Department of
Industry and Resources

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 2004-05

Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA ANNUAL REVIEW 2004–05

Frontispiece:
Collurabbie vista. Poor exposure, and its remote location 200 km north of Laverton on the margin of the Yilgarn Craton, give no hint of a potential major new nickel province discovered at Collurabbie in 2004. The best intercept in drilling of the Gerry Well greenstone belt by Falcon Minerals Ltd and WMC Resources Ltd was 8 m @ 1.23% Ni, 1.62% Cu, and 3.64 g/t platinum and palladium (Photo: MGA Zone 51, 427800E 7040000N). See 'Nickel–cobalt review' herein. The discovery followed up anomalies highlighted by GSWA's regional regolith geochemistry program on the KINGSTON 1:250 000 sheet.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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Perth 2005

MINISTER FOR STATE DEVELOPMENT
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Cover:
Classic olivine-spinifex texture in serpentinized komatiite, Marshall Pool, 70 km northwest of Leonora, Yilgarn Craton

Contents

GSWA mission statement

Our vision is to make Western Australia the focus of international mineral and petroleum exploration by becoming the benchmark for the delivery of prospectivity-enchancing, high-quality geoscientific products and services that meet the needs of our customers.

Our commitment is to provide, in a timely and courteous manner, up to date, quality regional geoscientific data, information, and advice to the mining and petroleum industries, Government, and the public to encourage and support resource exploration and facilitate informed land use planning and State development.

Our role is to elucidate the geological framework of Western Australia and reveal the potential for mineral and petroleum resources by providing spatially related geoscientific information, and regional geological, geophysical, and geochemical map products and reports. These products are based on the acquisition and analysis of field data, including submitted statutory exploration reports. As well, the Geological Survey evaluates mineral and petroleum resources as a basis for decision making by Government, and assists and advises on a variety of community needs, including urban planning and land use matters.

Our strengths are in field-based research, particularly regional geological mapping in both the Precambrian and Phanerozoic provinces of the State. The Survey also has prowess in the fields of structural geology, basin studies, carbonate sedimentology, mineralization studies, geochemistry and regolith studies, geochronology, paleontology, petrology, and geoscientific computer applications including database compilation.

Other areas of expertise include mineral economics, and financial modelling and evaluation of resources projects.

As a result of the application of these skills for over 100 years, and of its role as the depository of mineral and exploration reports, the Geological Survey is the custodian of an immense volume of information on the geology of the State and has become the premier pool of geoscientific expertise in Western Australia.

The year 2004–05 in review

by Tim Griffin, Executive Director

The year 2004–05 saw a strong rebound in the resources sector in Western Australia with both the mineral and petroleum industries benefiting from higher commodity prices, and the relevant exploration sectors experiencing a resurgence of interest and expenditure levels. However, despite this increase in total exploration expenditure, outlay on gold exploration in Western Australia actually declined and the State's share of the global exploration budget continued to decline as other jurisdictions, particularly Canada and South America, were more successful in attracting investment. Increasing the level of exploration investment in Western Australia is of the utmost importance if we are to maintain, in the long term, the high levels of production from resources that we currently experience. The Western Australian Government has provided some funding for increased acquisition of pre-competitive geoscience information, but significantly more funding is urgently required if we are to influence an increase in Western Australia's share of world exploration expenditure. Due to Western Australia's large area, it still lags behind many other jurisdictions that are competing for mineral exploration, particularly in the provision of fundamental datasets such as airborne magnetic and digital geochemical data.

Pre-competitive geoscience funding

Following the Premier's announcement in early 2004 of an additional A$12 million over four years for acquisition of new pre-competitive geoscience information, the first airborne geophysical surveys commenced in September 2004. The area selected for the initial surveys was the south Yilgarn region between Kellerberrin and Ravensthorpe. UTS Geophysics and Fugro Airborne Surveys were contracted to fly the surveys in three blocks at a line spacing of 400 m and a mean terrain clearance of 60 m. Additional data were acquired from private exploration companies to give total coverage of some 112 000 km^2. Initial magnetic and radiometric data were released in April 2005 and there was an immediate response from explorers taking up exploration tenements to cover targets identified in the new data, primarily for nickel and gold.

Further airborne surveys commenced late in the year in the Paterson area north of the Telfer gold mine, and planning is well-advanced for a helicopter-assisted gravity survey covering some 27 000 km^2 in this region, in conjunction with Geoscience Australia. Planning for additional airborne surveys in the northeastern Albany–Fraser Orogen and the northern Gascoyne Complex is also advanced. During the year 40 000 km^2 of new magnetic and radiometric data were also released for the Murchison area by Geoscience Australia.

GSWA production levels remain high

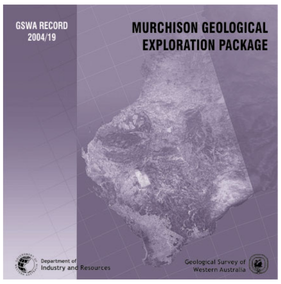
During 2004–05 GSWA published the following products:

- 47 geoscience maps, including seven at 1:100 000 scale
- 32 Records, Reports and other publications
- 21 digital information products

This output of geoscience products fell marginally below the previous year's productivity measured on a cost basis (output per million dollars). This was due, to a very large extent, to staff shortages in our GIS area as skilled GIS operators continue to be in high demand across the industry. Our GIS section, currently undergoing a major reorganization and staff recruitment exercise to address these issues, should significantly increase its productivity in 2006.

Geological Exploration Packages

The 'Geological Exploration Package' was a new digital product introduced in 2004 — with the first release for the west Musgrave region. This was followed up in 2004–05 with releases for the Murchison, Northeastern Yilgarn, Southeastern Yilgarn, and the West Tanami. The DVD packages are very popular with explorers as they provide a large amount of available geological and geophysical information that can be accessed with GSWA's handy GeoVIEWER.WA GIS viewing software provided with the packages, or loaded into the client's corporate GIS system. Depending on availability for each area, the packages include multiple aeromagnetic images (total magnetic intensity, reduced to pole, and first vertical derivative images), radiometric images, Landsat TM, ASTER, orthophotographs (1:25 000 and 1:100 000 mosaics), scanned 1:250 000 geological maps, and a revised geological interpretation based on new geophysical data and available geology. Packages also include copies of all relevant GSWA publications for the area as PDF files, including Bulletins, Records, Reports, maps and Explanatory Notes. These releases are designed to make all available data for a region accessible to explorers in advance of the release of our new 1:100 000-scale mapping.



Improved geochronology delivery

Delivery of quality geochronology data in a timely manner continues to be a priority for GSWA. The use of our freely distributed GeoVIEWER.WA software enables the combined GSWA and Geoscience Australia geochronology database for Western Australia to be accessed, searched, printed, or plotted. It is now possible to query the data for all dates for a particular formation, rock type, or tectonic unit, and to view or plot the results onto the State 1:500 000 or 1:2 500 000 geological maps. During the year there were two updates of geochronology information released, and it is planned to further improve delivery of results by making them available via our website (www.doir.wa.gov.au/gswa).

Hyperspectral scanning comes of age

In August–September 2004, the new CSIRO HyLogger, a rapid spectroscopic mineralogical drillcore-logging instrument, was trialled at GSWA's J. H. (Joe) Lord Core Library in Kalgoorlie. The HyLogger was developed by CSIRO and uses visible and infrared spectrometers and a high-resolution camera to log drillcore at a rate of up to 700 m of core per day. The system identifies alteration minerals such as micas, clays, and carbonates that are associated with many orebodies, but are difficult to distinguish with the naked eye. The trial was supported by local gold producers Placer Dome Inc. and Gold Fields Ltd (St Ives gold mine).

Hyperspectral scanning was also used for a trial airborne survey of the Kalgoorlie–Kanowna area to demonstrate to the exploration industry the effectiveness of this emerging technology. A collaborative program involving GSWA, HyVista Corporation, CSIRO Exploration and Mining, CRC LEME, MERIWA, and Placer Dome Asia Pacific collected new hyperspectral data on 26 flight lines covering some 2500 km^2 centred on Kalgoorlie. A map of kaolin disorder was released in June 2005, and a full report of the project and a series of mineral maps will be released early in 2005–06.

Web delivery of WAMEX reports is now turbo-charged

An exciting new, and vastly improved, online delivery system for open-file company mineral exploration (WAMEX) reports was implemented during the year. The system uses DigitalPaper XE, supplied through Fuji Xerox Australia, and is an integrated web-enabled browser-based viewing and document-searching application that allows you to view, print, or download documents online without the need to install additional software. Document viewing works rapidly even for very large files (e.g. 20 Mb), and an 'informed download' facility gives the option of choosing to download such files or ordering a copy on CD or DVD through our WAMEX agents.

The new WAMEX online facility comes at the right time as amendments to the Mining Act passed in late 2004 now allow release of exploration reports to open file five years after they are submitted to the Department. Some 21 000 closed-file reports will become eligible for release and GSWA has been allocated A$1.2 million over three years by the Western Australian Government to facilitate the massive task of scanning these reports.

