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MINES AND WINES OF SOUTHWESTERN WESTERN AUSTRALIA — A FIELD GUIDE

by MJ Freeman and MJ Donaldson

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

Record 2008/10
(Adaptation of Record 2006/20 and 2004/17 with additions)

MINES AND WINES OF SOUTHWESTERN WESTERN AUSTRALIA — A FIELD GUIDE

by
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Perth 2008

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Mines and wines of southwestern Western Australia — a field guide

by

MJ Freeman[1] and MJ Donaldson[2]

Introduction

This field guide has been prepared for participants in the field excursion '*Mines and Wines of southwestern Western Australia*', held in conjunction with 2008 Australian Earth Science Convention, New Generation Advances in Geoscience presented jointly by the Geological Society of Australia and the Australian Institute of Geoscientists held in Perth, Western Australia, in July 2008. 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 five 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.
- The Boddington gold mine currently being prepared to recommence large-scale mining by a joint venture of Newmont and AngloGold Ashanti.
- Premier Coal's Premier coal mine in the Collie Basin.
- Talison Minerals Ltd's Archean pegmatite-hosted Greenbushes tantalum–lithium–tin deposit.
- Cable Sands Ltd's Pliocene to Holocene titanium–zircon heavy mineral sands North Gwindinup deposits near Boyanup.

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 the production plants of alumina of Alcoa and Pinjarra and synthetic rutile of Iluka Resources at Capel. In addition, 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.

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Regional geology of southwestern Western Australia

Southwestern Western Australia has four main tectonic units: the Archean 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 Archean granitic gneiss and linear granite–greenstone terranes that range in age from 3.83 to 2.6 Ga and contain rare zircon grains dated at 4.4 Ga. The exposed craton covers about 390 000 km^2, 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 one 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 Archean 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 and Newmont Mining Corporation.

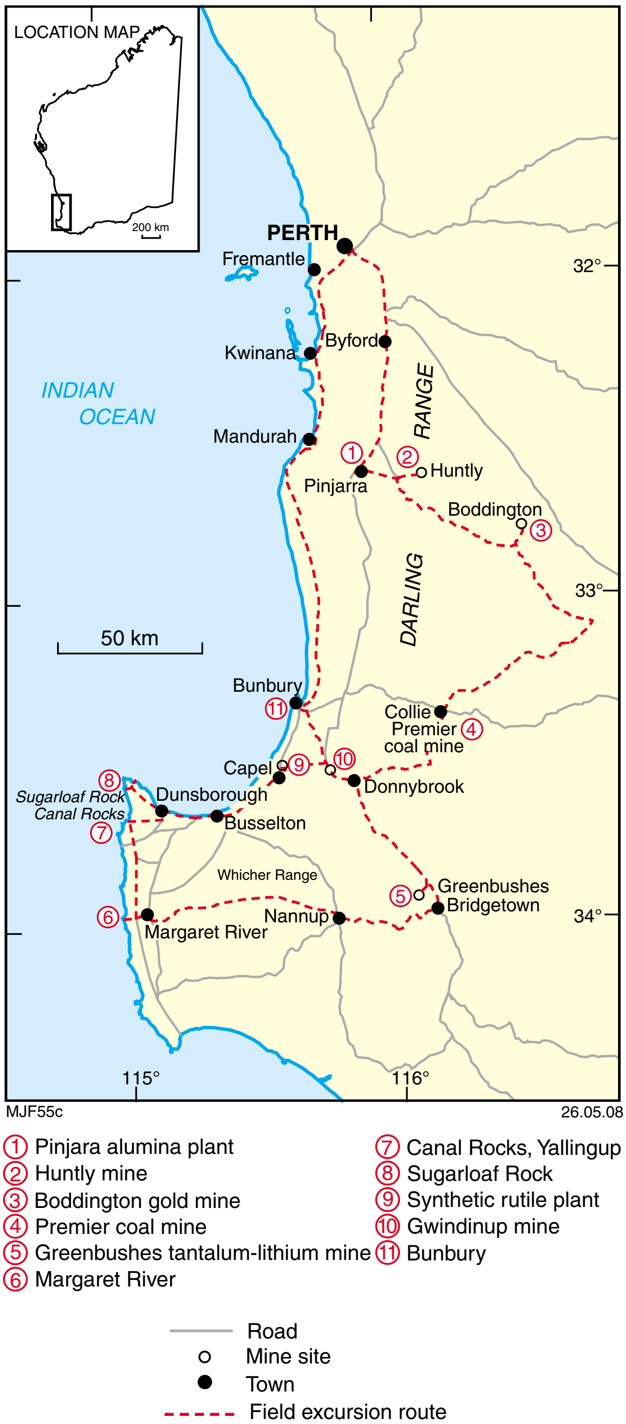

Figure 1. Map of southwestern Western Australia showing towns, roads, topographic features, and excursion localities mentioned in this field guide

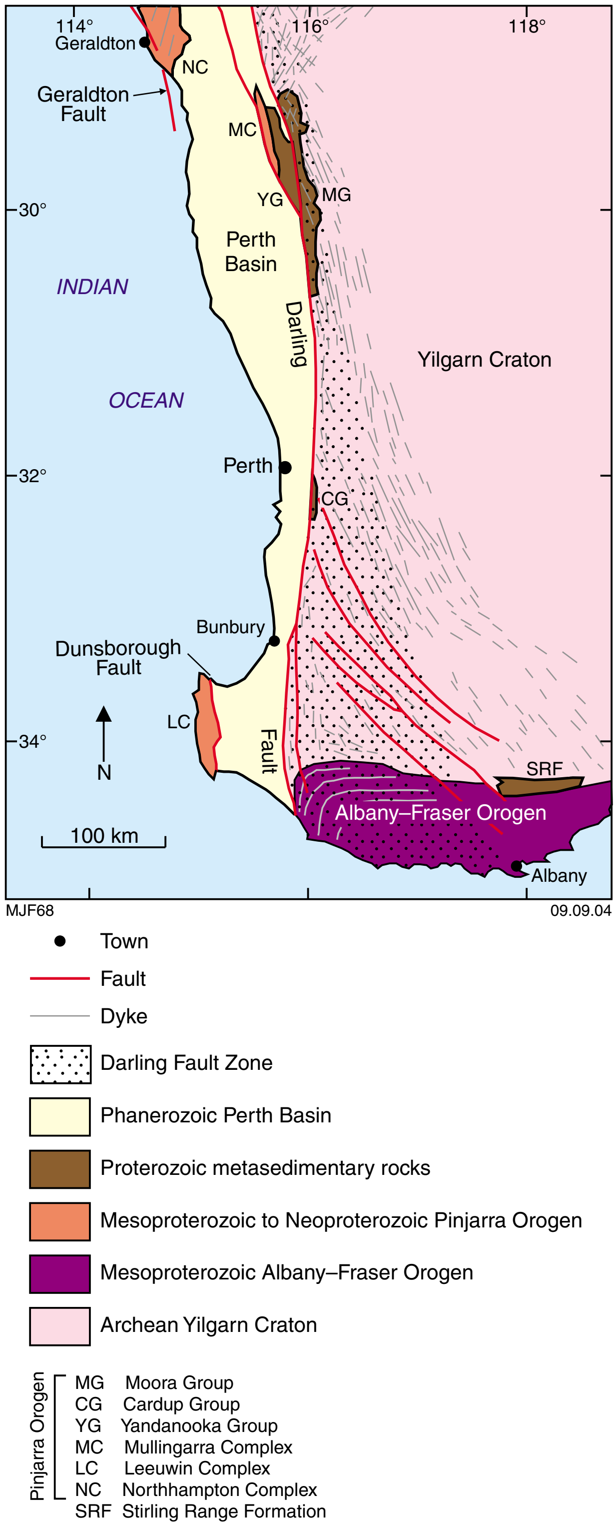

Figure 2. Tectonic units of southwestern Australia (modified from Janssen et al., 2003)

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 in 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 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 Archean 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) have 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 Northhampton, Mullingarra, and Leeuwin Complexes.
- Assumed Proteozoic 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.

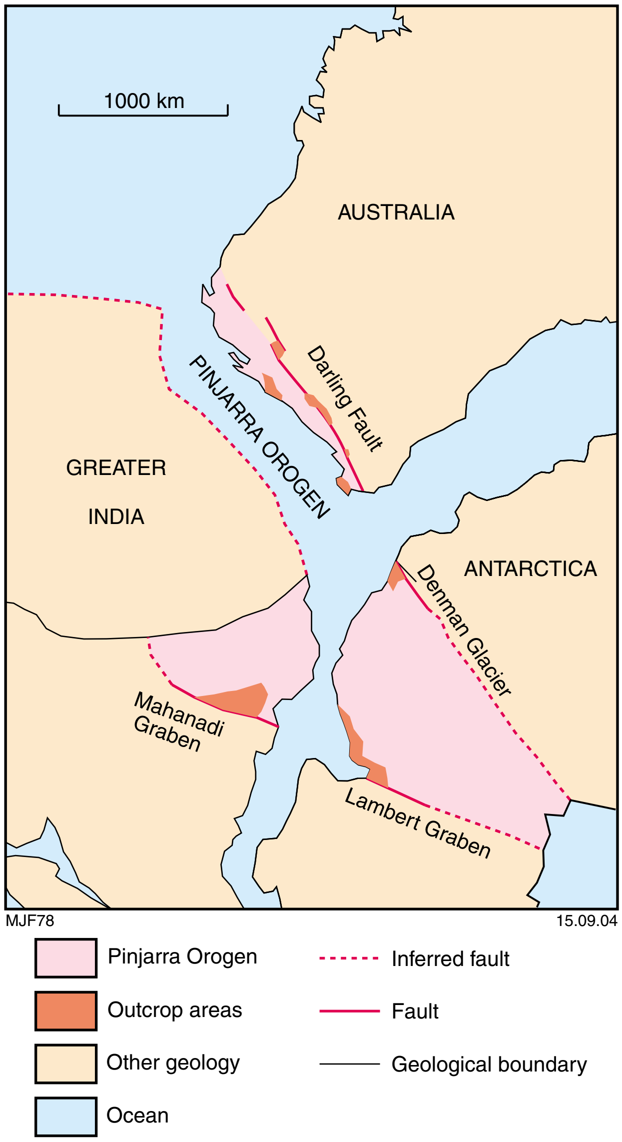

Figure 3. Gondwana reconstruction with parts of Australia India and Antarctica, showing inferred extent of the Pinjarra Orogen (modified from Janssen et al.,2003)

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 Archean 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.

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:

- D_1: A prominent gneissic foliation in felsic gneiss, folded around later structures.
- D_2: North-trending folds at several scales, including the 10 km-scale Naturaliste Antiform and the 50 m-scale Sugarloaf Antiform.
- D_3: Open east-northeasterly trending folds.
- D_4: 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 (Fig. 4) covers an area of about 100 000 km^2 extending west from the Darling Fault to the edge of the continental shelf and from the south coast northwards for 1000 km to where it grades into the Carnarvon Basin, Australia's premier hydrocarbon resource area. The Perth Basin is an elongate north-south rift-trough with a series of subbasins, shelves, troughs and ridges. It contains a sedimentary stack up to 15 km thick that mostly accumulated between Devonian and late Cretaceous times, though with some sedimentation occurring to modern times. The basin overlies the Pinjarra Orogen (Fig. 3).

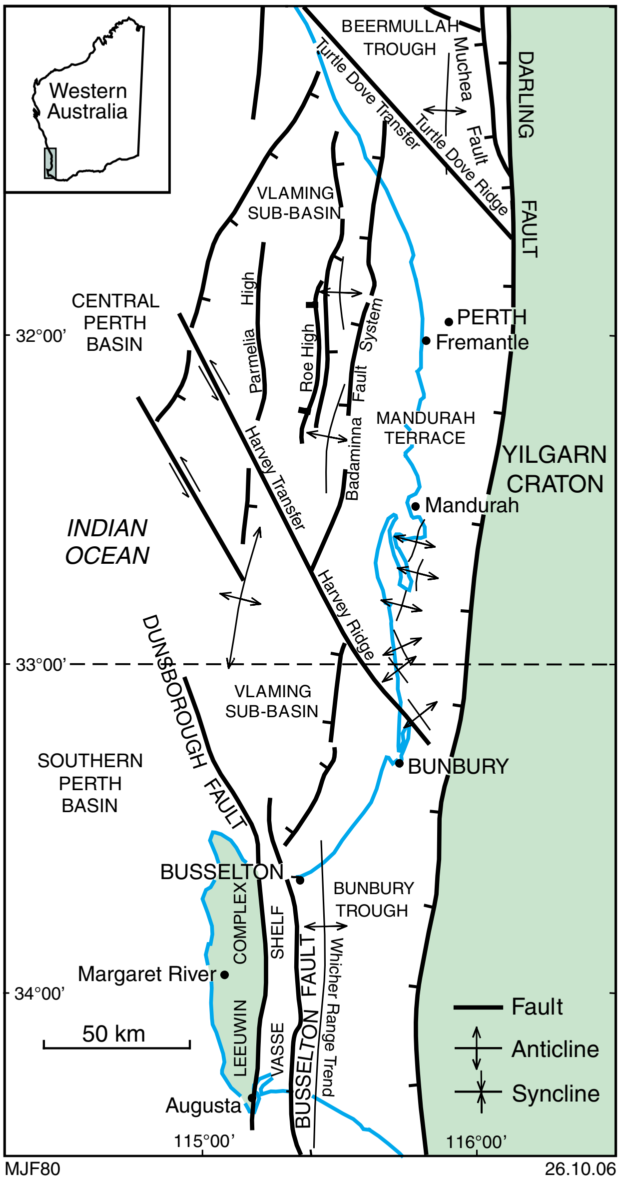

Figure 4. Basin subdivisions and tectonic lineaments of the central and southern Perth Basin (modified from Crostella and Backhouse, 2000)

Very limited outcrops of the weakly-indurated Perth Basin sediments occur, particularly south of Perth, and are restricted to areas where distinctive lithologies occur only as float. The one exception being Bunbury Basalt outcrops. Much of the area is covered by Cenozoic deep-weathering products or eolian sands that conceal the sediments and, therefore, most of the stratigraphic and lithological understanding of the basin is derived from oil wells and water bores.

A comprehensive description of the geology and hydrocarbon potential of the Perth Basin is contained in Crostella and Backhouse (2000), to which the reader is referred for detail.

The Southern Perth Basin is defined (Iasky, 1993) as that 200-km-long part south of the Harvey Ridge, a northwest-trending basement ridge (Fig. 4) and Crostella and Backhouse (2000) refer to it being the area south of Latitude 33°S. Structurally it consists of the:

- Bunbury Trough, containing up to 11 km of Permian-Cretaceous sediment (Iasky, op cit, refers to maxima of 4 km of Permian, 3 km of Triassic, 4 km of Jurassic and 300 m of Cretaceous sediments).
- Vasse Shelf to the west of the trough, containing between 500 m and 3 km of sediment.
- Vlaming Subbasin to the northwest, restricted to offshore areas marginal to the edge of the continental plate.

Figure 5 is an east-west cross section through the Perth Basin at about 33°44'S.

The development of the Perth Basin was strongly influenced by the Darling Fault, with the thickest sediment accumulation in the southern parts being adjacent to the fault in the Bunbury Trough (Fig. 4).

Sediment accumulation commenced in the south Perth Basin in the Early Permian with a diamictite (Mosswood Formation) representing the waning stages of a widespread, continental glaciation. This is overlain by the Sue Group, consisting of five, interbedded, formations dominated either by sandstone or coal measures. Le Blanc Smith and Kristensen (1998) defined the Sue Group to contain a lower Rosabrook Coal Measure and an upper Redgate Coal Measure, with both sandwiched within sandstone formations. Overlying the Sue Group is an earliest Triassic Sabina Sandstone (up to 500 m thick), followed upwards by the Lesueur Sandstone (up to 1700 m), and then in turn by the Jurassic Cattamarra Coal Measures (300 m to 1100 m) and Yarragadee Formation (up to 1500 m-thick). The next unit upwards, the earliest Cretaceous Parmelia Group, is overlain by a well-documented early Neocomian ‘Main Breakup’ unconformity. The Otorowiri Formation was deposited on the unconformity coinciding with the beginning of the tectonic activity that resulted in the marine flooding of the Perth Basin and ultimately the Neocomian fragmentation of Gondwana. At least two valley-infilling basalt flows then followed in quick succession at the top of the Parmelia Group, with the basalt flowing from undocumented vents possibly off the present south coast, north past the present site of Bunbury and then continued offshore for at least another 60 km. Dolerite sills intersected in several drillholes in the south Perth Basin are thought to be coeval with this basalt.

