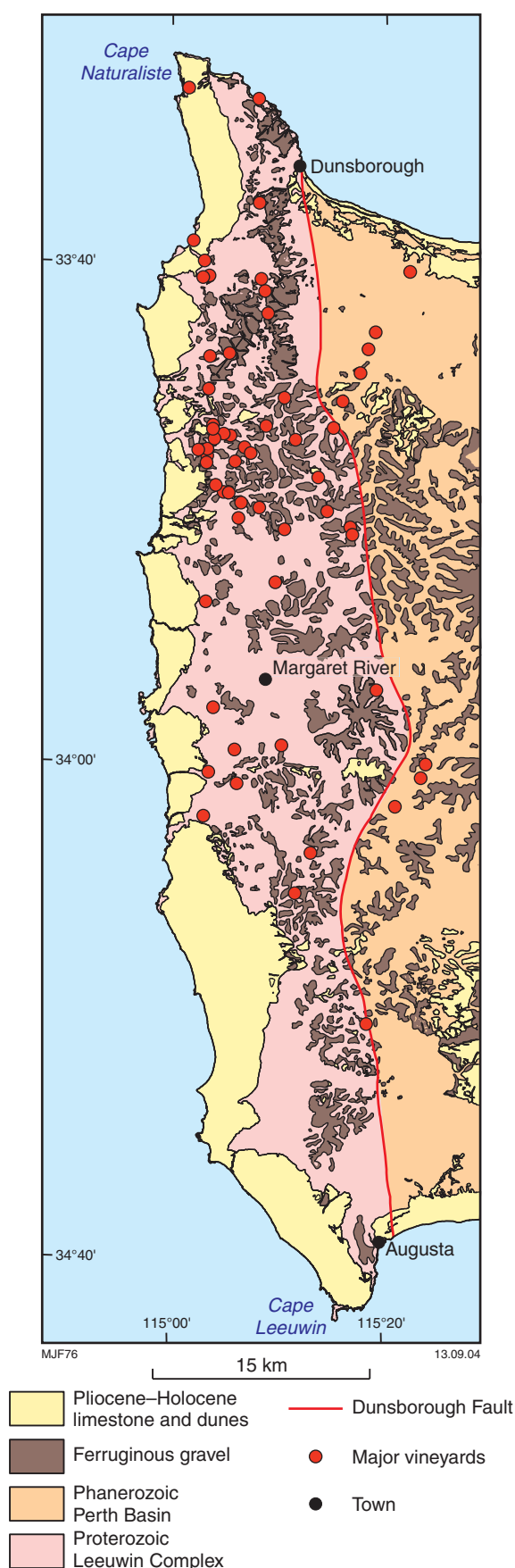


Figure 18. Map of 'The Capes' (Cape Naturaliste – Cape Leeuwin) region, showing the major Margaret River vineyards and main geological features

drained, but the calcareous subsoil can act as a water reservoir to slowly release water by capillary action in dry summers. Porous sandy soils developed from granitic rocks also provide good drainage, as do gravelly alluvial deposits, most famously demonstrated by the fine wines of Bordeaux. However, there needs to be a balance between good drainage and the water retention properties of the soil, particularly in areas (such as France) where irrigation is not used to supplement rainfall in the all important summer ripening period. Topographic considerations are also important in this regard, and the drainage benefits of gentle slopes are generally fully used. Poorly drained areas such as valley floors can easily become waterlogged even if other soil parameters are favourable, resulting in poor vine growth during spring or berry splitting in summer.

Very fertile soils, such as commonly found in valley floors, are generally not suitable for viticulture because they promote over-vegetative early vine growth and poor fruiting (Gladstones, 1992, p. 34). Wines from such sites can be 'simple' in taste, lacking the complexity that is characteristic of high-quality wines.