Web delivery of GSWA publications

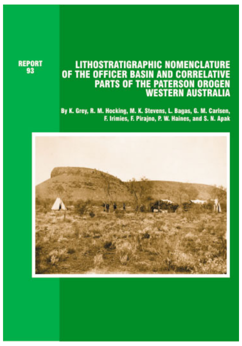
The implementation of the DigitalPaper system to allow online viewing and downloading of open-file exploration reports also gives us the opportunity to provide the same facility for other GSWA publications. By 2006 we hope to have all previous GSWA publications, including reports and maps dating from 1895, available for viewing online and downloading as PDF files via DigitalPaper direct from our website (www.doir.wa.gov.au/onlinepublications).

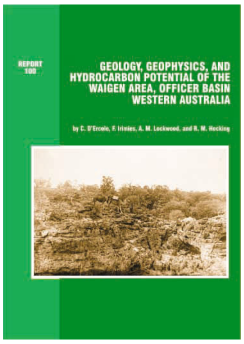
Work on Aboriginal lands accelerated

As GSWA focuses on greenfields areas of the State — where mapping has generally not been carried out for over 30 years — relationships are being forged with traditional Aboriginal owners to facilitate access to Aboriginal lands and land subject to Native Title claim. Geological mapping programs have commenced in the Musgrave and Tanami areas adjacent to the State's eastern border, and in the Cosmo Newbery area northeast of Laverton, and geophysical surveys are planned for the Paterson area near the Telfer gold mine. GSWA geologists are working with Aboriginal traditional owners to manage cultural sensitivities in these areas, and to provide some employment and training opportunities for local people. GSWA staff have attended meetings with traditional owners and representative bodies of these lands to explain the mapping process and its potential long-term benefits to the people of Western Australia.

Officer Basin studies draw to a close — for now

Investigations into the petroleum potential of the underexplored Neoproterozoic Officer Basin have been a major activity of GSWA's Petroleum Initiatives group for ten years. In 2005 four important reports on various aspects of the Officer Basin were released, integrating stratigraphic, seismic, and petroleum potential studies, as well as further details on GSWA's stratigraphic drillhole Lancer 1, drilled in 2003.





During the last ten years, important geoscientific knowledge and information on petroleum prospectivity of the largely unknown Officer Basin were obtained from seven deep wells, four drilled by GSWA and three by Amadeus Petroleum, one GA–GSWA deep-crustal seismic survey, and two GSWA gravity surveys. Some 25 GSWA publications on geology, geophysics, geochemistry, biostratigraphy, and petroleum geology represent a significant contribution to our knowledge of the prospectivity of the large, underexplored Officer Basin in Western Australia.

Onshore petroleum prospectivity promotion

Recent oil and gas discoveries in the northern Perth Basin have revitalized exploration activity in the region. There were two acreage releases — September 2004 and April 2005. In April 2005, to coincide with the APPEA Conference, DoIR released two petroleum-exploration blocks in the onshore western Canning Basin, and two blocks in the onshore northern Perth Basin, with closing dates for applications in October 2005.

Petroleum exploration information explosion

The program of scanning petroleum well-completion reports from hardcopy to PDF and TIFF formats continued in 2004–05 with a total of 671 reports added to the WAPIMS database, thus completing coverage for Western Australia's onshore basins. As part of the WAPIMS expansion program, well-log curves for a further 141 wells were loaded into the system, enabling the public to view the data via the web. Transcription of seismic-field and processed data from the Canning Basin was continued, to move these valuable data to new and more reliable media. Upgrades to the WAPIMS public interface were completed; 200 GB of data are now available online through WAPIMS.

Geological field excursions

During 2004–05 GSWA led field trips to the eastern Goldfields, the Southwest, and the Carnarvon Basin. The eastern Goldfields excursion in October 2004 attracted some 40 industry and research geologists in a 21-vehicle convoy to inspect key outcrops on the recently mapped sheets of ERAYINIA, YARDINA, YARDILLA, and MOUNT BELCHES southeast of Kalgoorlie. Participants were introduced to the Archean granite–greenstone geology of the area as well as the effects of the Proterozoic Albany–Fraser Orogen, and the overlying Cenozoic sedimentary rocks.

The Southwest excursion was billed as the *Mines and wines of the Southwest* and was part of the very successful SEG 2004 Conference organized by the Society of Economic Geologists. Over 700 registrants to this conference heard four days of invited speakers addressing the theme 'Predictive mineral discovery under cover'.

In May 2005 GSWA Petroleum Initiatives geologists led a group of industry geologists and geophysicists from Strike Oil, Chevron, and ENI Petroleum through a selection of outcrops in the northern Carnarvon Basin. The excursion focused on onshore correlatives of some of the exploration targets offshore in the southern North West Shelf.

Looking ahead

With petroleum and many of the minerals produced in Western Australia attracting record prices, and demand forecast to remain strong for these products for at least a few years, the State will continue to enjoy prosperous times … for a while.

More ore deposits and oilfields need to be discovered to continue to produce at these levels, and for this to happen we need to attract more exploration expenditure, particularly in greenfields areas of the State. There is an urgent need to stop the slide in the State's share of global exploration expenditure, and this is best done by making available more high-quality pre-competitive geoscience information. For Western Australia, this means more airborne geophysical surveys of frontier regions such as the Eucla Basin, Albany–Fraser Orogen, and the Kimberley area, but also more-extensive regional gravity surveys and compilations of open-file company geochemical data. The State Government's funding of A$12 million over four years, which commenced in 2004–05, is a welcome start in this direction but, as the Fardon Report recommended in 2001, and the Bowler and Prosser Reviews reinforced in subsequent years, much higher levels of funding to the Geological Survey are required if these goals are to be met. The State is in an ideal position now with record income from mineral and petroleum royalties (A$1.5 billion in 2004–05) to reinvest some of this windfall to ensure the sustainability of our envied lifestyle in Western Australia.

Overview of mineral exploration in Western Australia for 2004–05

by D. J. Flint

Overview

During 2004–05 mineral exploration expenditure* (excluding petroleum) for Western Australia rose sharply by 30% ($140.2 million) from $465.8 million to $606 million, which is the third year in succession where mineral exploration expenditure has risen in the State and follows a 10% increase over the previous year. However, mineral exploration is still well below (28% below) the peak level of 1996–97, when $845 million (in 2004–05 dollar terms) was spent (Fig. 1). The most recent quarterly data show that mineral exploration expenditure was levelling off during mid-2005, the peak of the field season, suggesting that any increase next year in mineral exploration expenditure will be smaller (Fig. 2). So far, the current boom does not appear as strong as at least three others that Western Australia has experienced over the last 40–50 years; i.e. the three exploration booms of 1970–71, 1987–88, and 1996–97 were stronger in 2004–05 dollar terms (Fig. 1).

The main interest in Western Australia continues to be exploration for iron ore and for nickel, with both of these sectors easily setting new records in exploration expenditure. The dominant gold sector suffered another decline in exploration during 2004–05, as has gold production, which has now declined for the last six years.

The Western Australian trend is consistent with the Australian trend. The 2004–05 level of mineral exploration expenditure within Australia is $1028 million, which is 27.6% ($222.4 million) higher than during 2003–04. However, mineral exploration expenditure in Australia is still well below the peak level of 1996–97, when $1404 million was spent (in 2004–05 dollar terms). Western Australia continues to attract the major proportion of mineral exploration expenditure in Australia (around 59%).

Unfortunately, the recovery in exploration expenditure in Australia and Western Australia has not been as strong as the worldwide recovery, and Australia and Western Australia have again both lost market share in the expanded pool of exploration capital (Fig. 3; based

* All $ figures in Australian dollars unless otherwise specified. All exploration expenditure figures and drilling statistics are compiled by the Australian Bureau of Statistics unless otherwise specified.

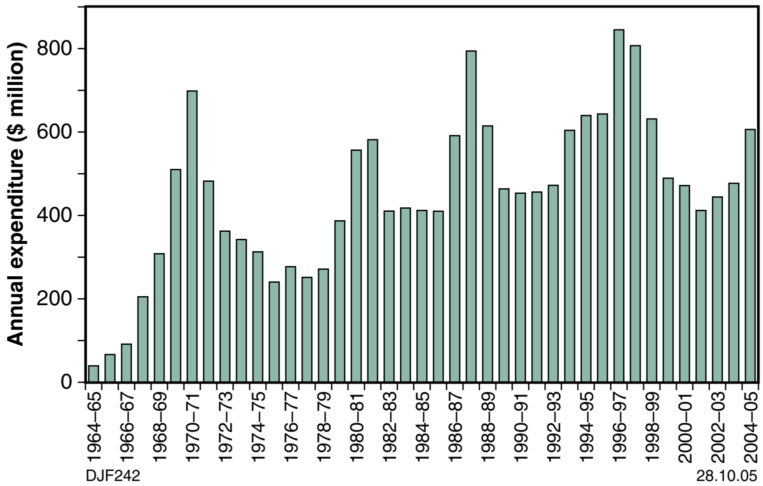


Figure 1. Mineral exploration expenditure in Western Australia, by financial year (2004–05 dollars)

on data compiled by the Metals Economics Group of Halifax, Canada, www.metalseconomics.com). During the last decade, the proportion of the world's non-ferrous mineral exploration expenditure in Australia has dropped from 23% to 15% of the total, whereas that for Western Australia has dropped from 12% to 8% of the total. The comparison with the situation in Canada is striking, with the proportion of worldwide mineral exploration expenditure spent in Canada recovering strongly after 1997, whereas the proportion has continued to fall in Australia and Western Australia (Fig. 3). This clearly illustrates what can be achieved with the combination of high-profile discoveries, ongoing exploration success, and favourable and innovative government regimes (including fiscal incentives to exploration).