Overlying the basalt is the early Cretaceous Warnbro Group, deposited in a marine environment over the heavily faulted and eroded Parmelia Group and older units. This includes the economically important Leederville Formation, currently being investigated as a major groundwater resource for Perth’s future water supply. The Warnboro Group is up to 730 m onshore, but thickens offshore to nearly 1400 m in the Vlaming Sub-basin.

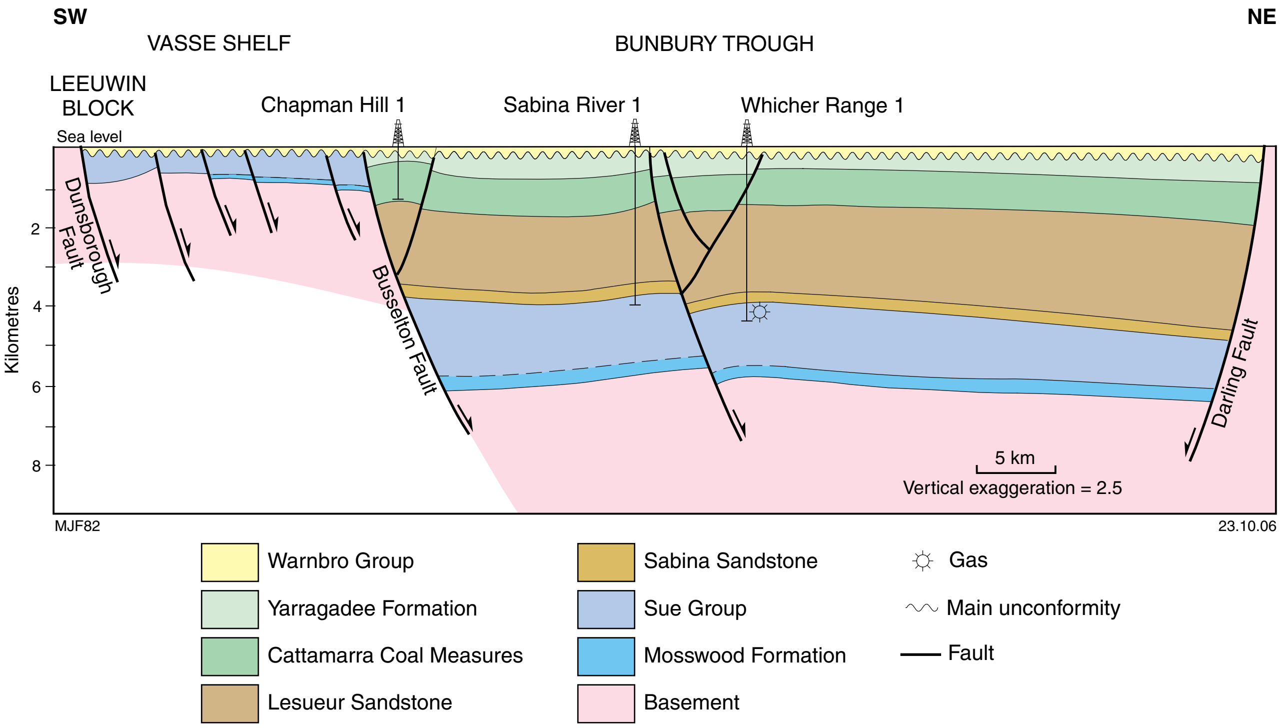

Figure 5. Structural section across Vasse Shelf and Bunbury Trough, southern Perth Basin (after Crostella and Backhouse, 2000)

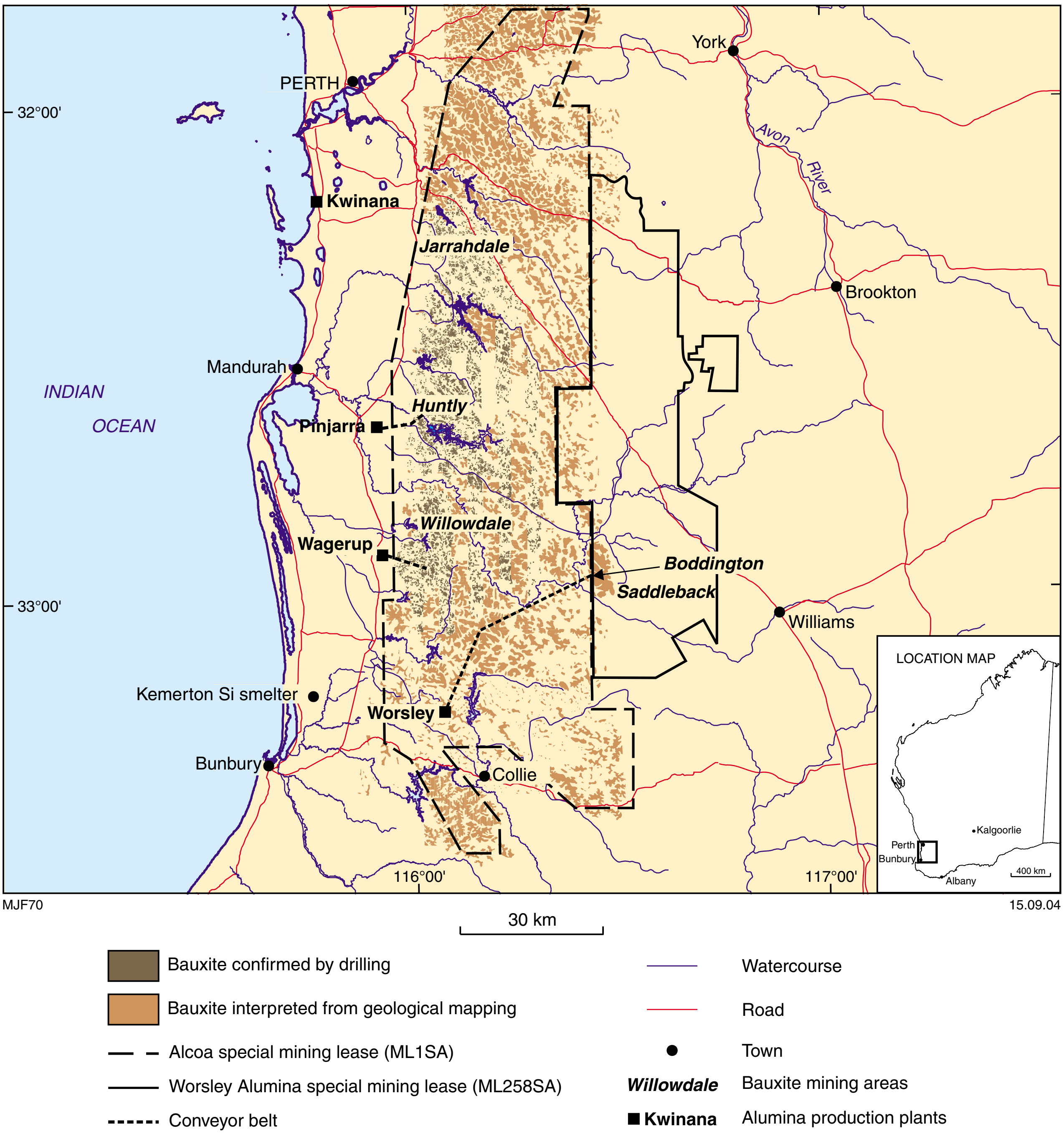

Figure 6. Map showing the extent of the Darling Range bauxite deposits, mining plant areas and State Agreement mining leases

These units are now overlain by Holocene coastal eolian sands that range from quartz rich to lime rich. Older lime-rich dunes are cemented by meteoric processes into eolian limestones (Tamala Formation).

The structure in the basin is dominated by north-trending normal and north-northwest-trending strike-slip transtensional faults (Fig. 4) related to the early Neocomian breakup tectonism as India split off and drifted west from the western margin of the Perth Basin.

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 prior to its subduction under the Himalayas (Sircombe and Freeman, 1999; Cawood and Nemchin, 2000).

Hydrocarbon production from the Perth Basin has so far been dominated by gas (supplied to the Perth market since the 1970) and more recently oil (trucked to Perth since 2004) from the Dongara region, located approximately 300 km north of Perth. Exploration in the southern Perth Basin in the 1970s located the Whicher gasfield, which though potentially large (4 trillion cubic feet; $10^{11}m^3$ in situ), and in new wells generates economic flows, does not maintain the flow rates.

Hydrocarbon production from Western Australia and offshore Commonwealth waters is rapidly rising. In 2007 total hydrocarbon output was valued at $16.7 billion. The industry paid directly $737 million in royalties.

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 rossa 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. 6).

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 more accurately considered to be a dissected plateau (Churchward and McArthur, 1980). Most of the plateau is capped with laterite with the duricrust and related materials of the lateritic profile commonly containing more than 20% Al_2O_3. This constitutes a widespread and valuable bauxite resource, currently reported 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.), which 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 of them in these forests. The presence of this flora is an important consideration in bauxite mining and rehabilitation.

Basement rocks underlying the lateritic profile include Archean igneous and metamorphic rocks of the Yilgarn Craton. In the area of the Huntly mine (Figs 1 and 6), the Archean 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 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}Pb–^{206}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 Ltd 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 (Av. Al_2O_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 it excluded private property. Scout drilling identified mineable deposits in the Jarrahdale–Dwellingup region, culminating in the delineation of 37 Mt containing 33% Av. Al_2O_3. Bulk sample testing demonstrated that the bauxite could be treated economically. In late 1961 the Aluminium Company of America (Alcoa) joined WANL, thereby contributing aluminium mining, smelting, and marketing expertise and development funds in order to accelerate 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 mining at Jarrahdale was established, Alcoa developed two new mines at Huntly and Willowdale (Fig. 6), 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 progressively closed down 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 and identified thick resources there. In 1979, Worsley Alumina Pty Ltd (WAPL) was created to develop this area as 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 currently transports ore by a 51 km conveyor belt to an alumina refinery at Worsley, near Collie.

* Available Al_2O_3 (Av. Al_2O_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).

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. 7). 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 7 shows an idealized lateritic profile which in the Darling Range, averages about 20 m in thickness. Not all the zones are necessarily present at a particular locality due either to their removal by erosion or to prevailing 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 the former is stockpiled for rehabilitation. This horizon also contains tree roots, rootlets and organic carbon, any or all of which 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. 7):

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 with the duricrust and friable fragmental unit constituting 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 two metres thick.

Duricrust (Fig. 8a) 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

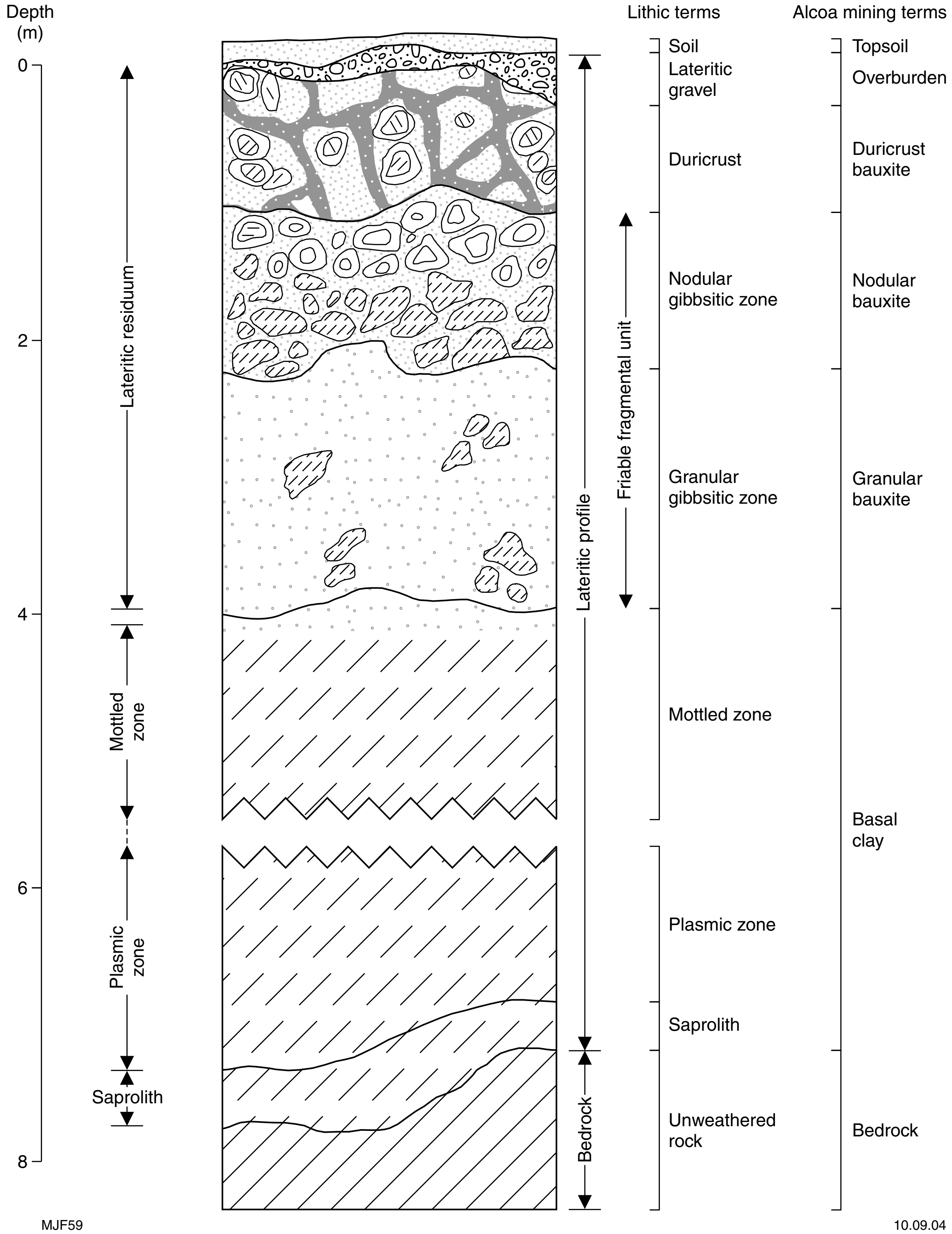

Figure 7. Generalized lateritic profile for Darling Range bauxite deposits (after Hickman et al. 1992)

is commonly one to three metres thick, but over mafic volcanic rocks of the Saddleback area it is typically about five metres 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 in order 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, rich in iron oxide compared to adjacent granite-sourced laterite. The **nodular bauxite zone** (Fig. 8b) contains nodules ranging from about 2 cm to10 cm and locally

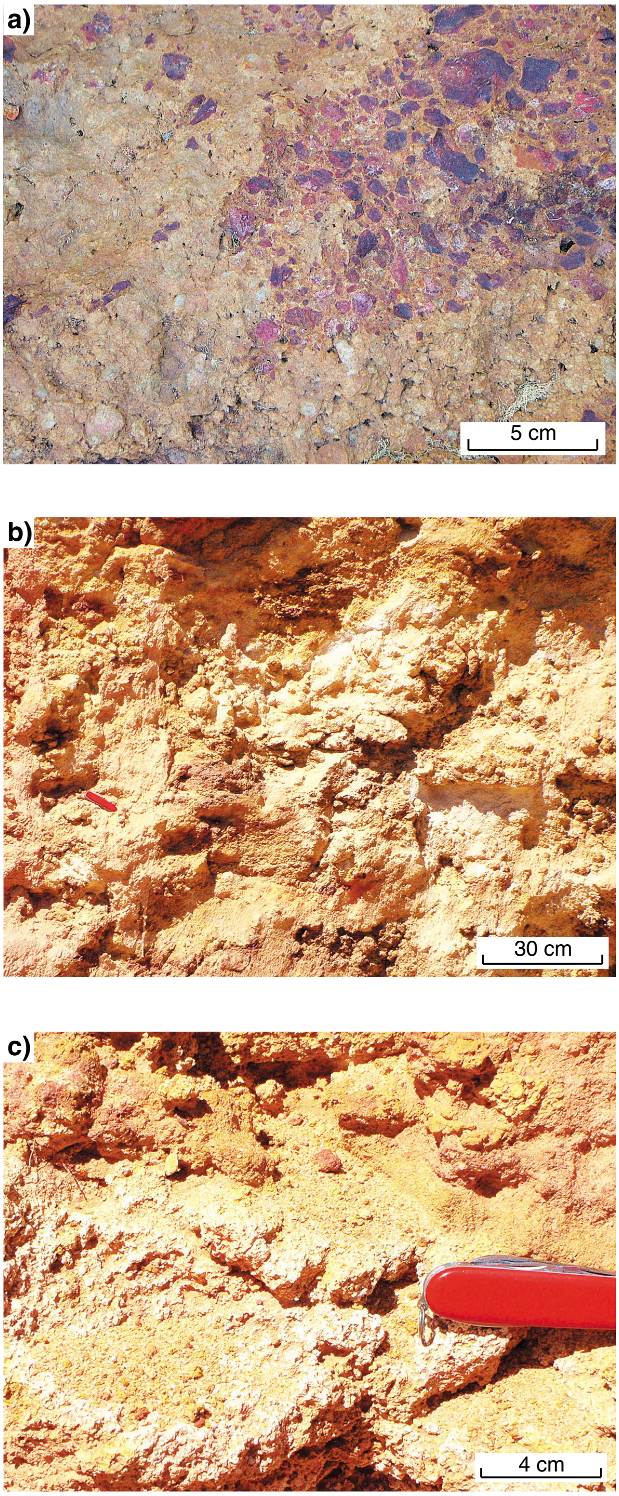

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Figure 8. Photographs of bauxite at Huntly mine site: a) duricrust with angular clasts of maghemite in gibbsitic ferricrete; b) nodular bauxite zone of friable fragmental unit; c) granular bauxite zone of friable fragmental unit

may contain 'floaters' of duricrust up to about one-metre across. Nodules are dominantly gibbsite and quartz, and are stained brown by iron oxyhydroxides. The **granular bauxite zone** (Fig. 8c) 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 two metres 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 one to five metres but can also 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 this is much thinner where the basement rock is dolerite. Within the lateritic profile dolerite remnants form unweathered spherical to subspherical corestones up to several metres in size.