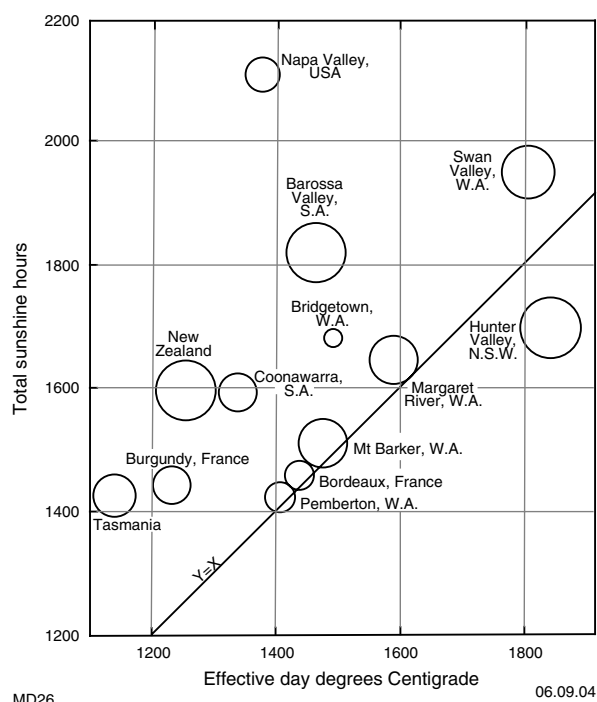
The inorganic chemical characteristics of soil (particularly trace elements, pH, nitrogen, potassium) also have a role in resulting wine quality, although this is not always easy to quantify. It is clear that adequate nitrogen and potassium contents are necessary for yield and fruit quality, but the role of trace elements such as copper, zinc, and manganese is less well known.

Another soil factor of some importance to viticulture is colour, apparently because of differing reflectance of useful light wavelengths back into the canopy from light-coloured compared to dark-coloured (especially red) soils (Gladstones, 1992, p. 36).

Climatic factors in wine production

Gladstones (1992) noted that many different soil types derived from a variety of bedrock types are capable of producing quality wine, and that climatic factors are also critical ingredients that determine the ultimate quality of both red and white table wines. Critical factors include adequate rainfall and a temperature range of 15–20°C during the growing season (September to November in Margaret River), and average mean temperatures of about 20–22°C during the ripening period (October to April).

Gladstones (1965, 1966) compared climates in the world's best wine-growing areas and recognized that the Margaret River area has a climate very similar to the prized region of Bordeaux in western France (Fig. 19), and it was this similarity that led him to recommend the Margaret River area as an ideal prospect for viticulture. J. S. Gladstones recognized that the Margaret River region was less susceptible to spring frosts than the Mount Barker – Frankland River area farther east, which had earlier been identified as the best prospect for viticulture in Western Australia (Olmo, 1956; see Gladstones, 1992, p. 5).



A number of vineyards were established in Margaret River soon after J. S. Gladstones' recommendation, and the region has since become one of Australia's premium wine-growing areas. Field trip participants will get an opportunity to sample typical Margaret River wines and discuss viticulture and wine-making practices with winery staff at several wineries (after mine visits!).

Figure 19. Graph of climate details relevant to wine-grape growing for Western Australia and selected other localities (modified from Gladstones, 1992). Sunshine hours = total sunshine hours for October to April (southern hemisphere) and April to October (northern hemisphere). Effective day degrees = biologically effective day degrees (Centigrade) as defined by Gladstones (1992)

Excursion localities

A number of the sites described below will not be visited, but are included as items of interest along the route. Field trip stops are indicated by locality numbers and shown on Figure 1.

Locality 1: Huntly bauxite mine

Note that it is a safety requirement that all visitors leaving the bus at the working face are to have their own steel-capped safety footwear. Other safety equipment will be provided at the mine site.

The Huntly bauxite mine was commenced in 1976 and is one of two operations of Alcoa World Alumina Australia, currently producing at a rate of 22 Mt/year of bauxite ore. Alcoa's other site at Willowdale produces 8 Mt/year of bauxite ore.