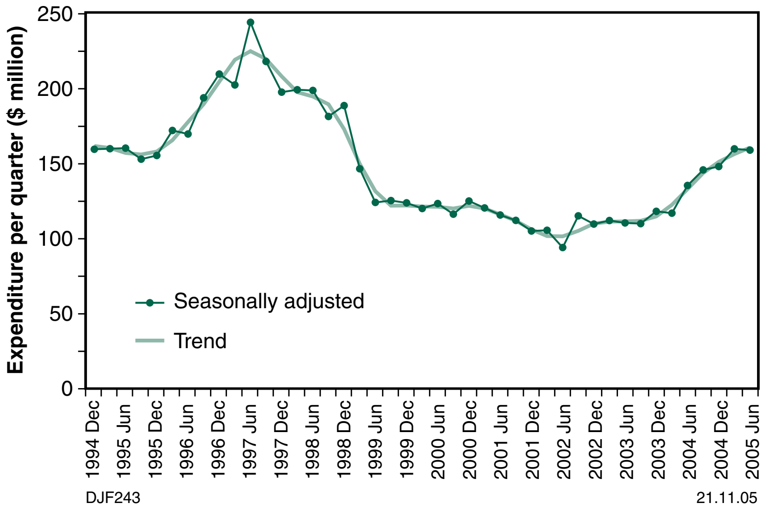


Figure 2. Mineral exploration expenditure in Western Australia, by quarter, on seasonally adjusted and trend terms (June 2005 dollars)

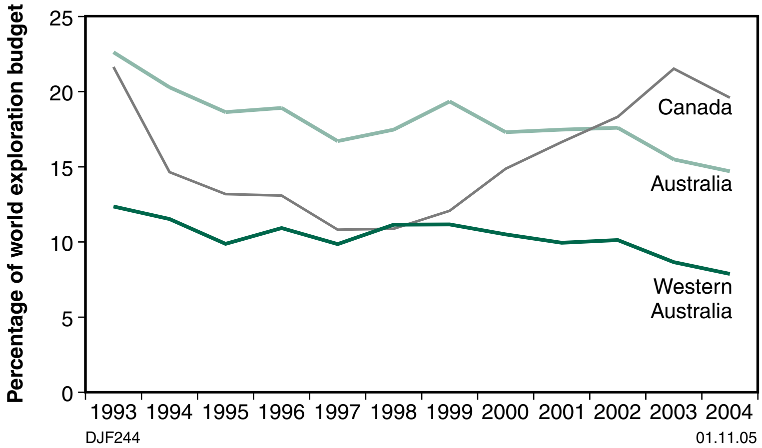


Figure 3. Non-ferrous mineral exploration expenditure — comparative market share of Canada, Australia, and Western Australia since 1993. Source: Metals Economics Group (Canada), ABS, and DoIR

Exploration and development highlights

Important gold discoveries are still being made in Western Australia, but few have been sufficiently spectacular to excite international attention. Perhaps the most newsworthy was that at Trident by Avoca Resources Ltd*, with a spectacular intercept of 27 m at 88 g/t Au, which included an intercept of the Athena lode at 10 m at 229 g/t Au. Other spectacular intercepts obtained were at Annean near Meekatharra (15 m at 45 g/t Au) by Mercator Minerals Ltd, at Burbanks near Coolgardie (25 m at 17 g/t Au) by Barra Resources Ltd, at Golden Eagle near Nullagine (29 m at 48 g/t Au) by Wedgetail Exploration NL, and at Blue Spec near Nullagine (3 m at 37 g/t Au and 1.5% Sb) by Northwest Resources Ltd. Further gold exploration success was achieved at some of the better 2003–04 projects, including Williamson–Regent (Lake Way), Sickle (Laverton), Brightstar (Laverton), and Withnell – Camel 1 and Wingina Well (Indee, Pilbara), the emerging gold province around Tropicana (southeast margin of the Yilgarn Craton), and gold–copper mineralization in the southwest Yilgarn Craton (Wongan Hills, Dominion Mining Ltd). Unfortunately, the investment market appeared to be mostly disinterested in good gold news during 2004–05.

Development highlights for gold in Western Australia are dominated by commissioning of the Telfer Au–Cu mine in the Paterson Orogen. Telfer is a world-class deposit and contains a total of about 26 Moz of gold and 950 kt of copper within its measured, indicated, and inferred resources. Gold production at Telfer during 2004–05 in the early commissioning phase was 160 000 ounces, but production during calendar 2006 is expected to be 800 000 ounces of gold. Other gold mines commissioned or being (re)developed during 2004–05 included Mungari East (85 000 ounces), Paulsens (5000 ounces; but 100 000 ounces per year expected for four years), and Lancefield (4000 ounces). Gold mines commencing production in mid-2005 were Lake Way (Calais, Williamson), Lord Henry and Lord Nelson at Sandstone, and Credo – Rose Dam.

In the nickel sector, the most notable greenfields exploration success during the last two years was at Collurabbie in the Gerry Well greenstone belt (northeast Yilgarn Craton), where Falcon Minerals Ltd and WMC Resources

* For further information on the numerous mines, deposits, or prospects mentioned in this article see the websites for the companies mentioned, which contain copies of company announcements to the Australian Stock Exchange (ASX). For location information, either see the relevant company websites, or DoIR's online databases (MINEDEX or GeoVIEW.WA) at www.doir.wa.gov.au, or Cooper and Flint (2005).

Ltd (the latter now part of BHP Billiton Ltd) announced in early 2004 a new nickel province. The discovery is a zone of combined nickel, copper, and platinum group elements (PGE) mineralization, but where the low Ni/Cu ratio and high PGE levels reported to date distinguish this mineralization from typical komatiite-hosted nickel sulfide mineralization. Significant brownfields exploration successes in the nickel sector include high-grade nickel sulfide mineralization at Prospero near Cosmos (Jubilee Mines NL), T5 at Flying Fox – Forrestania (Western Areas NL), McLeay near Kambalda (Independence Group NL), and Copernicus North in the east Kimberley region (Thundelarra Exploration Ltd). WMC Resources has successfully used an innovative deep-penetrating electromagnetic surveying technique ('Geoferret' technology) around Mount Keith that now more effectively explores for sulfide deposits at depths from 150 to 500 m below surface.

Nickel–cobalt production in Western Australia fell slightly during 2004, but is set to rise substantially with two advanced lateritic nickel projects. BHP Billiton (BHPB) is developing the Ravensthorpe project and plans to produce about 50 000 tpa of contained nickel, commencing production in late 2007. In the longer term, Heron Resources Ltd plans to produce about 50 000 tpa of contained nickel from the Kalgoorlie nickel project, with the bankable feasibility study for the project expected to be completed by the year 2011.

In the iron ore sector, 2004–05 was a time of unprecedented exploration throughout Western Australia, targeting many mineralization styles: channel iron deposits (CID); supergene-enriched hematite over Archean (Marra Mamba) to Paleoproterozoic (Brockman) banded iron-formations (BIF); primary magnetite in BIF of the Pilbara region; magnetite in Mesoproterozoic gneiss of the Albany–Fraser Orogen; clastic hematite in Paleoproterozoic–Mesoproterozoic sedimentary rocks of the Kimberley Basin (Cockatoo Island, Koolan Island) and Carr Boyd Basin (Pompeys Pillar); and for hematite in granular iron within the Frere Formation within the Paleoproterozoic Earaheedy Basin (Giralia Resources NL). Also in the Pilbara Craton, Fortescue Metals Group Ltd (FMG) has established substantial resources (more than 2000 Mt) of Marra Mamba supergene-enriched mineralization in the Chichester Ranges. There was considerable renewed interest by numerous companies in primary magnetite mineralization within BIF horizons throughout the Yilgarn Craton — to as far north as Wiluna (Golden West Resources Ltd) and as far south as Ravensthorpe (Resource Mining Corporation Ltd, Traka Resources Ltd). Numerous iron ore projects were at the feasibility stage.

All of the existing iron ore mines have expansion plans in place, and Koolanooka is being developed. The go-ahead has been given by BHPB for development of Western 4 (four mesas of CID mineralization along Marillana Creek) and Newman Orebody 18 (Brockman supergene-enriched mineralization), Robe River proposes development of the Mesa A – Bungaroo CID mineralization, and development proposals for Hope Downs and East Angelas were lodged by Hancock Prospecting Pty Ltd with Government.

At the Argyle diamond mine in the Kimberley region, Rio Tinto Ltd completed a full feasibility study on underground mining (which included an exploratory decline costing $70 million); negotiations with Government on the proposed development continued during 2004–05. Western Australia's second diamond mine in the Miocene lamproite pipes at Ellendale had a very successful year: mining expanded at Ellendale 9, mining commenced at Ellendale 4, trial mining started at the Terrace 5 gravels, and numerous other sites were being drill tested and bulk sampled (Kimberley Diamond Co. NL, Blina Diamonds NL). Greenfields exploration success during 2004–05 was in the west Pilbara Craton south of Karratha, where bulk sampling of the newly discovered Blacktop kimberlitic dyke and sill complex yielded 130 diamonds (totalling 5.22 carats) from a 33 t bulk sample (De Beers Australia Exploration Ltd, Helix Resources Ltd).