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 of the laterite in a railway cutting at Jarrahdale particularly in relation to the parent material. Figure 9 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 dominate 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. 10). Aluminium is strongly enriched in the upper part of the laterite profile in comparison to the bedrock (Fig. 10b), 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 Av. Al_2O_3. Iron is strongly concentrated in lateritic duricrust and the friable fragmental unit, and is higher over dolerite bedrock than granitic bedrock (Fig. 10c).

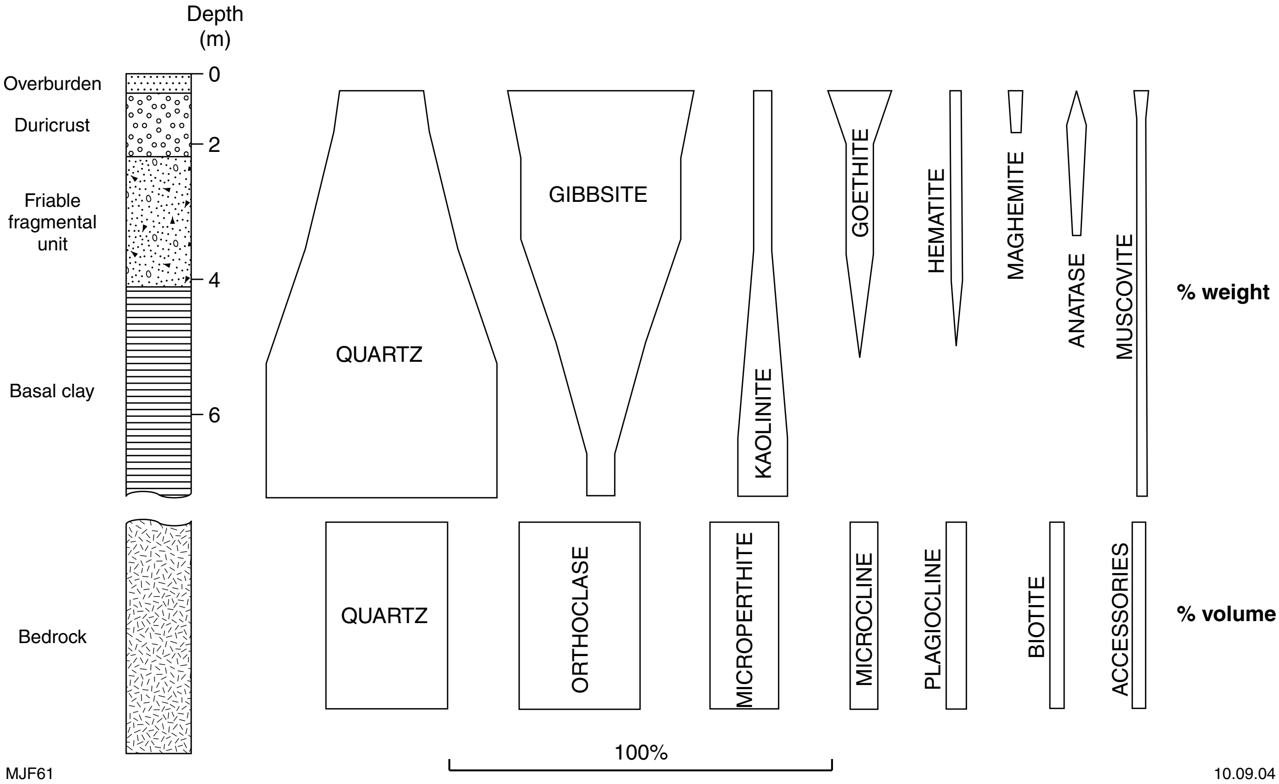

Figure 9. Generalized lateritic profile for Darling Range bauxite deposits (after Hickman et al., 1992)

Silica concentrations in the laterite profile are more related to bedrock chemistry than iron concentration. Quartz is retained through the profile, although surface grains 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, leading to 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.

Table 1. Chemical composition of bauxite and ferruginous laterite in the Darling Range

	Mount Saddleback		
	Darling Range bauxite derived from granite	*Ferruginous laterite derived from dolerite*	*High-iron, low-quartz bauxite derived from mafic rock*
		Percentage	
Total Al_2O_3	40.5	16.6	35–45
Av. l_2O_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_2O_3	10.0	52.4	22–32
TiO_2	1.2	2.3	2–3
Loss on ignition	23.6	17.1	22–2

SOURCE: after Hickman et al. (1992)

NOTES: Available Al_2O_3 (Av. Al_2O_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 loss (Hickman et al., 1992)

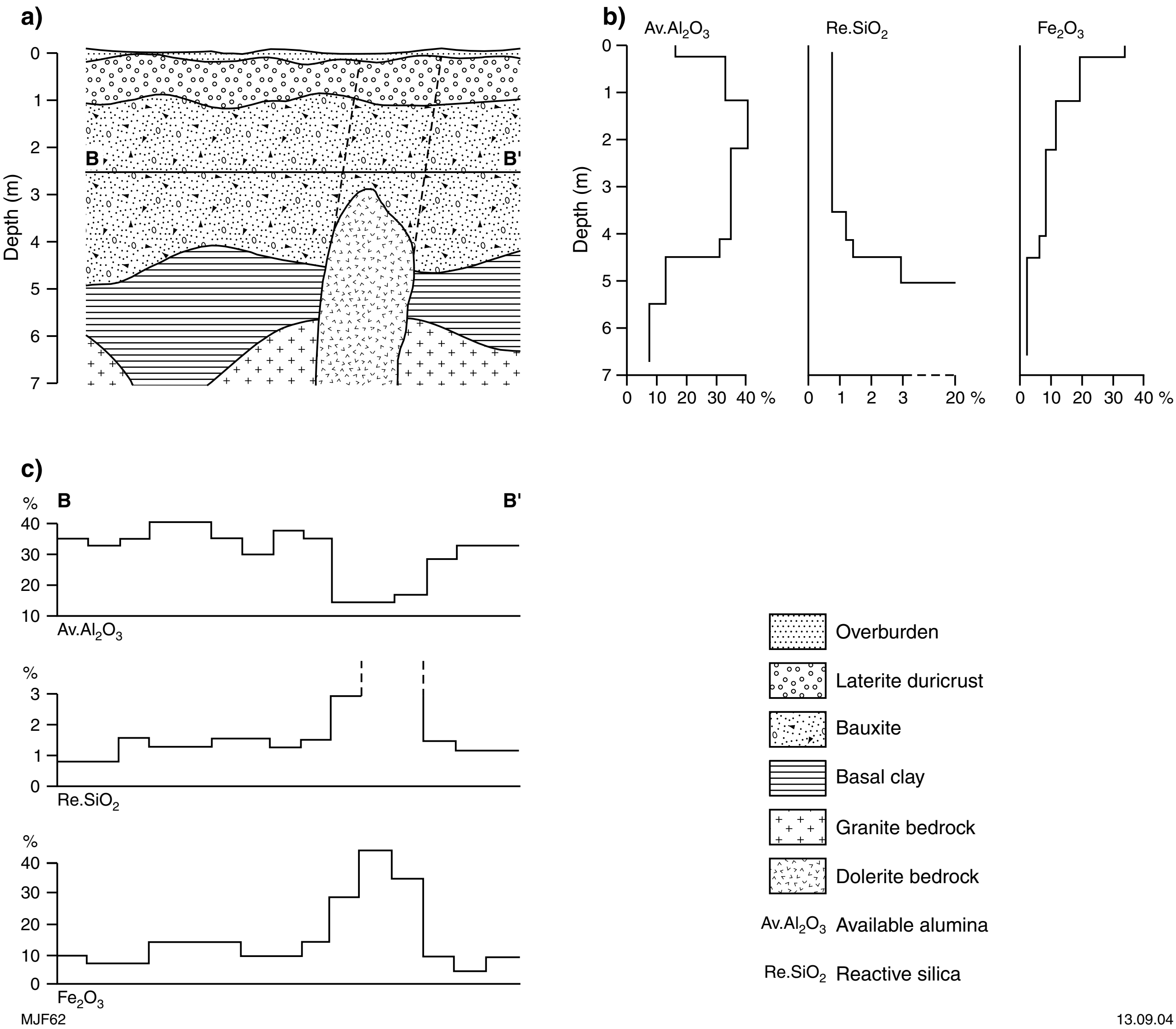

Figure 10. Chemical composition of a bauxite profile: a) cross section through lateritic profile above granite bedrock intruded by dolerite dyke; b) compositional profile with depth; c) lateral compositional variation across granite–dolerite bedrock (after Hickman et al., 1992)

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 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 therefore has 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 have 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:

- Av. Al_2O_3 >27.5%
- Re. SiO_2 <2.5%
- minimum thickness of two metres

- 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 km^2 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 two to five-metre wavelength and an amplitude of up to one metre. 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 Fe_2O_3 and Al_2O_3 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. Al_2O_3 (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.).

As at January 2003, proved–probable reserves at Worseley 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 2007 totalled 12.2 Mt, with a reported value of $4.7 billion for an average of $385/tonne. This is about 20% of world production and nearly70% of Australia's total alumina production. Since mining commenced in 1963 the industry has produced 228 Mt of alumina from the Darling Range.

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 about five years ahead of mining on an intermittent campaign basis. 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 at one metre below the depth at which the bit strikes clay.

Samples are analysed for Av. Al_2O_3, Re. SiO_2, Fe_2O_3, SO_4^{2-}, 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 11 shows stacked cross sections of part of a deposit, with cumulative downhole histograms of Av. Al_2O_3 and Re. SiO_2 values averaged from the top of the duricrust to the base of each drillhole sample plus the planned floor level and a batter slope.

Pre-mining environmental issues

Much of the Darling Range forest is infected with *Phytophthera 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 vehicle is permitted to leave an infected area without first 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 as habitats for fauna in rehabilitated areas. Before 2004 the remaining nonmerchantable timber was cleared and burned. However, much of this is collected and used in a silicon smelter operated by Simcoa at Kemerton, just northeast of Bunbury. Such vegetation usage displaces the use of higher-quality timber that was previously cut for the smelter, thus reducing the environmental impact of two mining-related operations.

Topsoil and then overburden are removed separately, initially using scrapers and then the hollows in the top of the duricrust are cleaned out with backhoes. The

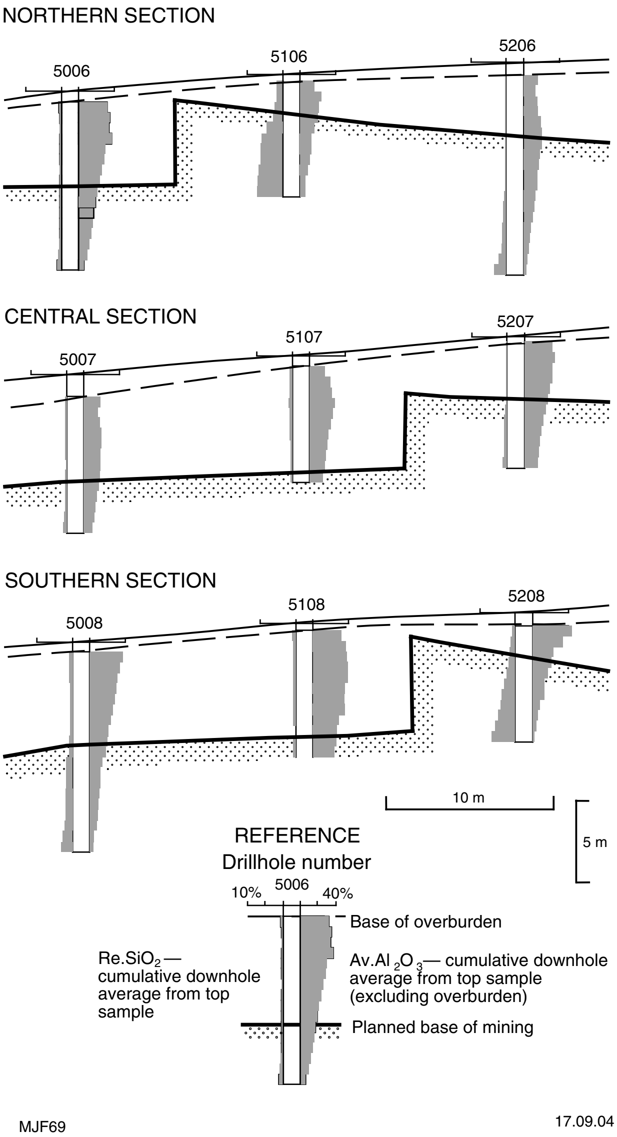

Figure 11. Stacked cross sections of pre-mining grade-control drillholes through the bauxite deposit at Huntly. Profiles show Av. Al_2O_3 and Re. SiO_2 grades as cumulative averages downhole from the base of overburden. Drillholes are on a 15 m × 15 m grid (source: Alcoa World Alumina Australia)

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 for approval before clearing operations commence. This group comprises representatives of the Department of Industry and Resources; the Department of Conservation and Land Management; and the Water Corporation.

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 three metres. Hydraulic excavators then load the bauxite into trucks for transport to crushers. The hauling fleet consists of 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. 6). The conveyor is extended each time the crushing locality is changed. A move to a new site at McCoys is planned for late 2004. 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 the 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 that of 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 the winter months.

A government 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 12 shows an area of mining and infrastructure at Huntly and the same area four years later when vegetation has been re-established.

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Figure 12. 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)

Boddington Gold Mine

The Boddington gold mineralization is located in the Saddleback Greenstone Belt, a supracrustal fault-bounded block located within the granitoids of the Yilgarn Craton. It is located 100 km south-southeast of Perth.

The Boddington Gold Mine was initially mined in two operations; an eastern mine operated by the Worsley Alumina joint venture partners and a western mine (referred to as the Hedges Gold Mine) operated by Hedges Gold Pty Ltd, a wholly owned subsidiary of Alcoa of Australia Limited. Initial mining of the oxide ore by open cut operations and higher-grade shoots by underground methods closed in 2001. However, a large low-grade resource in the fresh rocks is currently being developed for a second, major phase of extraction. At the time of the excursion, plant construction will be proceeding and pre-stripping of overburden for the major opencut mine will have commenced.