Following the requisite safety presentation, mine staff will conduct us to the mining operation to examine the geology of working faces, and view rehabilitated pits at various stages of regrowth. This is an active mining area and the actual locality visited will depend on operational issues of the day and weather conditions. It is expected we will see:

- mining operations, using loader and trucks, blast-hole preparation and equipment;
- pre-mining area with topsoil stripped off;
- ferruginous duricrust ore immediately below topsoil overburden, which forms a prominent red-brown to yellow-brown capping, with cemented pisoliths, cemented brecciated rock, and massive ferricrete;
- nodular gibbsitic bauxite, with rounded to subangular nodules up to 10 cm across and pisoliths in a finer grained sandy matrix, that is paler in colour than the overlying duricrust. Dark red-brown vertical zones up to several metres wide may be seen, showing the location of former dolerite dykes intruded into the granitic bedrock;
- granular gibbsitic bauxite that is similar to overlying nodular material, except it lacks the nodules;
- top of the mottled clayey layer forming the base of the mine.

Locality 2: Scarp Lookout

After leaving the Huntly mine site, we will drive westwards to Alcoa's Pinjarra alumina plant. En route we will stop at the Scarp Lookout for an overview of the size and extent of the plant.

Beyond the actual plant, to the west, are the red mud tailings dams for storage of the quartz and iron-oxide muds left after solution of the alumina. To the northwest (on a clear day) the heavy industrial area of Kwinana can just be perceived on the horizon about 60 km away, where Alcoa has its Kwinana alumina plant.

On the western horizon is the city of Mandurah, at the mouth of the Peel Estuary, about 25 km from the lookout.

The main land uses of the Swan Coastal Plain are dairy and meat-cattle raising and fattening, with concentrations of equine industry occupations, for both recreational and racing stud horses. Urban developments are proceeding southward from Perth.

Along the base of the escarpment are a number of small titanium mineral deposits, with a relatively large one under the alumina plant. The Perth Basin, under the Swan Coastal Plain, is covered with petroleum exploration licences. This part of the basin is poorly explored, with only four onshore exploration wells drilled about 200 km apart between Perth and Bunbury. The basin adjacent to the Darling Scarp here contains nearly 11 km of dominantly Mesozoic sedimentary rocks. About 300 km north of Perth are a number of producing gas- and oilfields, with recent discoveries having stimulated exploration in the basin, mostly north of Perth.

Locality 3: Pinjarra alumina plant

The Pinjarra alumina plant at the base of the Darling Scarp, on the eastern edge of the Swan Coastal Plain about 80 km south-southeast of Perth, is the largest plant of its type in the world, currently producing 3.4 Mt/year of alumina. A planned upgrade will shortly increase output to 4 Mt/year. The plant uses the Bayer process to extract alumina from the bauxite ore.

Bauxite arrives from the Huntly mine site by a conveyor and is stacked in four 500 m-long stockpiles. The stockpiles are built up sequentially in a number of passes by the stacker to blend the ore. Full-face recovery of ore from individual stockpiles is used to again provide additional blending. Some of the ore is fed into a second storage area for transport by rail to Alcoa's Kwinana alumina refinery.

Bauxite is milled in one of six semi-autogenous mills to $-500\ \mu\text{m}$, converted to a slurry and mixed with lime to precipitate any phosphate. The slurry is mixed with caustic soda and heated to 143°C at a pressure of 200 kPa to dissolve the alumina, leaving the quartz sand and iron oxides to be filtered off as red mud. Alumina is precipitated by a temperature reduction, stimulated by seeding with alumina nuclei. Careful attention is required to ensure the grain size and crystallinity of the alumina is within tight specifications. The alumina is finally fired at 1000°C . It is exported mostly through the port of Bunbury, about 120 km to the south.

The plant recovers only alumina from gibbsite in the ore. About 1% of the ore is boehmite, a monohydrate of aluminium that is insoluble at the P-T-pH conditions used for the gibbsite reaction, and is not recovered in the plant.

Waroona

Twenty kilometres south of the Pinjarra alumina plant, we drive through the town of Waroona, sited on an elevated area at the base of the Darling Scarp. Established in the 1800s as a wayside stop on the road between Perth and Bunbury, the settlers chose a place free from the risk of inundation as would occur on the plains to the west. They chose the top of a titanium minerals deposit! Demonstration drilling in the local sports oval on the town's annual show day has intersected thick black sands. However, the companies have considered it inappropriate to conduct exploration drilling through the town as there is strong opposition to mining other known deposits on the northern outskirts of the town. This is a case of geology being used to site a town based on landform attributes by settlers in the mid-1800s, without understanding the geological background of those forms. The same geological basis is the reason for the deposit to exist there, now sterilized under the high-value township developments.