In the Ti–Zr sector, the highlights were construction of new mines near Perth at Gingin and Wagerup (Iluka Resources Ltd), proposals to mine at Waroona and Cataby (Iluka Resources) and at Coburn near Shark Bay (Gunson Resources Ltd), and substantial resource upgrades to the Keysbrook deposit (Olympia Resources Ltd). At Coburn, a bankable feasibility study was completed on 600 Mt of mineralization, with mining proposed for 2006. Mining in late 2006 is also planned at Waroona (Iluka Resources). At Keysbrook (70 km south of Perth), a bankable feasibility study was completed in mid-2005 (only one year after floating of Olympia Resources on the ASX), which suggested an 11-year mine life, with mining to start in late 2006 or early 2007. For greenfields exploration during 2004–05, there was renewed interest in strandlines of the Eucla Basin in Western Australia following the discovery in late 2004 of zircon-rich heavy mineral sands in the Eucla Basin of South Australia at the Jacinth and Ambrosia prospects (Iluka Resources, Adelaide Resources Ltd).

Mineral exploration expenditure by commodity

Western Australia still accounts for the major proportion of exploration dollars expended in Australia for many of the major commodities — iron ore (99%), nickel–cobalt (94%), diamond (67%), gold (66%), heavy mineral sands (54%), silver–lead–zinc (13%), and copper (7%).

Within Western Australia, gold remains the main focus of mineral exploration, accounting for about 42% of all exploration expenditure (Fig. 4). Other target commodities for exploration are nickel–cobalt (24%), iron ore (22%), diamond (3%), heavy mineral sands (2%), copper–lead–zinc–silver (2%), and 'others' totalling 5%. Although there has been renewed interest in uranium during 2005, there has been nil exploration expenditure in Western Australia.

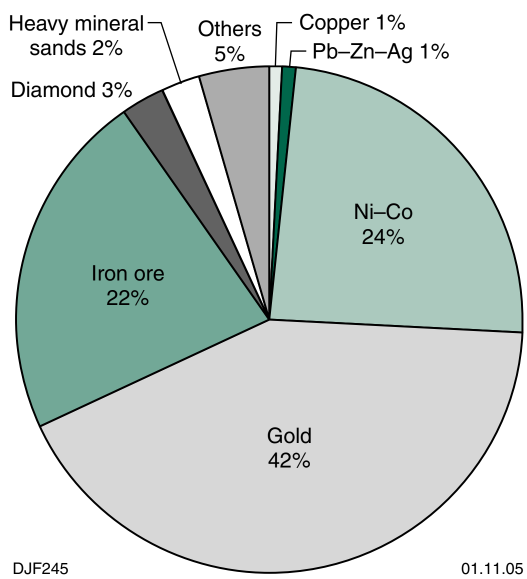


Figure 4. Mineral exploration expenditure in Western Australia, by commodity (2004–05)

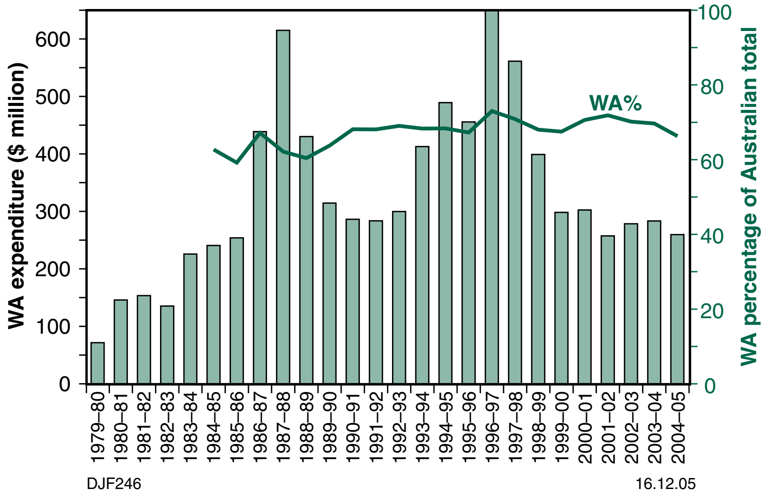


Figure 5. Gold exploration expenditure in Western Australia, by financial year (2004–05 dollars)

Commodities that attracted increased exploration expenditure in Western Australia during 2004–05 were iron ore, nickel–cobalt, heavy mineral sands, and 'others'. Commodities that attracted decreased exploration expenditure in Western Australia during 2004–05 were gold and diamond.

During 2004–05, $259.6 million was expended on gold exploration in Western Australia, which is a decrease of 8.4% ($23.8 million) from the $283.4 million spent in 2003–04 (expressed in 2004–05 dollars; Fig. 5). Gold exploration expenditure is now 60% below its peak levels experienced eight years ago during 1996–97. In addition, gold exploration expenditure in Western Australia is now at a level last experienced almost twenty years ago (2004–05 dollar terms; Fig. 5).

Gold exploration has been the backbone of the mineral exploration industry in Western Australia for many years, but the last ten years has seen it lose its shine — gold exploration expenditure was around 75% of the total mineral exploration expenditure in the mid-1990s, declining to only 42% during 2004–05. As it was in 2003–04, gold exploration companies found it easier to raise capital for nickel and iron ore exploration during 2004–05, hence there was a degree of refocusing and 're-inventing' themselves (e.g. Gindalbie Metals Ltd). Gold exploration was also hindered by gold miners experiencing higher costs, a relatively stable gold price, and lower profits, resulting in several development projects (for example, Coyote in the Granites–Tanami Complex) being put on hold. In general terms, a considerable amount of exploration was in an endeavour to convert near-mine mineral resources into ore reserves, thus limiting the chances of discovering new deposits. An inadequate level of greenfields mineral exploration is of ongoing concern for the future of gold mining in this State.

Exploration expenditure for nickel–cobalt rose dramatically during 2004–05, doubling in just one year, with a rise of 106% ($76.4 million) to $148.7 million (2004–05 dollar terms; Fig. 6). Exploration expenditure for Ni–Co has now risen strongly over the last three years and is now probably at an all-time record, surpassing the previous peak activity in 1997–98, which coincided with the exploration and development of the phase-1 nickel laterites (Murrin Murrin, Bulong, and Cawse). The recovery during the last three years, driven by high metal prices, was led principally by junior

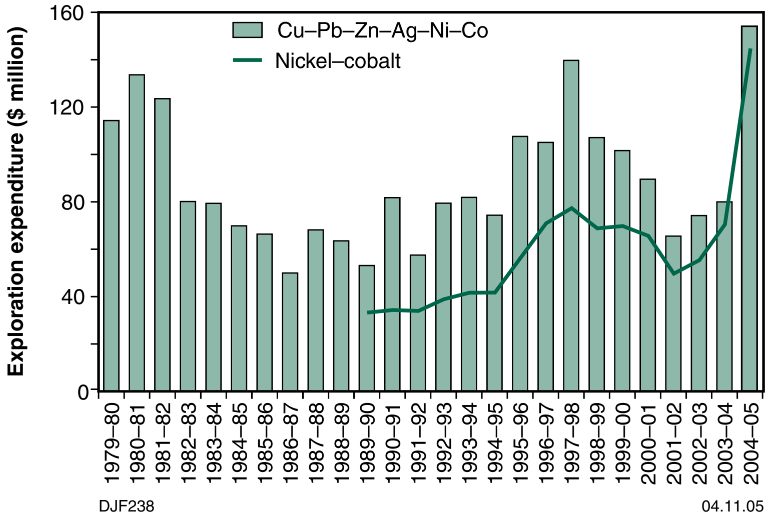


***Figure 6.** Base metal exploration expenditure in Western Australia, by financial year (2004–05 dollars). Base metals include copper, lead, zinc, silver, nickel, and cobalt. Note: the ABS did not separate Ni–Co data from total base metals until 1999–2000; Ni–Co data from 1989–90 to 1998–99 extracted from Hronsky and Schodde (in press)*

companies exploring for and developing nickel sulfide deposits (particularly in the Kambalda area at properties previously owned by WMC Ltd) and by BHPB completing the feasibility study for the large Ravensthorpe lateritic nickel project. Ravensthorpe alone will lift the State's nickel production by 30 000 – 50 000 tpa of contained nickel. In addition, Heron Resources has been advancing its Kalgoorlie nickel laterite project, also capable of producing up to 50 000 tonnes per year of contained nickel. However, the greatest exploration successes that have captured most attention have all been for nickel sulfide mineralization — at Collurabbie in the Gerry Well greenstone belt, at Prospero near Cosmos, and at the T5 deposit at Forrestania. Exploration for nickel in the Musgrave Complex was subdued after the excitement from 2000 to 2003, but WMC announced a potential resource of about 1 Mt of contained nickel and an equivalent amount of copper in the Babel deposit (in resources averaging about 0.47% Ni equivalent).