Regional setting and history

The Saddleback Greenstone Belt is 35 km long (NNW-SSE) and up to 12 km wide and is located within granitoids of the Western Gneiss Terrane of the Yilgarn Craton (Fig. 13)

Wilde (1976) identified the presence of the Saddleback Greenstone Belt rocks during the Geological Survey of Western Australia's 1:250 000-scale geological regional mapping program. Subsequently, Davy (1979) conducted a regional geochemical sampling and analysis program and defined a base metal and gold geochemical anomaly in the vicinity of the present mine area.

Reynolds Australian Mines Pty Ltd geologists then conducted surface chip sampling of the weathered materials and confirmed the presence of a gold anomaly. Vacuum-drill samples, which had previously been obtained by Worsley Alumina Pty Ltd during exploration for bauxite, were re-analysed for base and precious metals, thereby allowing for the calculation of a geological resource to be completed — estimated to be 15 Mt at 2.77 g/t gold.

Aircore, reverse-circulation drilling on a 50 by 50 m grid, vertically to refusal (bedrock), was completed between 1981 and 1984 totalling 2551 drillholes for 87 000 m. This led to the calculation of a mineable reserve of 45 Mt at 1.8 g/t gold with a 0.5 g/t cut-off.

Geology

The greenstone sequence of the Saddleback Greenstone Belt is subdivided into the Hotham, Wells and Marradong formations and includes marine to felsic volcanics, pyroclastics and sediments. The sequence is steeply dipping and faulted, and metamorphosed to greenschist facies (Symons et al., 1990).

The margins of the granite-greenstone terrane appear faulted except in the southwest and a little of the eastern parts where Wilde and Low (1980) considered them to be intrusive contacts.The sequence is dated at 2650 to 2670 Ma (Wilde and Pidgeon, 1986), which is similar to the greenstones of the Eastern Goldfields Province.

Lithology

The greenstones are divided into three formations:

1. *Hotham Formation* of metasediments and minor volcanics, consisting dominantly of siltstone with tuffs and agglomerate.
2. *Well Formation* of felsic to intermediate volcanic rocks including extrusive flows and volcano-sedimentary rocks.
3. *Marradong Formation* of mafic volcanic rocks, dominated by basaltic-composition rocks and interbedded, intermediate volcanic rocks and metasediments.

Gold mineralization is primarily contained within the Wells Formation. Symons et al. (1990) have documented the range of metalliferous minerals within the deposit. The host rocks were described by Allibone et al. (1998) as having major and minor chemical element signatures of an island arc tectonic setting. Immediately east of the minesite but within the greenstones, is a monzogranite intrusion with elemental signatures reflecting its genesis by melting of mid-crustal rocks in an intraplate setting (McCuaig et al., 2001)

The volcanics and sediments are intruded by diorite and rare, ultramafic intrusives and late-stage, crosscutting Proterozoic-dolerite dykes. The terrane area has an extensive deep-weathered surficial veneer and outcrop of the basement rocks is very limited. This is the reason why the rocks and their contained orebody were not located, until relatively recently, in a state (i.e. Western Australia), which had been extensively prospected for gold over the course of the previous century.

Symons et al. (1990) referred to five broad zones within the regolith that are, from the surface downwards:

1. *Lateritic gravels* — unconsolidated iron-rich pisoliths and gravels in a sandy or silty matrix.
2. *Hardcap laterite* — ferruginous and bauxitic indurated laterite. Relict bedrock clasts may be preserved.
3. *B zone laterite* — a friable, unconsolidated, yellow-brown to red-brown bauxitic layer in which the original rock textures have been destroyed.
4. *Clay zone* — kaolinitic clays displaying marked local variations in the degree of ferruginization, silicification and kaolinization and containing relict bedrock textures and quartz veins. Goethitic horizons occur throughout the profile. The upper portion of the clay zone is ferruginous to hematitic and commonly displays Liesegang rings.
5. *Lower saprolite* — the gradational zone between fresh bedrock and the overlying clay zone. Relict basement rock textures are preserved.

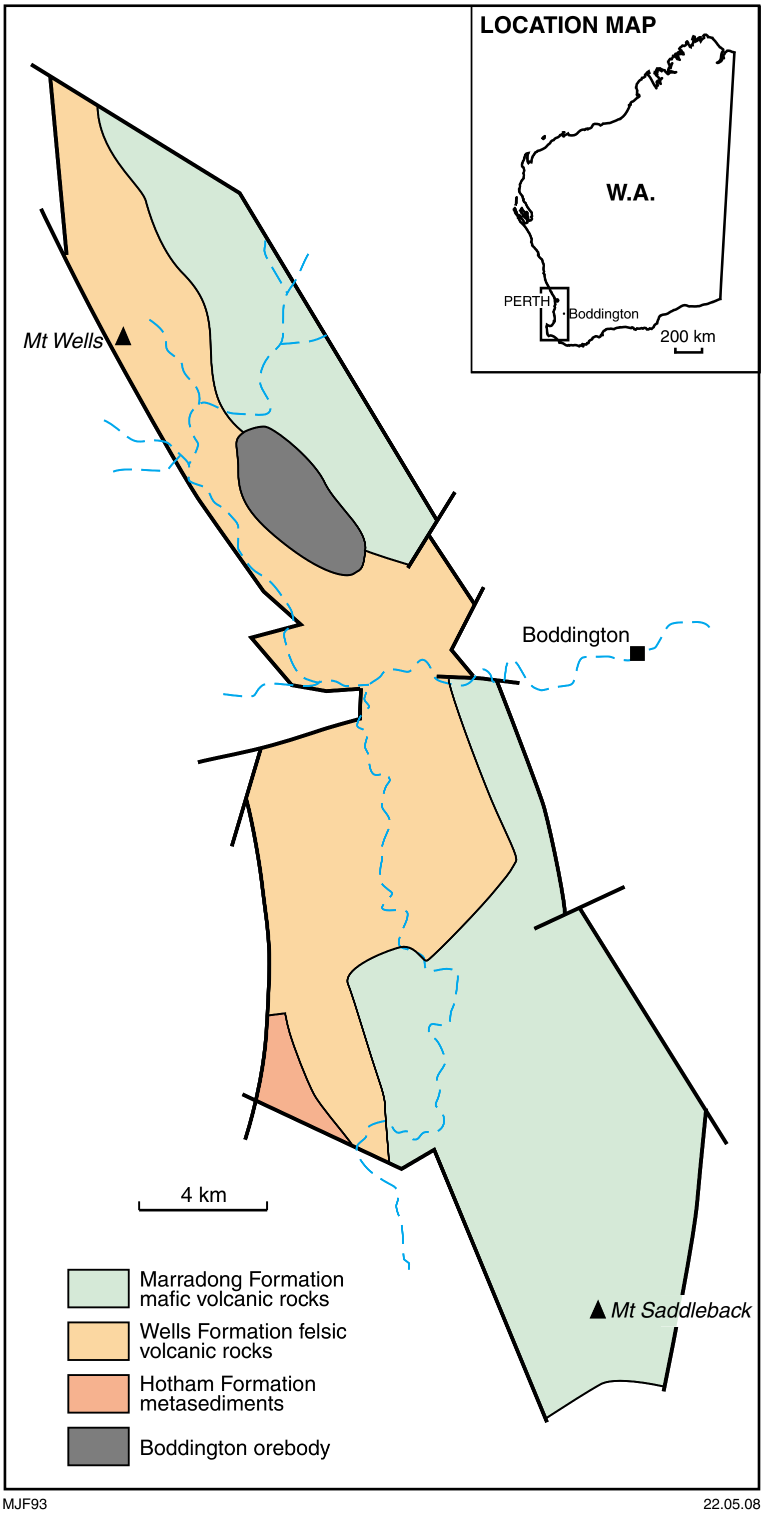

Figure 13. Generalized geology of Saddleback Greenstone Belt

Le Gleuher (2008), after Anand (2001), refers to six zones as follows:

1. Saprock.
2. Saprolite.
3. Clay zone, that contains red and white mottles.
4. Bauxite zone.
5. Duricrust, which in turn is considered as comprising two parts (i) a fragmental component with angular concretions up to three centimetres across and (ii) a pisolitic-nodular duricrust with maghemite-hematite cores set in a gibbsitic matrix, up to 25 mm in size.
6. Overlying soil.

Approximately 30% of the gold mineralization in the weathered zone occurred as a blanket within the hardcap and B-zone laterite; the upper ferruginous part of the clay zone and 70% within the lower clay and lower saprolite zones. The lateritic gravels contain anomalous gold concentrations but are generally discarded as overburden. The gold occurs as discrete grains, usually from 1 to 10 μm in diameter and is depleted in the upper-hardcap profile.

The primary mineralization is hosted within 2715–2690 Ma diorite-andesite and monzonitic rocks. Earlier mineralization is related to widespread zones of silica-biotite alteration dated at 2700 Ma (Stein et al., 2001) and later gold is in complex quartz(–albite–molybdenite–clinozoisite–chalcopyrite) veins (McCuaig, 2001) that give a Re–Os (on molybdenite) date range of 2625–2615 Ma.

Structural geology

Three generations of northwesterly-striking, ductile shear zones cut the Saddleback Greenstone Belt. Allibone et al. (1998) describe a steeply-plunging stretching lineation and asymmetric strain shadow around porphyroclasts with northeast-side-up dip-slip movements in D_1 and D_2 shears. These shears have different minerals and mineral relationships that demonstrate different generations of movement. Ultramafic intrusives are discordant to D_1 and D_2, implying that they postdate these two events. However, the ultramafic rocks contain alteration and deformation zones — now as talc–chlorite schist related to more widespread foliation in surrounding rocks. This is interpreted as representing D_3 deformation. Allibone et al. (1998) recognized D_4 deformation in the form of numerous west-southwest-striking brittle faults cutting all rocks older than 2675 Ma and including the D_1–D_3 shear zones, which are concentrated to a kilometre-wide zone within the mine itself. They interpret a sinistral movement along these faults.

Mineralization and geochemistry

The original mining was focussed on the secondary mineralization. The new operation being developed will focus on the primary mineralization within the bedrock. There are several styles of mineralization present in the deposit implying a complex petrogenesis in both the primary and secondary concentrating processes. Davy and EI-Ansary (1986) concluded that the gold distribution within the clay profile was redox and watertable related, but sampling in mine workings confirms that the distribution of gold within the clay zone reflects a primary control.

Allibone et al. referred to seven stages in the development of the deposit. Of those, only the first and last phases are associated with the accumulation of the mineralization as described below:

Early molybdenite(–chalcopyrite)-bearing veins: These are quartz–plagioclase–molybdenite(–fluorite veins) with traces of chalcopyrite and pyrrhotite — but lacking gold. They infer these are associated with a shallow-level intrusive emplaced between about 2714 and 2696 Ma.

Au–Cu–Mo–W mineralization during movement along D_4 faults: These contain two types of veining: i) quartz-dominated veins containing molybdenite, pyrite and gold and ii) clinozoisite–biotite–pyrrhotite–chalcopyrite veins with gold, and the latter veins cut the former.

Higher grades of Au (8–50 g/t) are related to the presence of a number of ultramafic dykes and the D_4 faults. Lower-grade mineralization (2–4 g/t) is hosted by narrow veins of variable mineralogy, but dominated by biotite–actinolite–chalcopyrite–pyrrhotite assemblages.

Diverse, hydrothermal alteration effects are widespread ranging from incipient albitization of plagioclase to complete destruction of the original texture. The earliest alteration is a pervasive pink-brown silicification, which consists of quartz and finely divided biotite. The quartz–actinolite–clinozoisite–biotite(–sulfides) veining overprints this alteration.

McCuaig et al. (2001) interpreted that mineralization controls include: northeast-trending fault and shear corridors; the intersection of late-stage faults with earlier ductile quartz–sericite shear zones and the intersection of late-stage brittle–ductile faults with competent lithologies. They cite evidence that the mineralising fluids were derived from the exsolution of volatile phases from a magma transport and boiling of the fluid through depressurization leading to deposition of the mineralization.

The lateritic profile at Boddington is residual and has resulted from prolonged weathering that led to the development of a thick, lower saprolite profile. Iron and aluminium hydroxides were precipitated contemporaneously at a redox front and the gold was precipitated in intimate association with these hydroxides to form the upper laterite blanket-style mineralization, but remaining essentially immobile in the lower saprolite zone.

Within the weathering profile there is a paucity of Na_2O, CaO, MgO and a marked reduction of K_2O, though this is still appreciable where muscovite persists (Le Gleuher, 2008). He also reported that Al_2O_3 is enriched upwards and Fe_2O_3 is enriched in the upper parts but depleted in the clay-rich component of the profile. Cu, Mn, Zn, Ni, and Co are concentrated in the lower saprolite but leached in the upper parts of the profile. In contrast, V, Zr, Mo, As, and Pb are concentrated up in the profile. Au increases upwards from the saprolite to bauxite zone reaching up to nine parts per million, though is markedly depleted within the lateritic duricrust and pisoliths.

Resources and mining

Since inception the Boddington Gold Mine and Hedges Gold Mine have together produced 190 tonnes (over 6 million ounces) of gold. Current mine redevelopment is based on total reserves of 649 Mt at 0.80 g/t (520 tonnes of gold and 696 Kt of copper as at 31 December 2007).

Capital cost for the redevelopment is approximately $1.8 billion and mine production is scheduled to commence in early 2009. The project is a joint venture between Newmont Ltd (66.7%) and AngloGold Ashanti Australia (33.3%).

Premier coal mine — Collie Coalfield

Regional setting

The Collie Basin is located 150 km south-southeast of Perth and 50 km east of Bunbury. Along with two smaller basins (Wilga and Boyup Basins) Permian sediments are preserves in northwest-trending graben, depressed within the Yilgarn Craton crystalline rocks (Fig. 14).

The geology and resources are well described in Le Blanc Smith (1993) and much of the following description has been taken from that reference. A total of 1400 m of sediments are preserved in the Collie Basin, with up to 1000 m being coal-bearing in up to 40 mappable seams.

Coal is produced at the rate of about six million tonnes per annum. Much of it is used locally for electricity generation in the Muja and Bluewater power stations, with additional uses for industrial applications as a source of energy; as a reductant and as a carbon source.

Exploration and history of the field

The coal was first identified in 1883 by a local grazier. However, initially he did not pass on his knowledge, and it was only in 1889 that the location of coal was announced and made public. Immediately, great interest was generated because of the huge energy potential and industrial advantages that came from the development of coal resources in the late 1800s.

In 1892, the WA State Government commenced a program of hand-augering and over about 10 months completed 18 holes, ranging up to 63 m in depth, in the vicinity of the known coal outcrops. In 1894 geologist HP Woodward (1894) mapped the extent of the basin.

Bulk sampling from a government mine shaft was tested and identified as having high energy content and relatively low ash. It was then successfully tested for use by the WA Government Railway. It was determined that in view of its energy content it was more economic to use Collie coal, rather than imported coal from Newcastle, in NSW.

A number of companies were established to mine the coal. Over the few decades after 1900, companies were formed, commenced mining and then their mines closed through unprofitable operations.

One of the major problems faced was the influx of groundwater into the mine workings from the coal seams and interseam sediments. The Collie Basin was originally virtually totally filled with fresh groundwater that had a relatively shallow groundwater surface. Much of the sediment is arenaceous with a relatively high storage coefficient and transmissivity values. Consequently, any excavations below the watertable produce strong inflows of groundwater that require management in order to protect mines and mining infrastructure.

In 1946, the then Bureau of Mineral Resources (BRM) based in Canberra, in collaboration with the GSWA, conducted a gravity survey over the basin and confirmed its structure and also that of the nearby Wilga and Boyup basins. Exploration activity by the GSWA followed, with several drilling programs initiated in order to confirm the gravity interpretation and the extensions of the coal-quality information from this relatively limited mining area.

Lord (1952) produced the first GSWA bulletin on the coalfield and Glover (1952) confirmed the Permian age of the coal-bearing sequence.