Iluka Resources Ltd holds the Waroona North deposit on the outskirts of the town, thereby preventing town growth and development. The company is completing mine plans for extraction of the ore, and in seeking to work with the community, it has established consultative arrangements with local Government and community representatives to involve them in planning for the post-mining use of the land.

Donnybrook gold and sandstone

Entering the Darling Range, the route passes through the orchard town of Donnybrook. About 2.5 km south of the township is an historic area of gold mining, and ridges to the north and south of the town are the source of Donnybrook Sandstone for building and facing stone. Gold was first found here in 1897 by prospectors who located alluvial gold and then auriferous quartz veins. Initial crushing of 175 t of quartz vein produced 15.6 kg of gold at an average grade of 89 g/t Au. Production ceased by 1906, with a total of 11 separate mines reported to have produced 26.1 kg of gold at an average grade of 15.5 g/t Au. Additional prospecting was carried out during the depression years of the early 1930s (Forman, 1936). The workings consisted of a number of adits and shafts, and Foreman (1936) referred to working to 12 m depth. Recent tourist developments have publicized and popularized the former workings.

The mineralization is in a northwest-striking band over 3 km, in both Yilgarn Craton rocks and sedimentary rocks of the Perth Basin. Basement host rocks are schist, hornblende gneiss, and quartzite. Overlying these and also containing the quartz vein is the Donnybrook Sandstone — a weakly bedded clean sandstone of Permian age. The Cretaceous Bunbury Basalt is immediately west of the sandstone, and possibly also contains some of the veins. The Bureau of Resource Sciences and Geological Survey of Western Australia (1998), followed by Hassan (1998), related the mineralization to hydrothermal activity adjacent to the Darling Fault. There has been spasmodic exploration since the 1980s by BHP Minerals, BP-Seltrust, West Coast Minerals, and most recently by Range

Resources. Diamond drilling to depths of 400 m intersected only low-grade gold mineralization.

Donnybrook Sandstone, of Permian age (Backhouse and Wilson, 1989), has been quarried from hills just north of the town since the early days of settlement. The pale-brown to buff even-textured sandstone, commonly with weak Liesegang rings, has been described as having 'a restful and relaxing appearance' (Mitcham City Council, South Australia, Newsletter August 2003). It has been used for many public buildings in Perth, the most significant being the present Parliament House. Currently, three producing quarries market the rock locally and throughout Australia as a range of products, including Meteor Stone and Beelarup Stone, for building stone, floor tiles, and facing slabs. An important future use will be the rehabilitation and restoration of the many public buildings that were constructed of the stone. The sandstone is extracted by a variety of methods, including splitting along lines of drillholes, blade-sawing, and using diamond-impregnated wire saws. Recent urban developments northeast of the town has resulted in residents complaining about nearby quarrying activities and the use of their roads by heavy haulage trucks.

Locality 4: Greenbushes tantalum mine

Sons of Gwalia Ltd, our hosts for this part of the trip, intend showing us the geology in the Cornwall and Lithium openpits and walking us through the gravity plant that produces tantalum and tin concentrates. The Cornwall openpit (Fig. 20) will be viewed from a lookout on the southern crest, looking towards the township of Greenbushes behind the screening bund covered with trees across the void. From this lookout the mineralized pegmatite is seen to dip west at about 45° in the far wall, and folded pegmatite can be seen in the eastern wall. Access to the Lithium openpit will depend on mining operations being conducted during the visit and the need for safety in the relatively restricted pit environment. The lithium pegmatite should be accessible as a brilliantly white rock enclosed in hornfels on the floor of the pit.



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Figure 20. Cornwall openpit, Greenbushes (looking north)

Locality 5: Yoganup titanium minerals mine

Iluka Resources Ltd will be the host for a visit to this mine, sited on the Yoganup strandline and within the Yoganup Formation. This mine commenced in the 1960s and originally contained high grades, but was then not mined for many years. Mining is now removing the lower grade envelope surrounding the original high-grade deposit, and is proceeding farther out onto the plain to a lower level deposit. The mine site will eventually be rehabilitated to farmland.