Iron ore exploration expenditure in Western Australia is now at the highest level ever recorded, with last year's record left far behind. During 2004–05 iron ore exploration expenditure jumped dramatically by 112% ($72.3 million), from $64.6 million to $136.9 million (2004–05 dollar terms; Fig. 7). This unprecedented iron ore boom was driven by strong customer demand for iron ore, particularly from China, and the iron ore price increases during the year of around 70%. The major producers in the Pilbara region have been able to respond fairly rapidly by expanding their operations at existing projects and planning new projects, with these including Western 4 at Yandicoogina, Brockman 4, and Mesa A – Warramboo. In addition, FMG has explored at a frenetic pace in the Chichester Ranges, particularly at Cloud Break and Christmas Creek. There is now unprecedented interest in iron ore throughout the State, including exploration for Archean magnetite deposits in primary banded iron-formations throughout the Yilgarn Craton. The high iron ore prices have greatly assisted the capital raisings of junior companies, opened up the industry to juniors, and lessened the duopoly of Rio Tinto and BHPB. There is now the prospect of a magnetite mine within the State in the next year or two, with perhaps Southdown the most likely magnetite deposit to

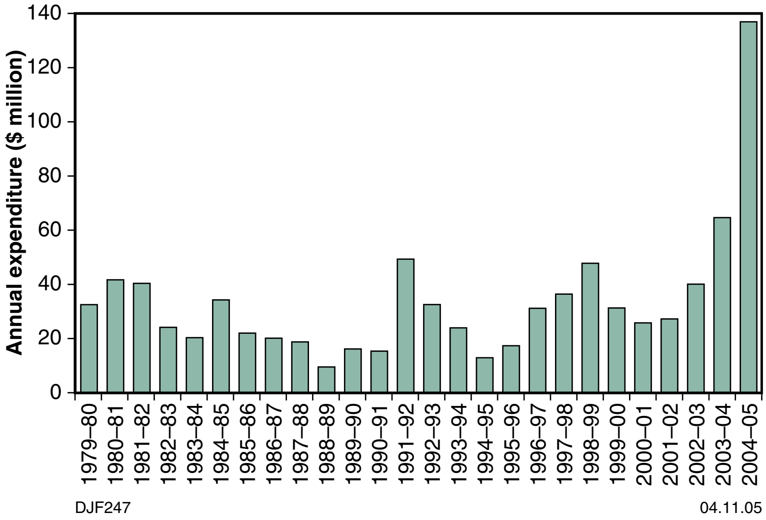


Figure 7. Iron ore exploration expenditure in Western Australia, by financial year (2004–05 dollars)

be developed first. At present over 60 companies are exploring for iron ore in Western Australia, with significant and diverse direct equity investment by Chinese, Korean, and Japanese companies — attempting to ensure long-term supplies and at lower prices than currently.

Diamond exploration expenditure in Western Australia is now at its lowest level for at least 25 years, decreasing by a further 8% during 2004–05, falling by $1.4 million to only $15.9 million for the year (2004–05 dollar terms; Fig. 8). This is the third year in a row that diamond exploration has declined. The fall was primarily due to reduced resource–reserve drilling activities at Argyle, with the openpit approaching the end of its estimated mine life and with the underground development option at the negotiating stage with Government. Although there were encouraging mining and exploration results in the Ellendale region, they were not sufficient to balance

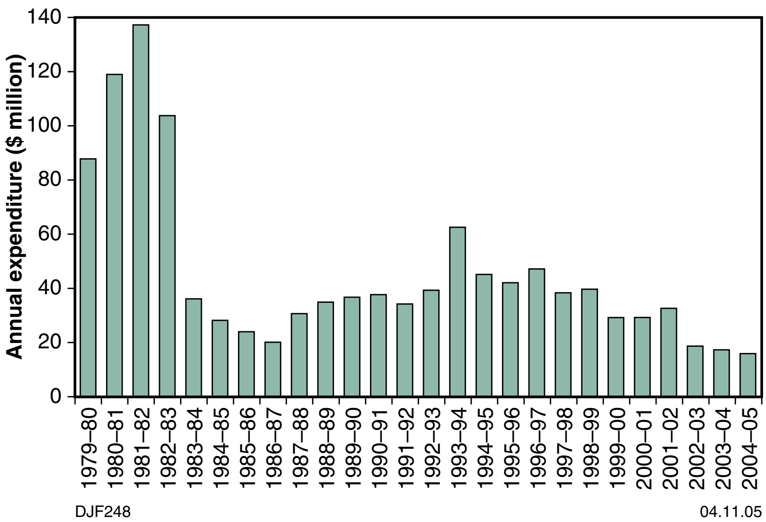


Figure 8. Diamond exploration expenditure in Western Australia, by financial year (2004–05 dollars)

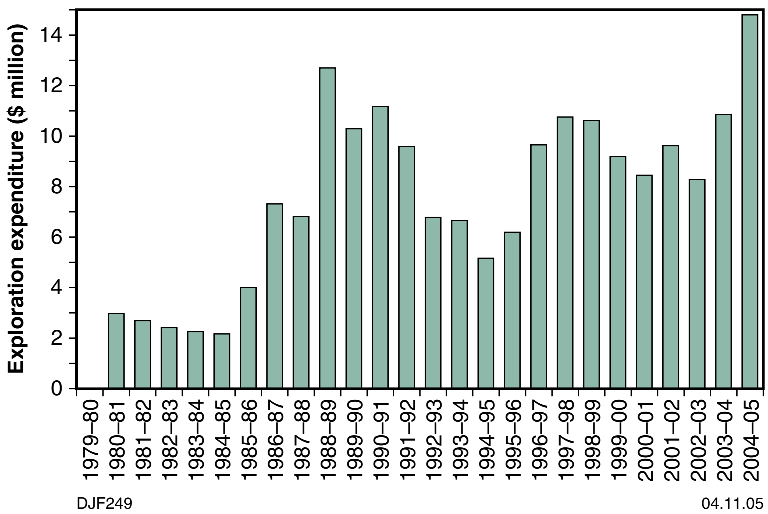


Figure 9. Heavy mineral sands (Ti–Zr) exploration expenditure in Western Australia, by financial year (2004–05 dollars)

the decreased exploration expenditure at Argyle. Diamond exploration expenditure has declined gradually over the last decade, and is now far below the peak level of $137 million in 1981–82 (in 2004–05 dollar terms) reflecting the general lack of exploration success, hence investor interest, in Western Australia. However, there has been some greenfield exploration success in the western part of the Pilbara Craton that may reverse investor sentiment.

Exploration expenditure for heavy minerals in Western Australia recovered strongly during 2004–05, rising by 36% ($3.9 million) to $14.8 million for 2004–05 — the second year in a row of such increases (2004–05 dollar terms; Fig. 9). Expenditure has been sufficient to break out of the band of $8 million to $11 million per year that has been the trend for the last decade. Exploration expenditure for Ti–Zr in Western Australia is now at the highest level for around 30 years. With the switch in exploration focus to the Murray Basin in Australia's eastern states in the mid-1990s, Western Australia's share of Australian exploration expenditure for heavy minerals had fallen from around 70% of the total in the mid-1990s to only 28% in 2002–03. However, during 2004–05 its share recovered to 54% of the total. The main greenfields exploration projects are Coburn, which progressed during 2004–05 to the development phase, and Keysbrook.

Exploration expenditure directed at copper–lead–zinc–silver in Western Australia improved during 2004–05 to total $9.5 million, attributed mainly to exploration and development of the Jaguar deposit (Archean VMS style) and the Magellan lead mine (supergene enrichment). There remains little interest in the Mississippi Valley-type Pb–Zn mineralization (sedimentary carbonate-hosted deposits) of the Lennard Shelf after Teck Cominco Ltd closed the mines in early 2004.

Exploration expenditure directed at 'other' minerals in Western Australia increased by 47% ($8.8 million) to $27.8 million in 2004–05. 'Others' include all industrial minerals, construction materials, PGE, tantalum, manganese, chromium, vanadium, rare earth elements, and coal–lignite. Exploration expenditure for these commodities is now at its highest level for the last 25 years; attributed to keen interest in the steel industry metals (manganese, chromium, and vanadium) and an awakening of interest in coal.

Drilling activity

Exploration drilling activity throughout Australia has now risen modestly for the third year in a row (as has general exploration expenditure), with this partially offsetting the huge decline from 1996–97 to 2001–02 (Fig. 10). The rise in metres drilled during 2004–05 for Australia was 18.8% (1.073 million metres) to a total of 6.784 million metres. The estimated mineral exploration drilling in Western Australia follows the same trend (based on Western Australia's proportion of the total Australian exploration expenditure for each year).