Two companies mine coal in the basin. The first, The Griffin Coal Mining Company Pty Ltd (Griffin Coal), was established in 1920 when operations were engaged in underground mining from the Hebe seam at Muja they mined into a borehole, resulting in massive influxes of water and slurry flooding the mine. The Company then initiated opencut mining and has continued with this activity to the present. The second, Western Collieries, was established in 1949 and continues to mine as Premier Coal after becoming a subsidiary of Wesfarmers Ltd in 1989.

Geology

The Collie coalfield occurs as an elongate and bilobate basin or graben with an axial length of 26 km northwest–southeast and 15 km across. The basin, and similarly with the Wilga and Boyup basins, is a downfaulted structure within the Yilgarn Craton. Figure 15 shows generalized stratigraphic sections. The basin contains up to 1400 m of Permo-Carboniferous sediments with low dips but numerous faults. The 900-m thick Permian sediments contain up to 74 m of coal seams between 0.5 and 13 m thick in 60 mapped seams. The coal is subbituminous with vitrinite reflectance ranging 0.43 to 0.60 for the deeper coals.

Total resources are 2400 Mt, and 5.8 Mt, valued at $264 M, were mined in 2007 in contrast to 7.2 Mt in 2006.

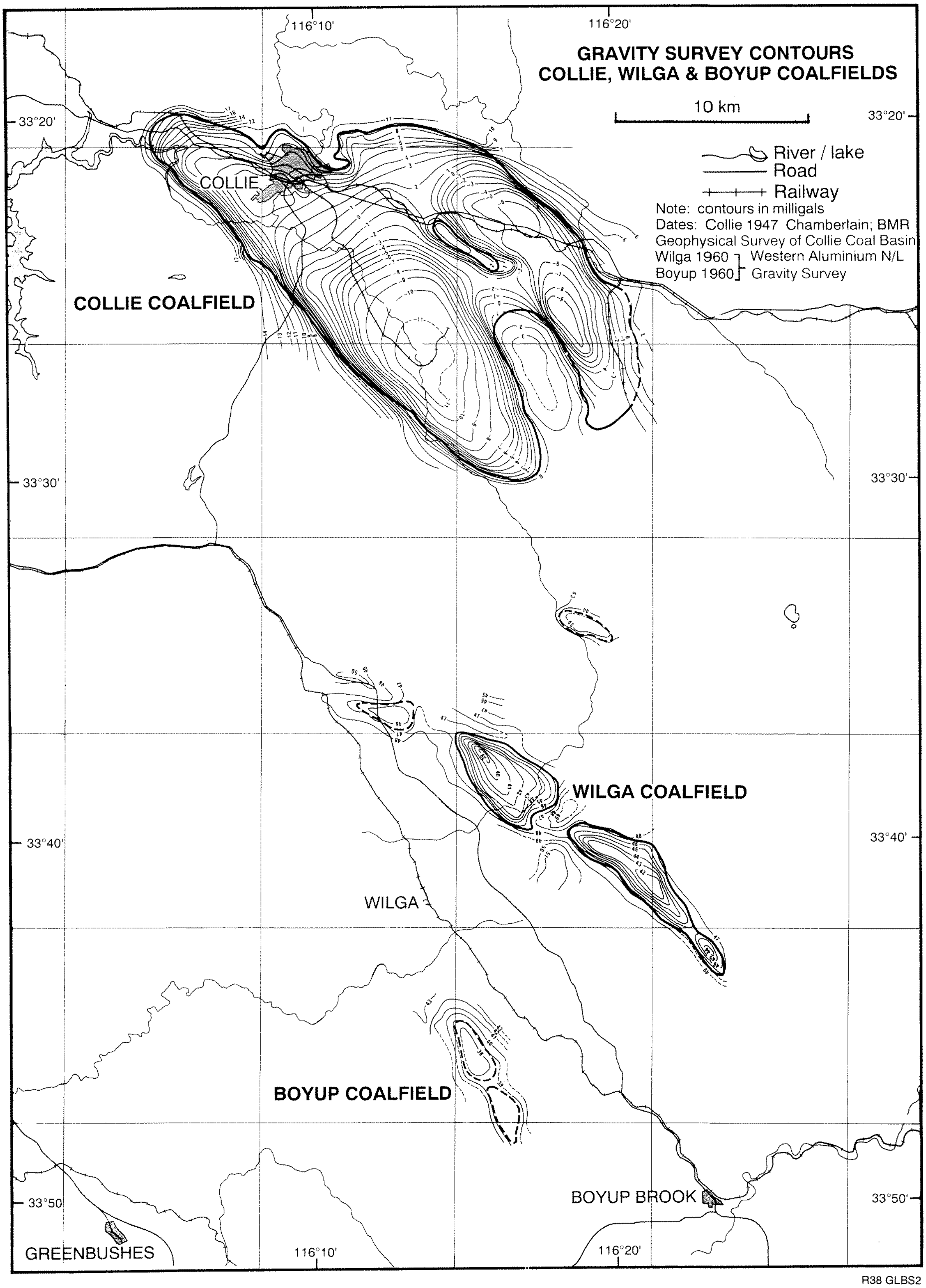

Figure 14. Collie, Wilga and Boyup Basins formlines as interpreted from original gravity surveys. After Le Blanc Smith 1993

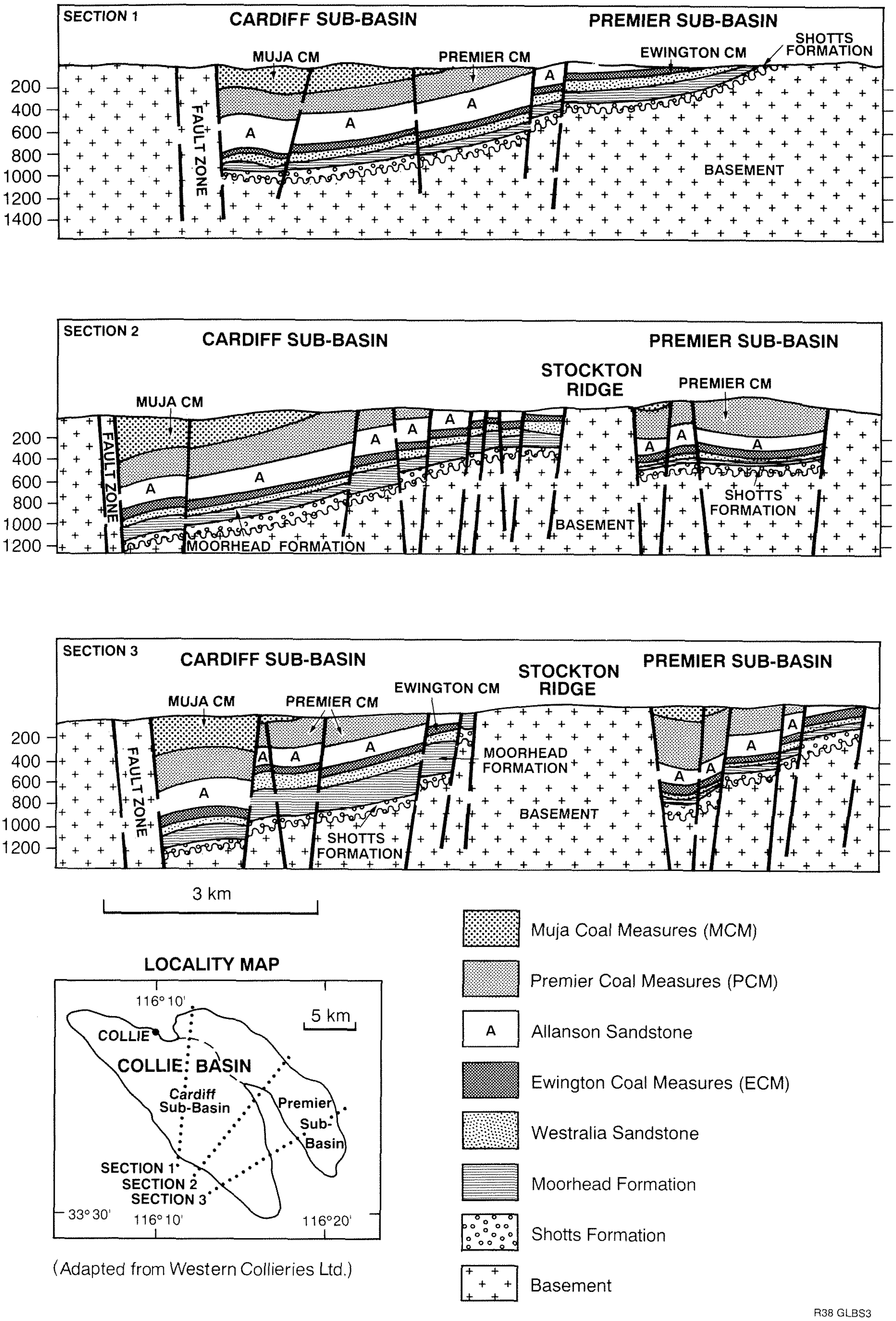

Figure 15. Generalized stratigraphic sections of Collie Basin (after Le Blanc Smith, 1993)

Stratigraphy

Understanding of the stratigraphy, and particularly that of the coal-seam sequence, was difficult because of the occurrence of numerous faults and the large number of seam splits.

Figure 16 shows the principal coal seams and stratigraphy.

The basal Stockton Group comprises the Schotts Formation overlain by the Moorehead Formation. The Schotts Formation is an early Permian diamictite 36 m thick in the type section, containing basement rock clasts up to 30 cm across in a silty mudstone. The Moorehead Formation consists of up to 230 m of pale-grey, laminated-claystone with thin interbeds of siltstone and sandstone and rare limestone. The Stockton Group is interpreted to represent the waning phases of a glacial epoch associated with the amelioration of the glacial climates. Overlying this is the Collie Group, consisting of five formations of coal measures with interbedded sandstone units, comprising:

- Muja Coal Measures
- Premier Coal Measures
- Allanson Sandstone.
- Ewington Coal Measures
- Westralia Sandstone.

The Westralia Sandstone, which overlies the Moorehead Formation conformably, contains a number of coarsening-upwards clay-to-sand beds with ripple cross-laminated sandstone and siltstone. In the type section it is 79 m thick. This Early Permian unit represents post-glacial, lacustrine-deltaic environments.

The overlying Ewington Coal Measures consists of 57 m of thick coal seams interbedded with sandstone and siltstone. There is a cyclic development of the sediments locally on an erosional base, commencing with one to two metres of sandstone overlain by rippled fine-grained sandstone, then laminated dark-grey siltstone with plant fossils and common carbonaceous to coaly filaments, overlain in turn by up to 5 m of bituminous coal. Total coal thickness in the Ewington Formation is 12 m. Three principal coal seams are the Moira, Stockton and Wallsend. Sandstone splits within the seams are common. Because of the inconsistent nature of the stratigraphy, other names are ascribed to these seams in different parts of the basin. The Ewington Formation is Artinskian age.

The Allanson Sandstone is similar to the Westralia Sandstone, consisting of up to 185 m of cross-bedded sandstone with interlaminated siltstone. However it does contain laminae of mudstone and coal and in one area may contain the one-metre thick Hymen Coal Seam.

The Premier Coal Measures, ranging up to 320 m in width, contain a multiplicity of thick coal seams interbedded with sandstone and siltstone. Cyclic sedimentation, similar to that found in the underlying Ewington Coal Measures (see above), is dominant. The Coal Measures are Artinskian to Kungurian (early Permian) in age, based on fossil evidence. It is interpreted to have been deposited in an alluvial plain to fan-delta, platform-environment.

The Muja Coal Measures consists of up to 450 m of thick coal seams interbedded with sandstone, conglomerate and siltstone. As with the other coal measures, it contains numerous fining-upwards cycles, culminating in coal seams that are topped with an erosional contact. There are nine principal coal seams of which the Hebe seam, at up to 13 m, is the thickest. The unit has more sandstone than the underlying Premier Coal Seams and also contains a number of coarsening-upwards siltstone-sandstone packages. The Muja Coal Measures are Late Permian and is interpreted to have been deposited in alluvial plain to fan-delta environment.

The Permian sediments are overlain unconformably by the Cretaceous Nakina Formation consisting of weakly indurated claystone, sandstone and conglomerate up to 20 m thick.

Throughout the Collie Basin the surface consists of variously laterized rocks culminating in ferricrete horizons.

Structure and tectonics

The sediments have been folded gently with northwest–southeast axes parallel to the axis of the basin. Fold limbs are asymmetrical with steeper, shorter, southwest limbs and flat-lying northeast limbs. Except in proximity to faults, dips rarely exceed 6°. Adjacent to faults, dips of up to 75° occur.

Extensive faulting is dominantly parallel to the basin axis and consists of dip-slip movements with splays and scissor-movements. Displacements range up to 50 m. The faults appear to have no reflection in the adjacent sediments — implying that it was all post-lithification in age.

The Muja Fault, located in the southwestern margin of the Premier Sub-basin, is well exposed in the Muja opencut. There, it dips northeast at 75° and the Permian sequence dips nearly parallel to it. These sediments overlie a phyllonite in the basement rocks, implying reactivation of older structures.

Coal resources

There is in excess of 10 000 boreholes into the Collie Basin thereby allowing for a good determination of the quantity and quality of the coal to be made. The total resource is estimated to be 2400 Mt, with some 880 Mt potentially available for opencut extraction (presuming seam thickness >1.5 m and a stripping ratio of <10:1).

Collie coal is typically water saturated, with up to 30% moisture as mined, although it dries quickly with exposure to the air. The specific energy content of Collie coals ranges between 18 and 22 MJ/kg as received (equivalent to 29-32 MJ/kg on a dry basis). The ash content generally ranges from 3% to 10% although within cores of seams it may be as low as 0.3%. Volatile matter, consisting of tars oils and organic gases (mostly methane), ranges from 22% to 37% as a rule. Methane content is relatively low and there appears to be little scope for extraction of

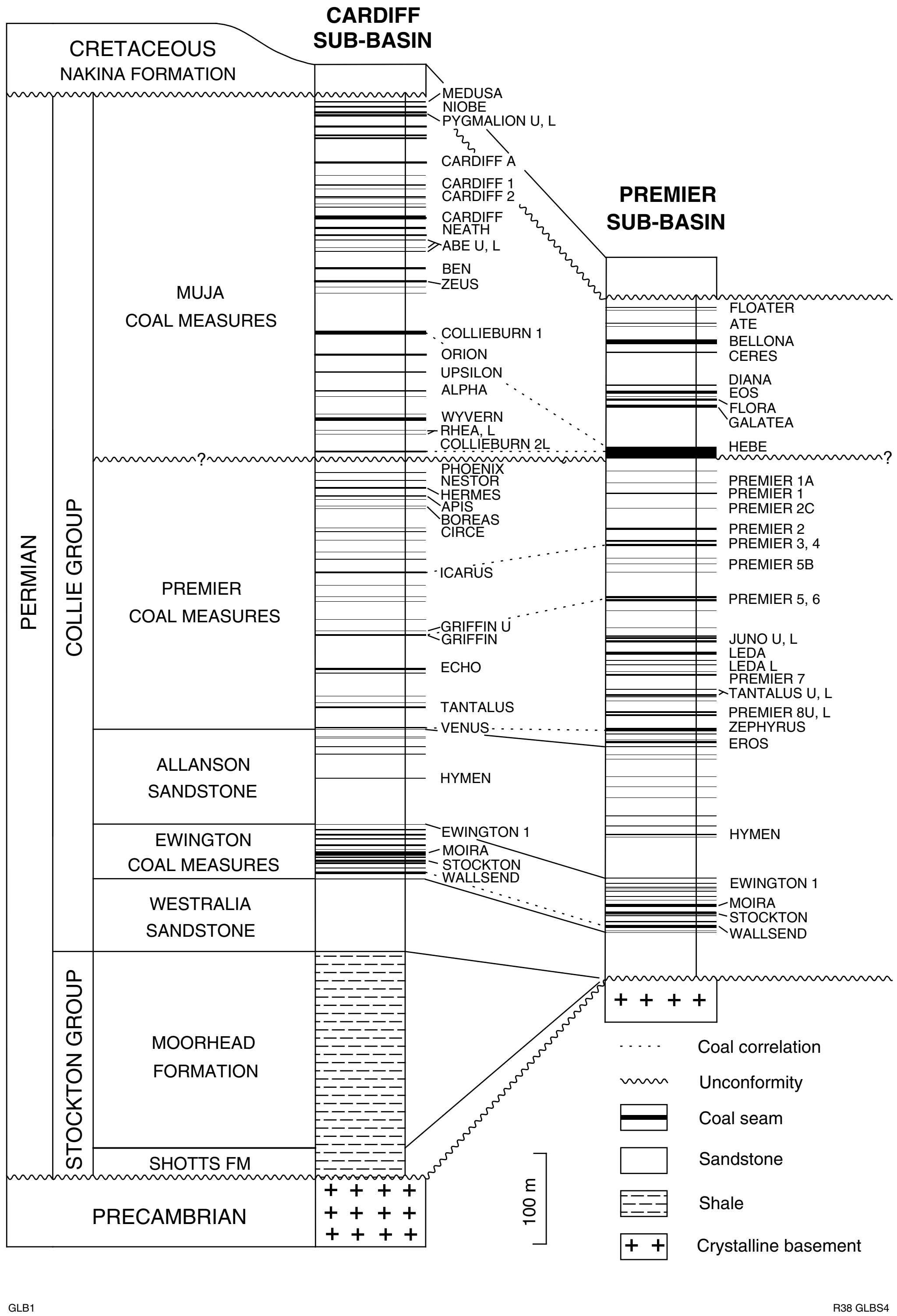

Figure 16. Principal coal seams of the Collie Basin. After Le Blanc Smith (1993)

coal-seam methane. Collie coal fixed carbon is typically 40%–50%. Sulfur tends to be low except near faults, with contents of from 0.3 to 0.5%. However, adjacent to some faults, sulfur content may increase up to 3% locally and mining in these areas is usually tightly controlled to minimize average levels. Vitrinite reflectance ranges 0.43 to 0.60.