Depending on the pits operating on the day, it should be possible to see:

- the mine sequence of mineralized Yoganup Formation sands, with horizontal planar to low-angle cross-beds, showing various degrees of mineralization. There are local remnant patches of very high grade ore with up to 2 m of almost pure black sands;
- the basal unconformity with the beach sands resting on basement sands of the Leederville Formation;
- the basal conglomerate with pebbles to cobbles of quartzite in mineralized to unmineralized sands, locally with silty or clayey components;
- the local setting with the mineralized sands underlying the basal slope on the Whicher Scarp, which is underlain by ferricrete duricrust and has a thin skeletal soil over rock at a depth of a few centimetres. Consequently, the scarp marks the limit of farming activities and remains covered with native jarrah-marri forest;
- several pits being mined simultaneously in order to generate blended feed with specification for markets. The nature of the deposit, the distribution of the various minerals with various contaminants and the requirements of the market specifications can result in feed being blended from up to six pits;
- the mobile conveyors used to transport ore from a central loading facility near a number of pits to the wet plant;
- clays washed from the ore being processed through thickeners and then spread out in shallow solar drying dams in successive 1 m lifts. These are eventually covered with sand tailings, ripped and returned to the postmining land use. Experimental codisposal techniques are in progress at some sites where the thickened clay slurry is mixed with sand tailings at the point of discharge, with an intention to reduce the area of solar drying needed to handle the fines.
- the wet plant, to see the relatively simple gravity-concentration process used to separate the high-density mineral grains using spiral concentrators.

Locality 6: North Capel dry plant and synthetic rutile plants

Iluka Resources Ltd operates three plants at the one site, about 10 km north of Capel (Fig. 1). The 'dry plant' uses magnetic and electrostatic separators to split the mine concentrate from the wet plant into its constituent minerals. A major issue in these plants is the minimization of dust exposure to staff and others nearby because of the presence of monazite and xenotime with their radioactive

elements. The plants operate with very high specifications in regard to radiation levels and radiation exposures. Plant throughput is nominally 1.0 Mt/year.

Iluka Resources also operates two separate synthetic rutile plants on the site, identified by the inclined rotary kilns. The smaller kiln was completed in 1985 and the larger in 1996. The capital cost for the second plant, referred to as SR2, was \$130 million. The feed for both plants is ilmenite from the company's mines in the Capel area, and coal from mines at Collie, 80 km east of Bunbury. The plants produce synthetic rutile containing about 95% TiO₂, and byproducts of iron oxides and gypsum, using the Becher process.

Waste power from the synthetic rutile process is fed into a cogeneration plant for production of electricity, supplying all electric power requirements of the plant and a surplus, which is sold to the State's Western Power utility. This was built at the time of the SR2 plant construction for a capital expenditure of about \$30 million.

Rehabilitated mine sites at Capel

On leaving the North Capel plant, we travel southwest past the town of Capel. Just past the town, where the highway becomes a single bitumen road, we pass a rehabilitated mine site that has been returned to grazing land use. It can be recognized by the absence of old trees. On the right-hand side of the road is a small lake, which is the final void left after mining. About 93% of the volume of the ore mined and processed has been replaced, allowing the land surface to be returned to a level similar to that before mining.

Locality 7: Canal Rocks, Yallingup

Warning: The coastline in southwestern Australia is dangerous. It can be subject to large swells and king waves and some beaches have strong rips and tidal currents. The gneiss outcrops can become very slippery when wet, and care should be taken when walking on the outcrops. Coastal limestone cliffs are also dangerous and some have collapsed suddenly with disastrous consequences. It is necessary to keep away from these at all times.

At Canal Rocks, felsic gneisses of the Leeuwin Complex outcrop in spectacular coastal outcrops. The gneisses include massive to layered rocks with alkali-feldspar, aegirine-augite, and amphibole. Just north of Canal Rocks, Wilde and Nelson (2001) described hornblende-biotite granite gneiss dated by SHRIMP U-Pb zircon methods at 702 ± 7 Ma, which they interpreted as the time of crystallization of the monzogranite precursor to the gneiss. As discussed above in **Titanium mineral deposits of the Swan Coastal Plain**, the Leeuwin Complex gneisses are one of the probable ultimate sources of titanium minerals in the deposits of the Swan Coastal Plain.