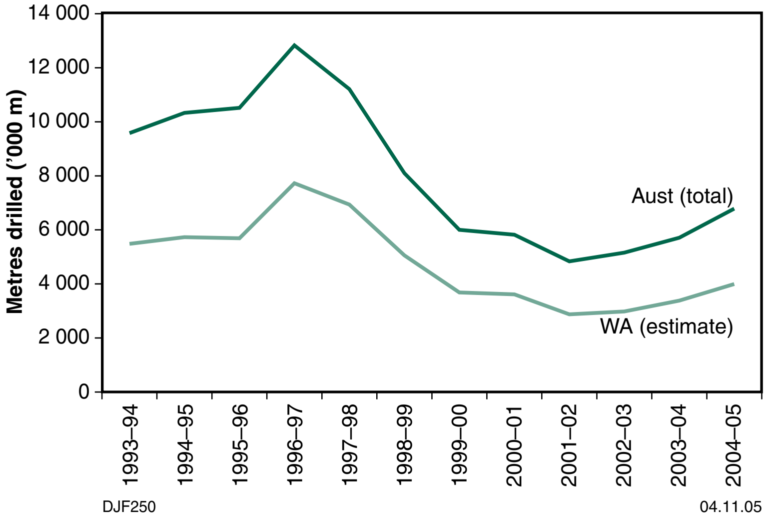


Figure 10. Mineral exploration drilling in Australia and Western Australia, by financial year (metres drilled)

However, mineral exploration drilling in Australia and in Western Australia is now at a level of around half that during the last boom of 1996–97. This highlights several factors, including the extreme severity of the five-year downturn (1996–97 to 2001–02) and that current drilling probably lacks the significant component of RAB drilling in greenfields areas, which characterized the previous exploration boom peaking in 1996–97. The data support the suggestion that Government financial incentives should be directed at stimulating more greenfields exploration.

If the current lack of drill-rig availability is partly due to a loss of drilling capacity from the Western Australian (and Australian) exploration industry then this will be a limiting factor to any immediate increase in mineral exploration expenditure.

Mining tenement activity

Despite mineral exploration expenditure during 2004–05 increasing by around 30%, the mineral tenement statistics* remain static. The number of granted tenements (all tenement types combined) increased by only 2.4% (380) from a total of 15 967 at 30 June 2004 to 16 347 at 30 June 2005 (Fig. 11). The area under granted tenure remained essentially unchanged. The distribution of tenements, both granted and under application, is shown in Figure 12.

The longer term data covering several exploration booms clearly show the link between exploration expenditure and tenement activity (Fig. 11). The

* Tenement data supplied by the Department's Mineral and Title Services Division and published in Department of Industry and Resources Annual Reports.

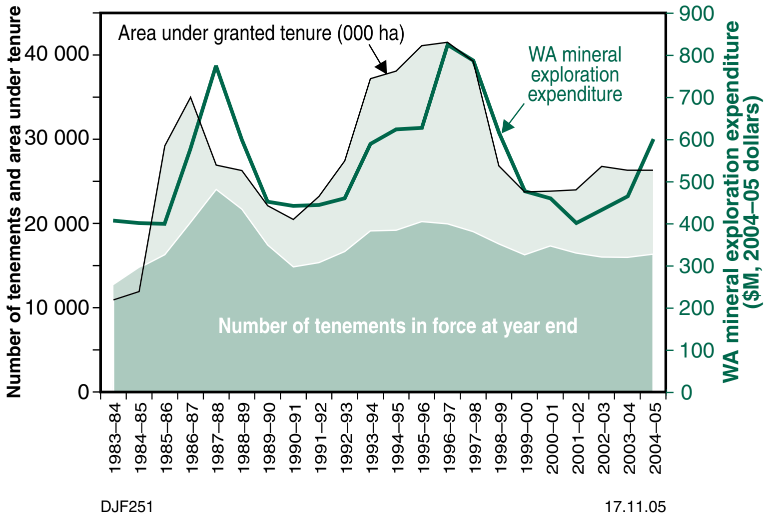


Figure 11. Tenement activity, Western Australia (1904 and 1978 Mining Acts). Source: DoIR

trend in the area under granted tenure closely follows the trend in broad mineral exploration expenditure, but the area under granted tenure is yet to rise significantly during the current boom.

Figure 11 also illustrates that the number of granted tenements is showing less volatility and hence less correlation with fluctuations in mineral exploration expenditure. Although the number of granted tenements rose sharply during the exploration boom that peaked in 1987–88, the rise in granted tenements during the boom of the mid-1990s was quite subdued. This trend persists in the current exploration boom, which so far is of smaller magnitude (Fig. 11).

The data suggest (but do not prove) that the trend towards brownfields exploration since the last boom peaked in 1996–97 has not yet been significantly reversed. The trends are also consistent with the hypothesis that Western Australia has become a ‘mature’ area for mineral exploration.

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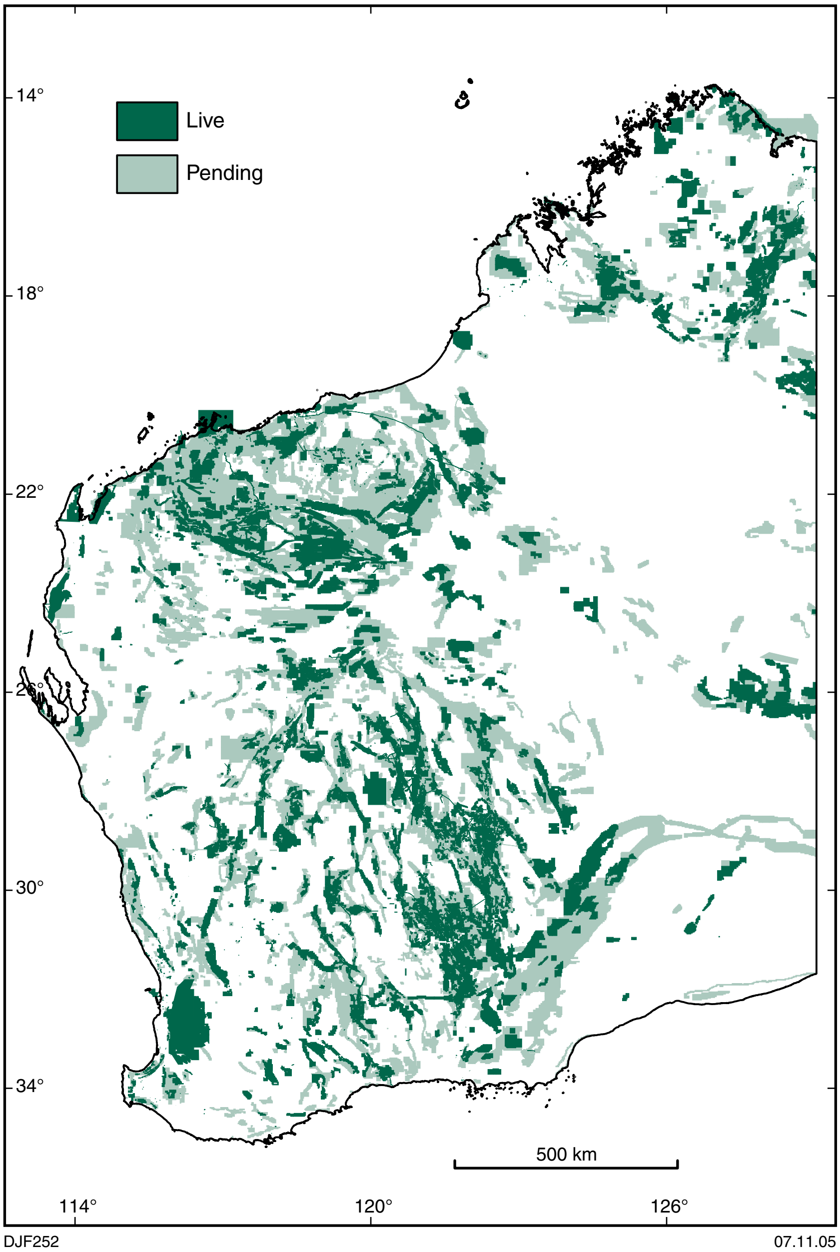

Figure 12. The distribution of mining and exploration tenements, granted and pending, in Western Australia as at 30 June 2005

Nickel–cobalt in Western Australia: commodity review for 2004–05

by P. B. Abeysinghe and D. J. Flint

Production

In 2004 Australia ranked third after Russia and Canada in global production of nickel, with an output of 177 kt of nickel (contained within nickel concentrate, matte, and refined nickel), which was valued at about A$3229 million*, and 100% of this production is from Western Australia. Of the Western Australian production, 81% (143 kt) was from nickel sulfide deposits and the remaining 19% (34 kt) was from nickel laterite deposits. Table 1 gives 2004–05 nickel production figures released to the Australian Stock Exchange by a number of companies in the State. The production of cobalt (as a byproduct) in the State during calendar year 2004 was 4551 t valued at A$262 million. Figures 1 and 2 illustrate the trends in the production of nickel and cobalt in Western Australia since 1998.

Nickel–cobalt production in Western Australia fell slightly during 2004, but is set to rise substantially with two advanced lateritic nickel projects. BHP Billiton Ltd (BHPB) plans to produce about 50 000 tpa of contained nickel from their Ravensthorpe project, commencing production by the third quarter of 2007. In the longer term, Heron Resources Ltd plans to produce about 50 000 tpa of contained nickel from the Kalgoorlie nickel project, with the bankable feasibility study for the project expected to be completed by 2011.