The coal classifications in general use do not cater for Collie coals precisely. The latter are bituminous to subbituminous in rank, containing a high water content and having low, specific energy content for such coals.

Mining production and use

Coal production in Western Australia is effected solely from the Collie Basin. In 2007, production from the basin was 5.8 Mt having a value of $263 M. This includes the combined output of both Premier Coal and Griffin Coal.

The major use of the coal is for electricity generation in power stations adjacent to the basin. They have a total installed capacity of 1.4 GW. Prior to 1990, Collie coal generated up to 70% of Western Australia's grid electricity, but since then the proportion has been decreasing as natural gas from the Northwest Shelf has been increasingly used in order to reduce CO_2 production.

The coal is mined using hydraulic or electric shovels and excavators, loaders and trucks depending on the actual operation. Overburden and interburden is removed to expose a clean coal surface. The coal is crushed and stockpiled as mined. In contrast to many coal-production facilities interstate, no wash plant exists at Collie.

Backfilling of open cuts is normally completed, topsoil replaced and the area planted to native vegetation. In some cases, sterile grasses are planted to stabilize soils when the latter are first replaced, rather than being propagated by seeds to allow for a transition to native vegetation.

Greenbushes tantalum–lithium–tin deposit

The Greenbushes pegmatite, about 270 km south of Perth, contains one of the world's major tantalum deposits as well as 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 historically produced more than 4138 t of tantalite (Ta_2O_5) and more than 68 000 t of Li_2O (in spodumene), as well as significant quantities of tin and high-purity kaolin. Production in 2007 amounted to 193 000 tonnes of spodumene; 435 tonnes of tantalite and 111 tonnes of Sn with a gross value of $137 M.

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. DW Stinton, a kangaroo hunter, was the first to take up a 400 acre (100 ha) mining lease at Greenbushes, and was also 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, although 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 a depth of about 50 m, increased with further price rises in the period 1975–1980, and the Greenbushes deposit was proven 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. Following the placing of Sons of Gwalia in voluntary liquidation in 2004, Talison Minerals Ltd was created to continue the operations.

Talison Minerals 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.

Geological setting

The Greenbushes pegmatite is part of an Archean pegmatite swarm (Fig. 17) 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 rock 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) confirming 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 km^2 area (Fig. 17). 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 latter has several discrete layers separated by country rock (Fig. 18a) comprising:

- 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–Kfeldspar–spodumene(–tourmaline–apatite–mica).

The Lithium openpit, 500 m to the south, contains the same broad compositional layers, but with a wide quart–spodumene(–muscovite–albite–microcline–perthite) **Lithium Zone** developed within the Albite Zone (Fig. 19b).

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. 19c). 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 Figure 19.

Ore mineralogy

Ore minerals identified from the Greenbushes deposit are listed in Table 2. 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.

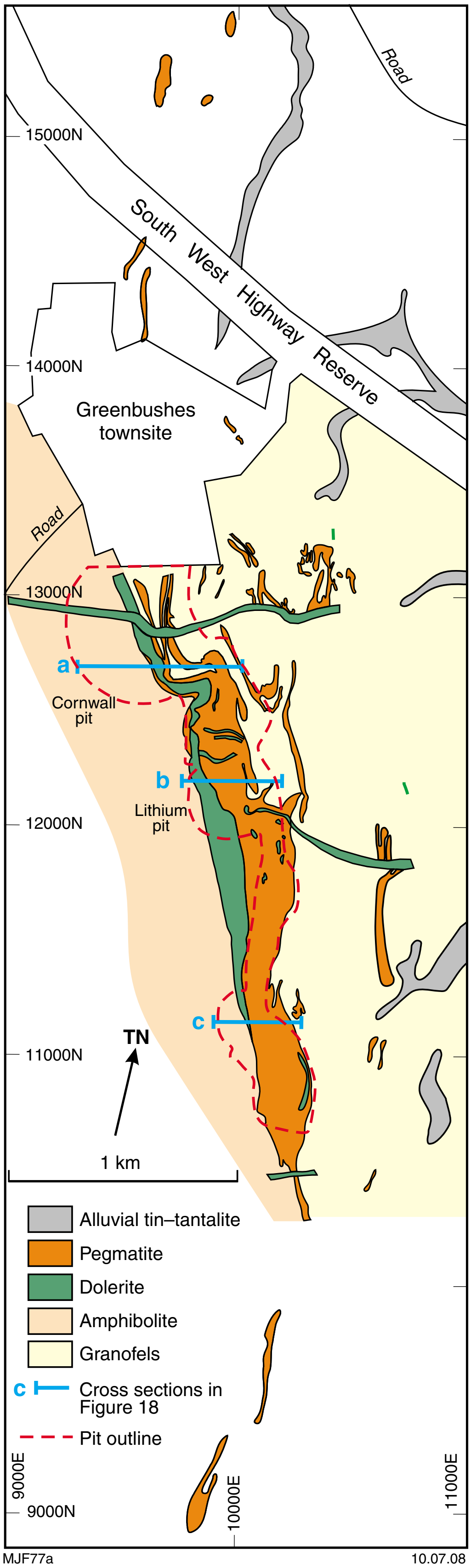

Figure 17. Geological plan showing the distribution of pegmatite and main mining areas at Greenbushes modified from Hatcher and Glynick (1990) and Sons of Gwalia Ltd, (2004, written comm.)

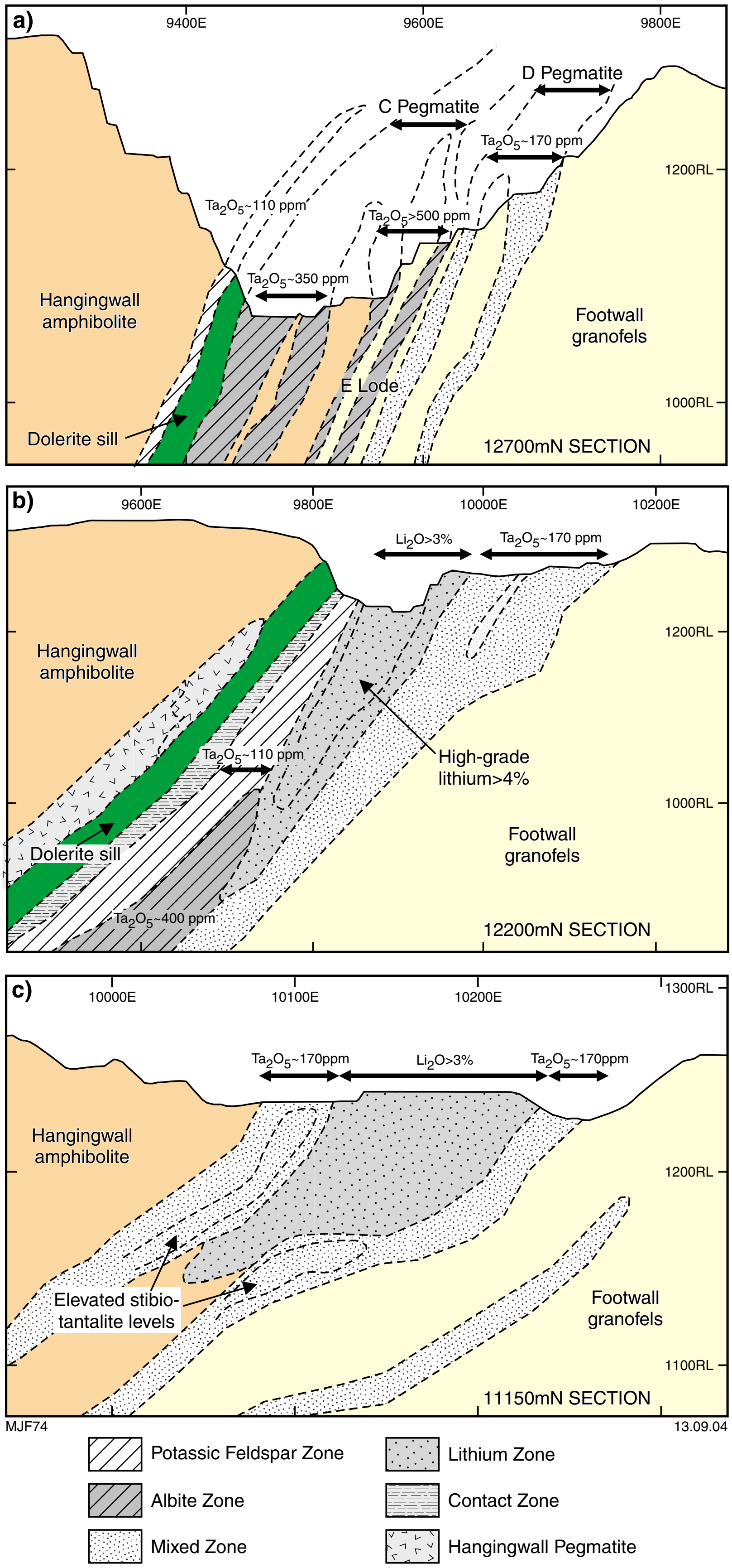

Figure 18. Cross sections through the Greenbushes pegmatite deposit showing ore zonation: a) Cornwall openpit at 12700 mN; b) Central Lode Stage 3 at 12200 mN; c) Central Lode Stage 1 at 11150 mN (after Sons of Gwalia Ltd, 2004, written comm

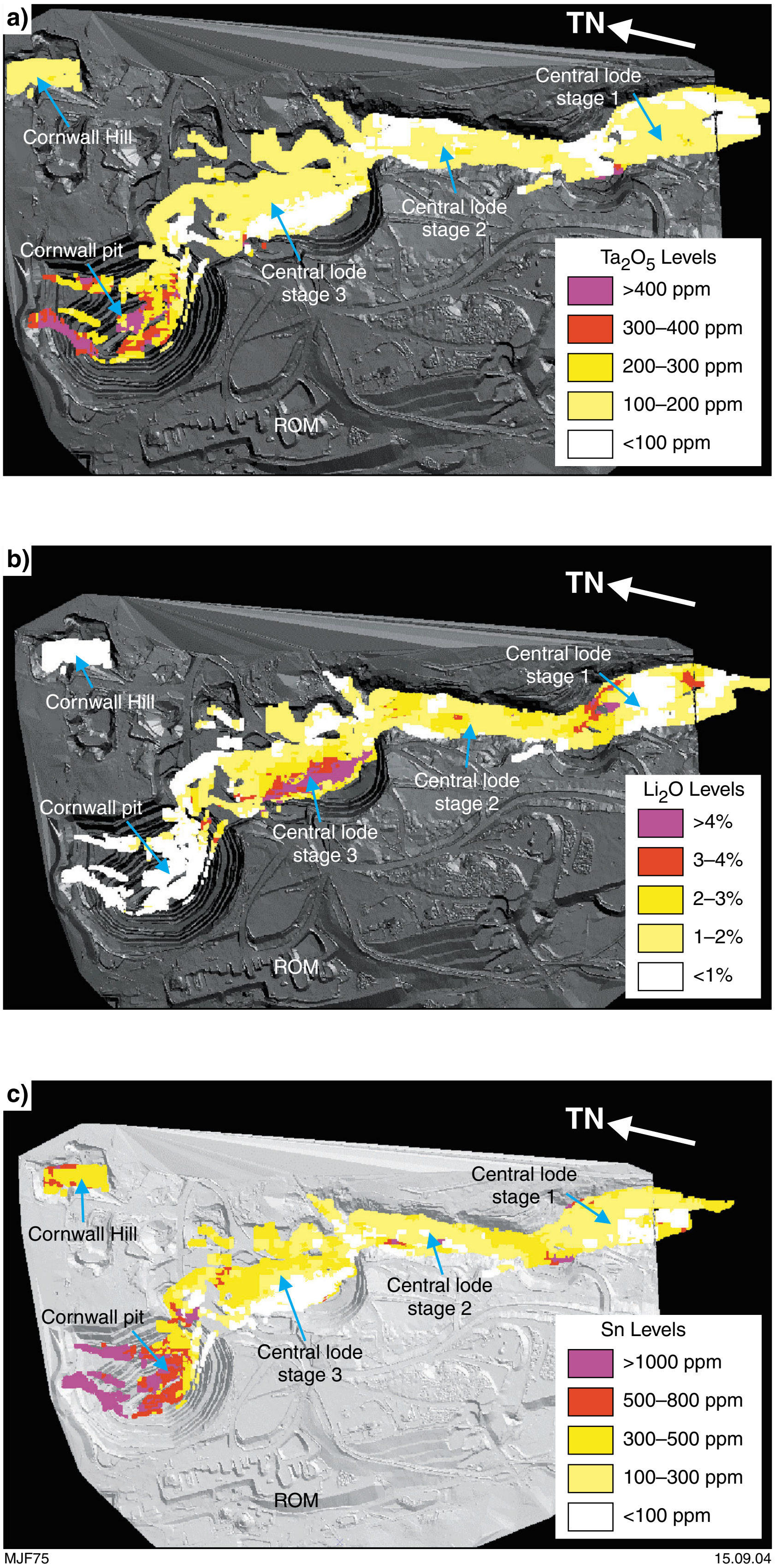

Figure 19. Metal grade distribution in the Greenbushes openpits: a) tantalum; b) lithium: c) tin (after Sons of Gwalia Ltd, 2004, written comm.)

Table 2. Economic minerals, Greenbushes tantalum mine

Minerals	*Chemical formula*
Tantalum	
Columbo–tantalite	$(Fe, Mn)(Nb, Ta)_2O_6$
Stibio-tantalite	$(Nb,Ta)SbO_4$
Microlite	$((Na, Ca)_2Ta_2O_6.(O,OH,F))$
Ta–ilmenite	$Fe^{2+}(Ta,Ti)O_3$
Ta–rutile (struverite)	$(Ti,Ta,Fe_3+)3O_6$
Wodginite	$(Ta,Nb,Sn,Mn,Fe)16O_{32}$
Ixiolite	$(Ta,Fe,Sn,Nb,Mn)_4O_8$
Tapiolites	$(Fe,Mn)(Ta,Nb)_2O_6$
Holtite	$Al_6(Ta,Sb,Li)[(Si,As)O_4]3(BO_3)(O,OH)_3$
Lithium	
Spodumene	$LiAlSiO_6$
Lithiophilite	$Li(Mn^{2+},Fe^{2+})PO_4$
Ambligonite	$(Li,Na)AlPO_4(F,OH)$
Holmquisite	$Li(Mg,Fe^{2+})3Al_2Si_8O_{22}(OH)_2$
Lepidolite	$K(Li,Al)_3(Si,Al)_4O_{10}(OH)_2$
Tin	
Cassiterite	SnO_2

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

The main lithium ore mineral is spodumene, which is commonly about 70 mm, but has been noted as crystals more than one millimetre in size. Spodumene is a monoclinic pyroxene; typically colourless to white, but it also has several colour forms including green hiddenitewith minor iron and chromium and pink (kunzite) containing minor manganese. Other lithium-bearing minerals identified at Greenbushes are also listed in Table 2. 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. 17): 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 17. 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 being prepared for blasting using twin-boom, jumbo-drills. The underground mine was designed to produce 600 kt of tantalum ore per year, but is currently (June 2008) 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% Ta_2O_5. 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% Ta_2O_5.