This locality is included in the field trip to give participants an appreciation of the complexity of the Leeuwin Complex, as well as to provide a first look at the rugged Indian Ocean coastline typical of 'The Capes' region.



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Figure 21. Shelly Beach, Bunker Bay, showing the unconformity between Leeuwin Complex gneiss and overlying Pleistocene–Holocene Tamala Limestone



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Figure 22. Sugarloaf Rock, Yallingup

Locality 8: Shelley Beach, Bunker Bay

At Shelley Beach (Fig. 21), K-feldspar-augen granite gneiss of the Leeuwin Complex is unconformably overlain by a coarse boulder conglomerate, and the Pleistocene–Holocene calcarenite of the Tamala Formation. There is a pronounced planar surface to the top of the conglomerate at about 10 m above the current sea level, which is interpreted as a wave-cut platform.

Locality 9: Sugarloaf Rock

Sugarloaf Rock is a small but prominent island of Leeuwin Complex gneiss about 4 km south of Cape Naturaliste (Fig. 22). The rocks on the peninsula immediately south of Sugarloaf Rock comprise pink-pegmatite-banded granite gneiss and grey-banded granodiorite gneiss (Janssen et al., 2003). These rocks are folded into a D_2 antiform cored by the granodiorite gneiss. Migmatite segregations are in both types of gneiss, and discrete amphibolite layers are parallel to the S_1 foliation.

SHRIMP U–Pb zircon ages from both gneisses yield ages of about 730–750 Ma for zircon cores (Collins, 2003) and this is interpreted as the age of crystallization of the igneous protolith. Ages for zircon rims of about 520 Ma are interpreted as related to the upper amphibolite- to granulite-facies metamorphism and migmatite formation (Collins, 2003; see also discussion Wilde and Nelson, 2001; and Janssen et al., 2003).

Locality 10: Minninup rehabilitated mine site

Cable Sands (WA) Pty Ltd mined the beach and dunes at this coastal site for titanium mines between 1988 and 1990, over a length of about 4 km. This stop provides an

opportunity to view the excellent restitution of coastal landforms and vegetation following the mining activity (Fig. 17).

Mining commenced about 1.5 km south of the car park, immediately north of the distinctive rounded hill that marks the end of the regular frontal dune seen in the distance, and progressed to about 2 km north of the car park. The total resource mined was about 4.5 Mt at 12% total heavy-mineral concentrate.

Cable Sands held the mining lease over the dunes. Westralian Sands Ltd (now Iluka Resources Ltd) held the lease over the beach. In order to efficiently mine the deposit, Cable Sands mined and processed all ore from both leases, and provided concentrate to Westralian Sands on a cost basis.

A dredge with an attached floating wet plant was used to extract and immediately process the ore. The dredge-pond level was well above sea level and maintained using groundwater.

Ore on the beach was mined using scrapers that dumped the ore in the mine path for the dredge to consume. Scrapers would race down the beach as a wave receded, load the bowl, and then proceed up the beach before the next wave broke. The scrapers would also return sand tails to the beach, allowing the wave action to level out the surface.

The dune form was recreated similar to the pre-mining shape, using an elevated discharge pipe up to 35 m long, moved and elevated by winch-controlled cables. Rehabilitation was to a very high standard. The recreated dune forms were covered with logs salvaged from the mine path, spread with mulch containing seeds, and then recalcitrant species were planted out by hand. Weed grasses had invaded large parts of the dunes before mining, and much spraying of these during the rehabilitation process has reduced their spread and allowed native species to return.

Figure 17a shows the final stages of sloping the dunes with a bulldozer, looking southwestward towards the start of the mining area.

Since mining was completed, significant quantities of heavy minerals have accumulated on the beach. After mild conditions have prevailed for several weeks, the beach can be covered with a 5–10 cm layer of black sands, implying that a significant accumulation of the minerals is present offshore.

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