Development highlights — nickel sulfide projects

There are about 300 nickel sulfide mines, deposits, and exploration sites in Western Australia, distributed in the Yilgarn Craton, Pilbara Craton, Halls Creek Orogen, and Musgrave Complex. Most of the nickel sites in the State are in the Yilgarn Craton, around Kalgoorlie, Kambalda, Leinster, Murrin Murrin, Forrestania, Lake Johnston, and Ravensthorpe. The Kambalda region was the centre for much of the nickel sulfide exploration and mine development, with recommencement of mining from Wannaway, Redross, Mariners, Blair, and Zone 29 deposits. Other significant developments in the mining sector were the opening of the Sally Malay mine in the Halls Creek region, Maggie Hays mine in the Lake Johnston region, Lanfranchi nickel sulfide mine near Kambalda , and the Radio Hill mine in the Karratha region. The development of the Flying Fox deposit in the Forrestania area began in late 2004. A bankable feasibility study was completed for the Sherlock Bay deposit near Karratha and a feasibility study commenced for the Copernicus deposit at Halls Creek.

* This paper is a condensed version of Abeysinghe and Flint (in prep.). See their original paper for a complete list of references.

Table 1. Western Australian nickel production 2004–05

Project	*Operator*	*Production Ni (t)*	*Mineralization type*
Leinster Nickel Operations	WMC Resources Ltd[(a)]	35 079[(b)]	Sulfide
Mount Keith Operations	WMC Resources Ltd	31 833[(c)]	Sulfide
Long	Independence Group NL	8 869	Sulfide
Miitel	Mincor Resources NL	6 884	Sulfide
Wannaway	Mincor Resources NL	923	Sulfide
Redross	Mincor Resources NL	1 537	Sulfide
Mariners	Mincor Resources NL	670	Sulfide
Blair (Area 57 orebody)	Australian Mines Ltd	1 457	Sulfide
Carnilya+Zone 29	View Resources Ltd	1 460	Sulfide
Cosmos	Jubilee Mines NL	11 025	Sulfide
Silver Swan	MPI Mines Ltd	6 165	Sulfide
Emily Ann	LionOre Mining International Ltd	9 882	Sulfide
RAV8	Tectonic Resources NL	1 569	Sulfide
Beta Hunt	Reliance Mining Ltd (now Consolidated Minerals Ltd)	4 758	Sulfide
Radio Hill	Fox Resources Ltd	2 109	Sulfide
Sally Malay	Sally Malay Mining Ltd	4 582	Sulfide
Murrin Murrin	Minara Resources Ltd	28 631	Laterite
Cawse	OMG Cawse Pty Ltd	5 180[(c)]	Laterite
Total: nickel sulfide		128 802	
Total: nickel laterite		33 811	
Total: Western Australia		**162 613**	

NOTES: (a) WMC Resources Ltd now part of BHP Billiton Ltd
(b) Does not include June 2005 quarter (not available)
(c) Estimated

Development highlights — nickel laterite projects

There are about 160 nickel laterite mines, deposits, and exploration sites in Western Australia, mostly distributed in the Yilgarn Craton. The only producing nickel laterite mines were at Murrin Murrin, 60 km east of Leonora, and at Cawse, about 55 km northwest of Kalgoorlie. Heron Resources signed a joint venture agreement with Inco Australia Ltd to develop its Kalgoorlie nickel project, which has the largest resource inventory of any Australian nickel laterite project, and is estimated to contain a total measured, indicated, and inferred resource of 903 Mt grading 0.74% Ni and 0.05% Co. During 2004 work progressed well at BHPB's Ravensthorpe

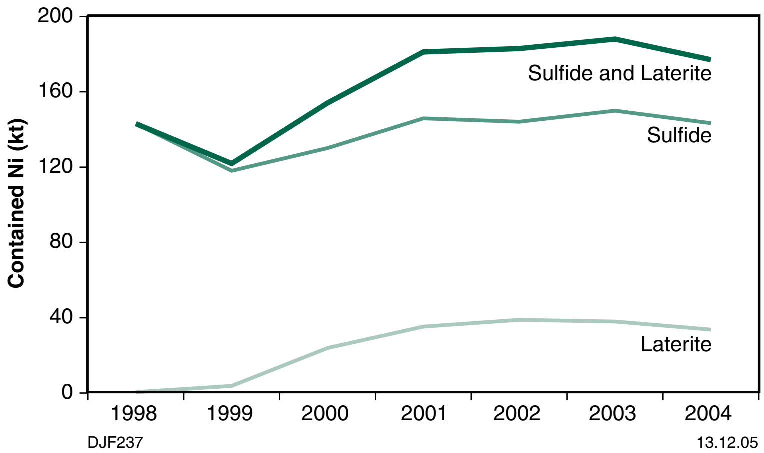

Figure 1. Western Australian nickel production, by year from 1998 to 2004

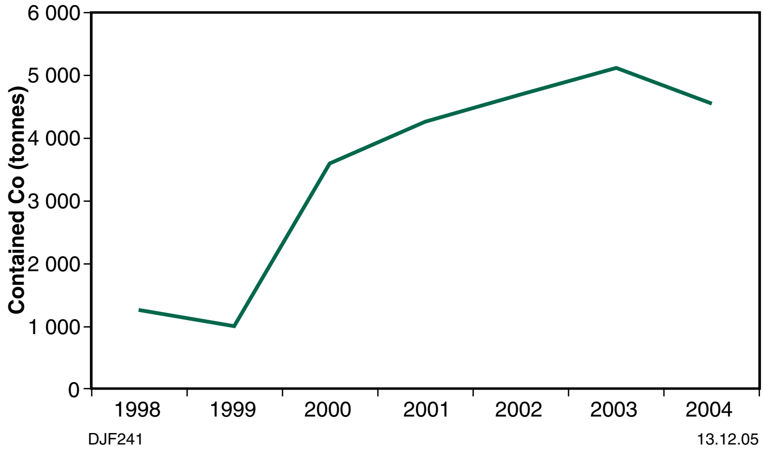

Figure 2. Western Australian cobalt production, by year from 1998 to 2004

nickel laterite project. The project involves openpit mining from three adjacent nickel laterite deposits Halleys, Hale-Bopp, and Shoemaker-Levy, which have a total proved and probable reserve of 263.3 Mt at 0.65% Ni and 0.029% Co. Mining will commence at the Halleys deposit and is expected to continue for the first 11 years of operation. The development is expected to produce a total of around 50 000 tpa of contained nickel, but, with the grade declining after the first seven years, the output will be 30 000–35 000 tpa of contained nickel from year 8 to year 28 of the project. The project at Ravensthorpe is on-track for initial deliveries of its mixed hydroxide product to an expanded Yabulu refinery in Queensland during the first half of 2007.

Exploration

During 2004–05 about 170 companies explored for nickel in Western Australia. Exploration expenditure for nickel–cobalt has risen sharply over the last three years and is now at record levels, exceeding A$140 million per year (Fig. 3). Expenditure in 2004–05 was slightly more than double that of 2003–04.

The areas of interest for greenfields exploration were the northern parts of the Yilgarn Craton (such as Gerry Well greenstone belt), the Kimberley region, Musgrave Complex, and the west Bangemall region. In the Yilgarn Craton Kambalda-type komatiite-hosted nickel deposits in the Archean greenstone belts and Raglan-type komatiite-hosted deposits in rifted continental margins were the main targets. In the Kimberley region, Musgrave Complex, and west Bangemall region the main targets were Voiseys Bay-type deposits associated with tholeiitic intrusions, and Noril'sk-type deposits in rift- and continental-flood basalts.

The most notable greenfields exploration success was at Collurabbie in the Gerry Well greenstone belt of the Yilgarn Craton, where WMC Resources Ltd (now part of BHPB) announced a new nickel province. The discovery is a zone of combined nickel, copper, and platinum group elements (PGE) mineralization extending over 7 km along strike. A number of significant drill intersections have been obtained, including 5.77 m at 3.00% Ni, 1.96% Cu, and 5.29 g/t Pt+Pd from 279.43 m in drillhole CLD159. The low Ni/Cu ratio and high PGE levels reported to date distinguish this mineralization from typical komatiite-hosted nickel sulfide mineralization.

A number of companies had brownfields exploration success near their existing operations:

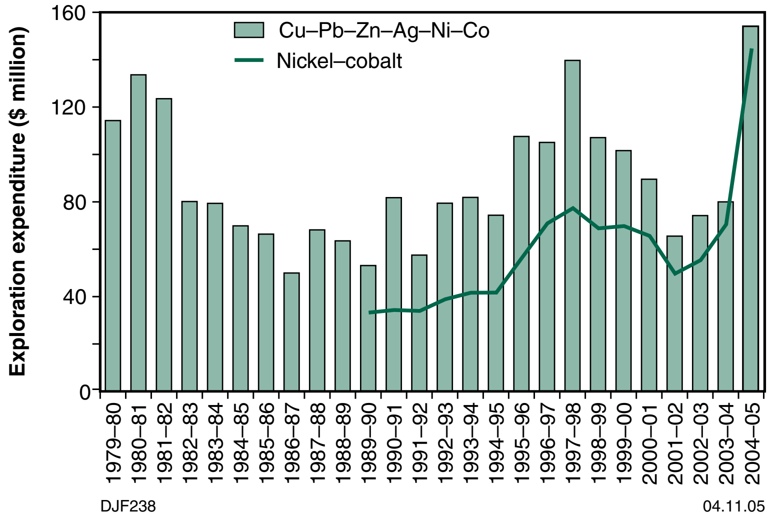

***Figure 3.** Western Australian base metal and nickel exploration expenditure, by financial year (2004–05 dollars), (Australian Bureau of Statistics, and Hronsky and Schodde, in press)*

- WMC Resources has successfully used an innovative deep-penetrating electromagnetic surveying technique (‘Geoferret’ technology) around Mount Keith, which now more effectively explores depths from 150 to 500 m below surface.