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 509 tonnes (1 119 504 lbs) of Ta_2O_5 in concentrate; 553 t of tin and 126 534 t of lithium–spodumene concentrate. Talison Mineral's other tantalum mine, Wodgina in the Pilbara region of Western Australia, produced 1 172 507 lbs of Ta_2O_5 in concentrate in the same period, thereby just beating Greenbushes to the title of the world's largest producer (Sons of Gwalia, 2004).

Talison is the largest lithium minerals producer in the world, supplying about two thirds of global demand.

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' or 'heavy-mineral sands'). In 2007 the industry produced about 1.5 Mt valued at $755 M, down from $882 M in 2006. It is the sixth-most valuable sector of WA's mining industry, with additional economic benefits derived from the downstream processing of titanium minerals to produce white pigments in three plants operating in this State. The titanium minerals mining industry directly employs some 2000 people.

Two regions dominate production: the Bunbury-Capel region located some 200 km south of Perth, and the Eneabba region lying 240 km north of Perth. This field guide concentrates on the southern region. The extent of the economic mineralization is shown in Figure 20.

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 a specific gravity greater than about 2.85 may also be recovered in the 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 some 450 km north of Perth and monazite and xenotime are marketed intermittently.

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

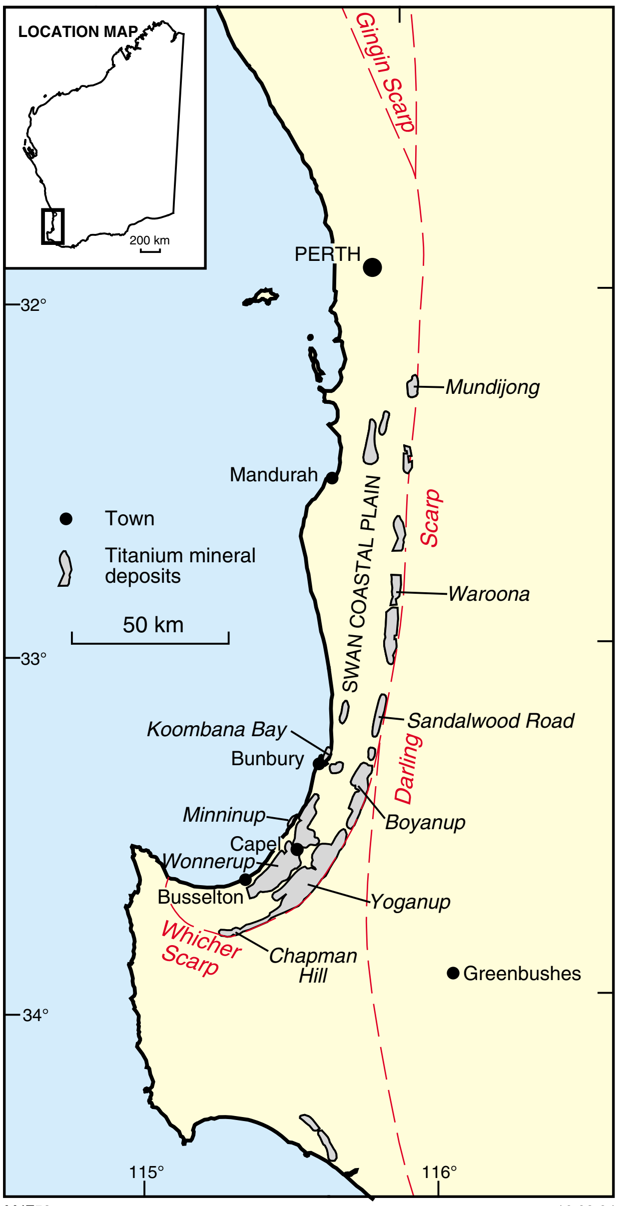

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Figure 20. Map showing the distribution of titanium mineral deposits on the Swan Coastal Plain

Regional geological setting and geomorphology

The Swan Coastal Plain (Fig. 20) extends north from the Whicher Scarp located some 250 km south of Perth and extending for about 650 km. It is 12–35 km wide and is bound on the east by the Darling Scarp, by the Whicher Scarp in the south and the Gingin Scarp in north. These three scarps are dominantly erosional now, but the Darling Scarp was initiated as a structural feature related to the Darling Fault.

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 and 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 — representing 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 comprises thick calcareous eolianite deposits that in places form high coastal cliffs, extending offshore as islands and shoals representing the eroded remnants of submerged dunes that formed at sea levels lower than at 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 (and described in more detail elsewhere in this guide) lies the Archean Yilgarn Craton, whilst south of the Whicher Scarp and east of the Gingin Scarp are the 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 their study of 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 Sands (1956) Ltd and Perron Bros Pty Ltd commenced mining of deposits at Koombana Bay on the northern outskirts of Bunbury in 1956. Cable Sands has continued mining in the area to the present day. 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, which is now the world's second-largest producer of these minerals.

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

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

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 still stands up 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). Identified initially as a wedge of sand at the base of the Darling and Whicher Scarps, it is now recognized as a sheet extending west, partly across the Swan Coastal Plain below the Guildford Formation, and 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. 20).

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 paleo-environment reflects a beach and nearshore depositional setting. Adjacent dune sands are commonly mineralized and where this occurs the economic deposits are tabular.

Economic 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. 20).

The ages of the deposits are poorly constrained because of the lack of methods required 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 if time permits (Figs 1 and 20).

Figure 20 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 (written comm.), 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, which is a J-shaped bay on the north side of the 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 is due to these same factors.

Characteristics of the deposits

The concentration of economic minerals in the strandlines ranges from a background of less than one percent 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.

The mineable thickness is up to about eight metres in the Capel strandline and about 10 m in that of 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.

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.

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 J-shaped bays downwind and down-swell of headlands. The size and scale of the headlands and adjacent bays can vary markedly. Three smaller-scale cases include:

1. A deposit at Sandalwood Road (Fig. 20), where Cable Sands finished mining in 2003, is located north and presumably in the lee, of a prominent outcrop of vein quartz.
2. The Yoganup Extended deposit, adjacent to an outcrop of Bunbury Basalt just off the Whicher Scarp.
3. The Yoganup West and the high-grade part of the Tutunup West deposits that are also controlled by similar basalt paleo-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, lying about 50 km to the west of the site (Fig. 20).

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 land owners 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 depending 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 one metre 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, routinely completed only 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 effected in company-owned laboratories in order to define mineral constituents precisely which are important to the 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, which is held for up to four years and 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 km^2 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.

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 Government of Western Australia). Therefore, mining on some land on the Swan Coastal Plain does not require a mining lease and in which case it is removed from the requirements of the Mining Act. Mining attracts royalties, payable to the Government of Western Australia, usually levied 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 State Government struck a flat royalty rate of $1.50 per tonne on ilmenite upgraded in Western Australia. The fact that the state has now become a prime producer of synthetic rutile in the world clearly shows the wisdom of the government's use of the royalty regime in order to magnify the wealth creation derived from its mineral endowment within Western Australia. In the 1970s much of the ilmenite was not even marketable and the industry was highly dependent on the zircon and rutile production in order to its maintain operations.

Mining, processing, and rehabilitation

Mining techniques employed depend on the level of the deposit in relation to the watertable. 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, which is located 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 on-going; with intent to develop a co-disposal 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 continues 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 sulfuric 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 TiO_2 content from the stoichiometric 53% TiO_2 up to levels of more than 65% TiO_2.

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 with all costs effectively being borne by the mining operation. Figure 22 shows the Yoganup North mine site near Boyanup, 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 by replanting it with native coastal vegetation (Fig. 23). This locality will be visited on the field excursion.

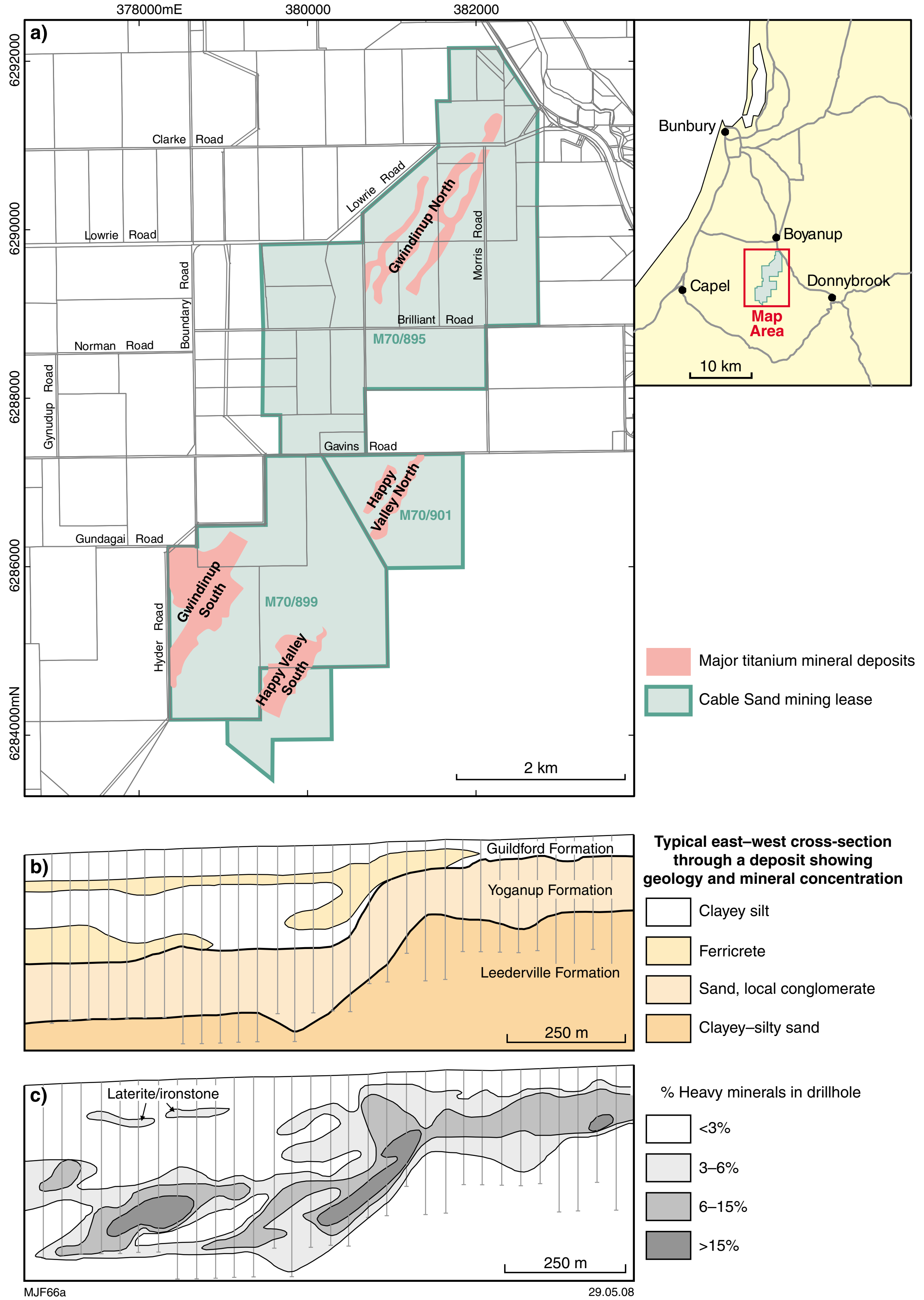

Figure 21. Gwindinup titanium mineral mining area: a) map of titanium mineral deposits; b) geological cross section through Yoganup strandline; c) cross section through Yoganup West strandline showing total heavy mineral concentrations in drillholes (after Bemax-Cable Sands, 2006 and Iluka Resources Ltd, 2004, written comm.)

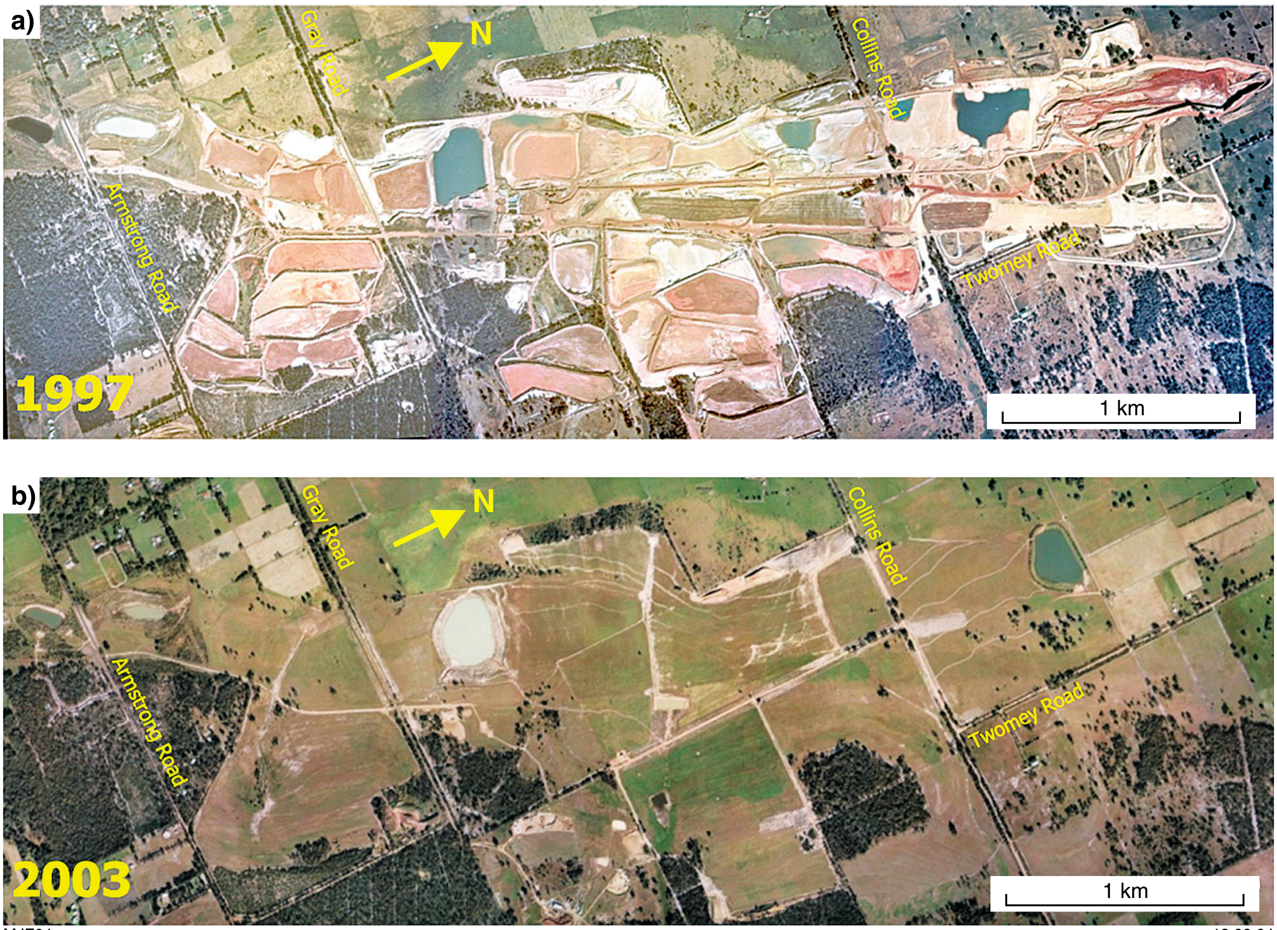

Figure 22. Aerial photographs of Yoganup North mine: a) during mining in 1997; b) in 2003 after rehabilitation (photos courtesy of Iluka Resources Ltd)

Environmental and social issues and economic aspects of mining

The titanium minerals industry operates in areas where there is much competition from alternative uses of land. 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. Most recently there has been a 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, which has scattered remnant specimens of tuart eucalypt trees, a species known for its tall imposing forest trees. There is strong community attachment to the tuarts and even though Cable Sands was able to offer significant conservation offsets resulting 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 post-mining replacement of the developments. Titanium mineral 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 the 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, has facilitated the incorporation of maps showing the location of deposits into a range of WA 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 has resulted in the expression of 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

Figure 23. 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

also in the total loss of the gross value of the deposit, which may be five to twenty-five times the profit.

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 termed locally as 'The Capes'. This area extends about 100 km north to south and about 20 km east to west (Fig. 24) and contains more than 100 individual vineyards and wineries. Most lie within 5 km of the Indian Ocean, which accounts for the strong maritime influences on the climate. The region has about 3000 ha (~7000 acres) of vineyards, which represents only about two percent of Australia's total area under vines. However, it produces a much larger proportion of the country's 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 around only 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. This includes several million cases alone of its Bin 65 Chardonnay from the Murray River area in northern Victoria, while 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 bounded by the Dunsborough Fault, which parallels the coastline about 10 km inland (Figs 2 and 24). With minor exceptions, where some younger units onlap the Leeuwin Complex across the fault, the Dunsborough Fault marks the western limit of the southern Perth Basin. The latter is 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 Archean Yilgarn Craton consisting of granite–gneiss and granite–greenstone terranes.

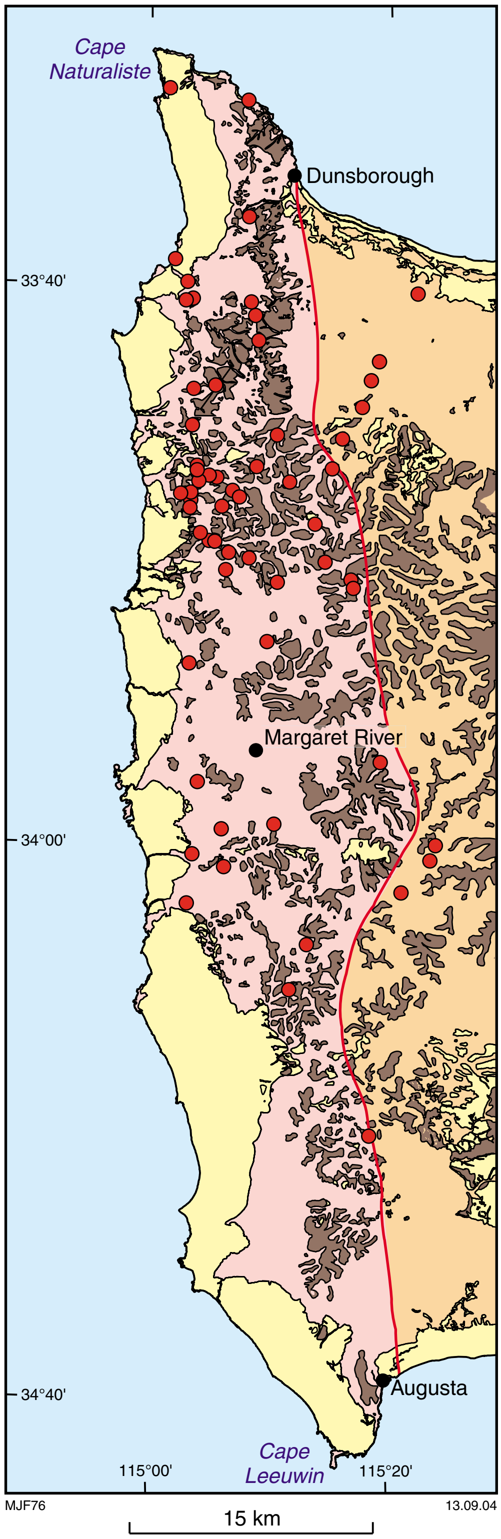

Figure 24. Map of 'The Capes' (Cape Naturaliste – Cape Leeuwin) region, showing locations of major Margaret River vineyards and main geological features

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. 24).

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 24, 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 located to the west of the Dunsborough Fault; east of the sand and limestone deposits of the Naturaliste Ridge and are therefore largely underlain by Leeuwin Complex granitic–gneiss (Fig. 24).

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, which is related mainly to the local drainage and topography, provides a variety of soil types throughout the region.

It has long been recognized by wine makers (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 rossa 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, including 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 rossa, derived from limestone, is typically well drained, but the calcareous subsoil can act as a water reservoir to slowly release water by capillary action during 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 the Bordeaux region. 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 become easily waterlogged — even if other soil parameters are favourable — resulting in poor vine growth during the spring or berry splitting in summer.

Very fertile soils, such as those 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 play a role in the resulting wine quality — although this is not always easy to quantify. It is clear that adequate nitrogen and potassium contents are necessary for good 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 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 determining 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 across the world's best wine-growing areas and recognized that the Margaret River area has a climate very similar to that of the prized region of Bordeaux in southwestern France (Fig. 25). It was this similarity that led him to recommend the Margaret River area as an ideal prospect for viticulture.

Gladstones also recognized that the Margaret River region was less susceptible to spring frosts than the Mount Barker–Frankland River area farther to the east, which had previously 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 Gladstones' recommendation and the region has

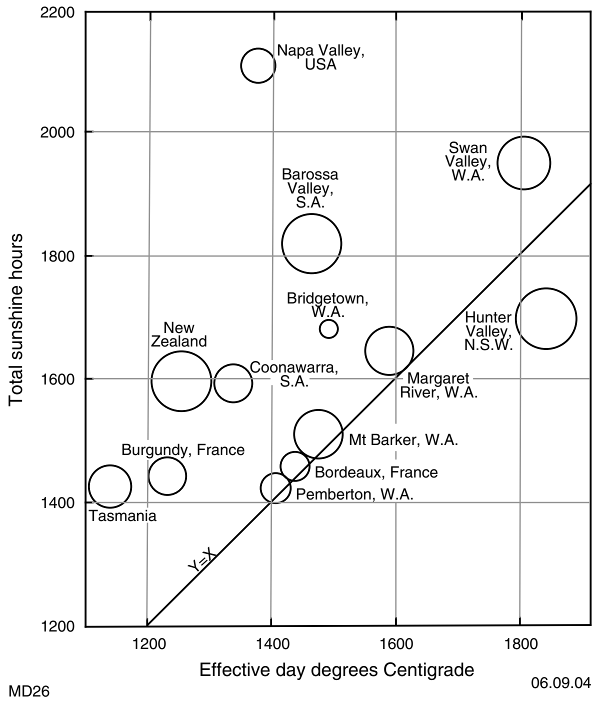

Figure 25. Graph of climate details relevant to wine-grape growing for Western Australia and selected other localities (modified from Gladstones, 1992). Sunshine hours = total sunshine hours for October to April (southern hemisphere) and April to October (northern hemisphere). Effective day degrees = biologically effective day degrees (Celsius) as defined by Gladstones (1992)

since become one of Australia's premium wine-growing areas. Field trip participants will have an opportunity to sample typical Margaret River wines and discuss viticulture and wine-making practices with winery staff at several wineries (after mine visits!).

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: 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 via 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 µm, 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 one percent 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.

Scarp Lookout

After leaving the Pinjarra alumina plant site, we will drive eastwards to Huntly mine site. En route we may 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, lying 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 development is proceeding southward from Perth.

Along the base of the escarpment are a number of small titanium mineral deposits together 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, lying 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 to the north of Perth.

Locality 2: Huntly bauxite mine — McCoy's mining area

Note: there 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 producingat 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 of the vegetation. This is an active mining area and the actual locality visited will depend on operational issues pertaining on the day as well as the 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.

Boddington townsite development issues

The redevelopment and enlargement of the Boddington Gold Mine, centred 13 km northwest of the town, has resulted in marked growth of this country town. However, bauxite resources within State Agreement Mining Lease 258SA, held by Worsley Alumina Pty Ltd, occur within 2 km southwest of the town centre.

The local planning scheme was developed by the Shire of Boddington in collaboration with the Department of Industry and Resources, and, based on research by Worsley, the Shire has stipulated that no further residential developments shall be approved within a 1.2 km buffer of the bauxite resource area. This buffer includes a relatively large area of undeveloped flat to slightly sloping land southwest of the town centre. Elsewhere, however, the town is constrained by rising ground that is less suitable for housing. The consequence is that the planning to protect one mine's future resources (bauxite) is creating difficulties for another mine (gold) that needs the town to grow to house a local workforce.

Locality 3: Boddington Gold Mine

The Boddington Gold Mine is currently being redeveloped with a capital input of $1.8 billion — the largest gold resource yet to be mined in Australia. The operation is developing a very large new opencut mine and processing plant. The current mine plan is for a final void covering 120 ha to a depth of 600 m.

The Boddington Gold Mine Management Company will host our visit. Because the site is currently under development there may be restrictions on access to parts. It should be possible to view remnant parts of the original opencut in the weathering zone, although overburden removal will be well-advanced to expose the new ore zones in the fresh bedrock. However, the various components of the weathering profile should be visible and it is planned to include viewing of core of both the mineralized and unmineralized fresh rocks.

Worsley Alumina mining areas

Worsley bauxite mining is progressing in the Mount Saddleback district, some 15 km south of Boddington. This bauxite is developed on metasediments and metavolcanic rocks and typically has a thickness of the order of NN m, in contrast to the NN m that is developed over the granitic rocks within Alcoa's mining areas.

Worsley's mining process is similar to Alcoa's, entailing removal of vegetation and topsoil; mining of the bauxite; recontouring the land profile; reapplying topsoil and then revegetating to native vegetation. The bauxite is crushed and transported by a 52.5 km conveyor (purportedly the longest in the southern hemisphere) to the alumina production facility near Collie.

Mining plots can be seen at several sites to the right-hand-side of the road. Most are now completed and are in various stages of rehabilitation.

Locality 4: Premier Coal opencut

Premier Coal will host a visit to view coal seam geology, mining and rehabilitation at the Premier mine site.

Coal is mined using a variety of equipment but predominantly with electric or hydraulic shovel and truck. The coal is transported by truck to a crusher where it is crushed and stacked onto a blended stockpile. The blended stockpile is reclaimed and delivered by conveyor to local power stations. Equipment in current use includes:

- two P and H 2800 electric shovels
- two Leiber 994B excavators
- one Leiber 994B shovel
- one Cat 994 loader
- nine Cat 793B trucks (240t)
- four Euclid R260 trucks (220t).

Lesser quantities of coal are sold for industrial applications as a process reductant, for use in kilns and as a source of charcoal.

During the visit we will see the coal seams with interbeds of sandstone to shale, and common vegetable fossil remains on bedding planes in the finer sediments. Faulting with inclined dips and gentle folding should be apparent. Coal-seam washouts occur and may be apparent.

Locality 5: Greenbushes tantalum mine

Talison Minerals — 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. 26) 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 brilliant white rock enclosed in hornfels on the floor of the pit.

MJF72 25.08.04

Figure 26. Cornwall openpit, Greenbushes (looking north)

Whicher Range gasfield

Five wells drilled into a large closure of a doubly-plunging gentle anticline (centred 10 km north of the road and 30 km northwest of Nannup) have led to the determination that the structure may contain the order of 10^{11} m^3 of natural gas, sufficient to supply the total Perth market for up to a decade. However, the wells have either generated economic, initial flows that have decreased during a period of several hours to uneconomic rates, or otherwise failed to produce economic flows.

Gas, with minor condensate, was intersected in the first hole (Whicher Range 1) at a depth between 3950 m and 4273 m in the Willespie Formation, the Late Permian uppermost component of the Sue Group, which is the equivalent of the Collie Coal Measures of the Collie Basin. The gas source is believed to be the in situ coal seams and keratogenous carbonaceous shales within the Willespie Formation. Figure 5 shows a generalized cross section through the structure.

The Sue Group represents Permian sedimentation in fluvial to lacustrine paleo-environment in a slowly subsiding rift of the Perth Basin, between the Darling Fault to the east and the 500 Ma crystalline basement of the Leeuwin Complex to the west. Total thickness of the stratotypes of each formation in the Group is over 1500 m. Following deposition, the sequence was subjected to northwest-directed transtensional movements and north-trending normal faulting that generated broad folding of the units. The gas is contained within the sands of the 750 m-thick Willespie Formation, being contained by intraformational argillaceous and silty horizons and coal seams.

A very large methane resource is present in the 100 to 400 km^2 closure of the northeast gentle anticline. (Fig. 5). However, technical solutions are required to extract the gas from wells at economic flow rates. Part of the problem appears to be caused by the hydration of various clay minerals in the sand-grain interstices, leading to the clay swelling and thus closing lateral interstitial permeability within the sands, caused through the use of water as the drilling circulation medium. Attempts to use liquid CO_2 as a fracturing medium and to drill using air circulation has led to other technical difficulties.

A similar anticline, referred to as Whicher Range South, was identified by seismic surveying completed in the late 1990s. This is interpreted to be analogous to the Whicher range structure. Not one well has been drilled into that structure. If techniques can be developed to turn the Whicher range gasfield into an economic producer then another potentially similar-sized structure awaits drill-testing.

Locality 6: Prevelly and mouth of the Margaret River

The Margaret River enters the Indian Ocean through a small estuary between hills of the Leeuwin Complex gneiss, overlain by Cenozoic coastal dune deposits. The Cenozoic deposition occurred on a highly undulatory surface: the wave-cut platform offshore from the car park formed in the cemented eolian dune limesands, whereas just to the north the Leeuwin Complex tors on the beach are at a higher level. Most of the coastal hills covered in vegetation are dune forms. The Surfer's Point surf break is world class and is the venue for international surfing competitions, with consistent breaks up to metres high. To the south is the coastal holiday resort village of Prevelly. The State Government is currently preparing to release an area similar to the existing townsite for residential development and is therefore having to manage the various community perspectives ranging from those who want no change in the present status to those strongly supportive of growth in the number of permanent residents.

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 needs to 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.

Locality 8: Sugarloaf Rock

Sugarloaf Rock is a small but prominent island of Leeuwin Complex gneiss about 4 km south of Cape Naturaliste (Fig. 27). The rocks of 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).

Figure 27. Sugarloaf Rock, Yallingup

Ludlow and Minninup rehabilitated mine sites

Cable Sands (WA) Pty Ltd mined the Ludlow deposit between 2005 and 2008. The majority of the area was previously covered with pine forest, planted in the 1950s. However there was a concerted program of opposition to the mining by various environmental groups and individuals on the basis that the mining would affect the nearby Ludlow Tuart National Park and the tuart forest it contained.

The mining was restricted to two relatively shallow and narrow strand-lines to a maximum depth of four metres. After removal of the titanium minerals the sands were replaced and revegetated to native vegetation. In addition to using the wealth from the mining to cover the costs of returning the pine forest to native vegetation, the company provided a significant additional block of land to link the Ludlow Tuart National Park with the Vasse-Wonnerup Estuary conservation area (a wetland of international importance for migratory birds).

In the second example, Cable Sands (WA) Pty Ltd mined the beach and dunes at the Minninup coastal site for titanium mines between 1988 and 1990, over a length of about 4 km. This feature provides an opportunity to view the excellent restitution of coastal landforms and vegetation following the mining activity (Fig. 23). 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 which has 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 the 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 it. 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, which was 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 23a looking southwestward towards the start of the mining area shows the final stages of sloping the dunes with a bulldozer. 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 become covered with a 5–10 cm layer of black sands, implying that a significant accumulation of the minerals is present offshore.

Locality 9: 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% TiO_2, 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 10: Gwindinup titanium minerals mine

Cable Sands Pty 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 2008.

The mine site will eventually be rehabilitated to farmland. Depending on the pits operating on the day, it could 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 two metres 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 sites 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.
- Clays washed from the ore being processed through thickeners and then spread out in shallow solar drying dams in successive one metre lifts. These are eventually covered with sand tailings, ripped and returned to the postmining land use. Experimental co-disposal 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.

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