- Jubilee Mines NL discovered high-grade mineralization at Prospero near Cosmos mine, 35 km northwest of Leinster, and estimated an inferred resource of 1.06 Mt at 5.72% Ni for the deposit. Jubilee Mines also identified promising mineralization at nearby Alec Mairs and Anomalies 1 and 4, extending the considerable success around Cosmos.

- In the Forrestania belt, Western Areas NL reported considerable exploration success at Forrestania, with new resources reported for Flying Fox T5 deposit (inferred resource of 0.63 Mt at 6.9% Ni) in addition to those reported for Flying Fox T1 and Flying Fox T2 deposits.

- Independence Group NL announced the discovery of the high-grade McLeay nickel deposit south of Victor South deposit at the southerly extension of the Long nickel mine, near Kambalda.

- Drilling by Mincor Resources NL north of North Miitel mine and south of Miitel mine, about 40 km south of Kambalda, produced high-grade nickel intersections.

- In the Leinster and Wiluna regions, LionOre Mining International Ltd increased its exploration activities at Wedgetail and Harrier deposits of the Honeymoon Well project. LionOre Mining has suggested the possibility of production from Honeymoon Well by mid-2008.

- WMC Resources commenced pre-feasibility studies at the Yakabindie deposits.

- Exploration drilling by Consolidated Minerals Ltd at Beta Hunt and East Alpha near Kambalda has doubled the global resource to 2.1 Mt at 3.6% nickel, with 1.045 Mt in the measured and indicated categories.

- Thundelarra Exploration Ltd discovered the Copernicus North orebody (north of Halls Creek) that has similarities to Voiseys Bay-type nickel

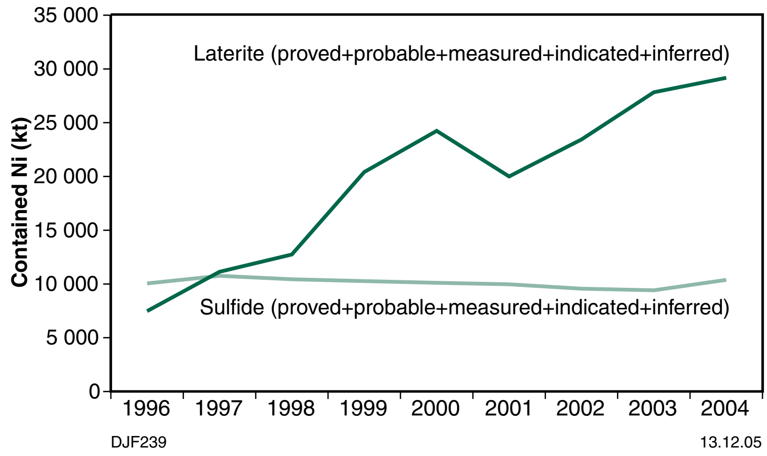

Figure 4. Western Australian nickel sulfide and nickel laterite resources, by year since 1996

mineralization. There was also significant exploration around Copernicus and Salk North deposits in the Halls Creek region and the area is proving to be highly prospective for Voiseys Bay-type nickel mineralization.

Mineral resources and ore reserves

Total resources of nickel (in all JORC categories and in all deposit styles) have increased throughout the last decade, largely due to the successful delineation of nickel laterite resources. Resources of nickel laterite have increased about fourfold over the last 10 years, whereas resources of nickel sulfide have remained almost unchanged (Fig. 4).

Figure 5 illustrates the more detailed trends for nickel laterite and nickel sulfide in all JORC categories. For nickel laterite, the increase has been relatively uniform in both inferred resources, as well as reserves and measured and indicated combined. However, for sulfide nickel, the overall long-term trend is more of resources switching classifications with no net increase or decrease. The current trend for sulfide nickel resources is most likely to be broken if and when an initial resource estimate for Babel and Nebo (West Musgrave) is compiled.

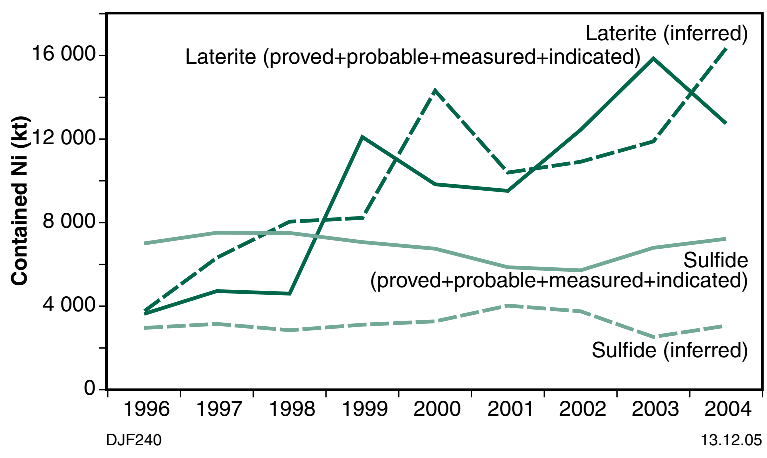

Figure 5. Western Australian nickel sulfide and nickel laterite resources (measured + indicated + inferred), by year since 1996. Measured and indicated resources also include any converted to ore reserves

Table 2. Nickel sulfide projects in Western Australia, ranked by contained nickel. Includes nickel in all resource and reserve categories

Nickel sulfide deposits[(a)]	*Operator*	*Contained Ni (kt)*
Mount Keith	WMC Resources Ltd (BHP Billiton Ltd)	2 321
Leinster	WMC Resources Ltd (BHP Billiton Ltd)	1 726
Yakabindie	WMC Resources Ltd (BHP Billiton Ltd)	1 677
Honeymoon Well	LionOre Mining International Ltd/OM Group	1 016
Cosmos	Jubilee Mines Ltd	412
Emily Ann – Maggie Hays	LionOre Mining International Ltd	236
Jericho	WMC Resources Ltd (BHP Billiton Ltd)	207
Kambalda	BHP Billiton Ltd /Independence Group NL/Breakaway Resources Ltd	191
Sherlock Bay	Sherlock Bay Nickel Corp Ltd	162
Panton	Platinum Australia Ltd	158
Widgiemooltha North	Titan Resources NL	147
Miitel–Redross	Mincor Resources NL	127
Worthy	Westralian Nickel NL	115
Silver Swan – Black Swan	LionOre Mining International Ltd	110
Cliffs	WMC Resources Ltd (BHP Billiton Ltd)	102
		8 707

NOTES: (a) Excludes deposits of less than 100 kt

Table 3. Nickel laterite projects in Western Australia, ranked by contained nickel. Includes nickel in all resource and reserve categories

Nickel laterite deposits[(a)]	*Operator*	*Contained Ni (kt)*
Mount Margaret	Minara Resources Ltd	3 464
Murrin Murrin	Minara Resources Ltd/GME Resources Ltd	3 441
Ravensthorpe	BHP Billiton Ltd/Traka Resources Ltd	2 530
Weld Range	Minara Resources Ltd/Dragon Mining NL/Sons of Gwalia Ltd	2 475
Wingellina	Acclaim Exploration Ltd	2 269
Honeymoon Well	LionOre Mining International Ltd/OM Group	2 250
Bulong	Heron Resources Ltd/Inco Australia Ltd[(b)]	2 099
Goongarrie	Heron Resources Ltd/Inco Australia Ltd	1 498
Siberia	Heron Resources Ltd/Inco Australia Ltd	1 358
Wiluna	Agincourt Resources Ltd	833
Highway	Heron Resources Ltd	712
Kalpini	Heron Resources Ltd	670
Pinnacles	Peninsula Minerals Ltd/Bannerman Resources Ltd	350
Ghost Rocks	Heron Resources Ltd	312
Eucalyptus Bore	GME Resources Ltd	227
Yerilla	Heron Resources Ltd/Inco Australia Ltd/Minara Resources Ltd	171
Irwin Hills	Yilgarn Mining Ltd/Minara Resources Ltd	153
Lake Rebecca	Heron Resources Ltd/Inco Australia Ltd	152
		24 964

NOTES: (a) Excludes deposits of less than 100 kt
(b) Kalgoorlie nickel project comprises deposits operated jointly by Heron Resources Ltd and Inco Australia Ltd
Cawse: figures are not available

Tables 2 and 3 indicate the ranking of nickel sulfide and nickel laterite deposits in Western Australia by contained nickel (ore reserves and resources combined).

For deposits averaging 1% Ni or greater, Western Australia has about 8% (10 Mt) of the global nickel resources (130 Mt) and about 11% (1.6 Mt) of the global cobalt resource of 15 Mt.

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Evidence of early life from international collaborative drilling in the Pilbara Craton

by A. H. Hickman

Abstract

The Geological Survey of Western Australia has played a major role in three international geoscientific drilling projects in the Pilbara region of Western Australia. Thirteen diamond drillcores, obtained from some of Earth's best preserved Archean sedimentary and volcanic rocks, are now starting to provide important new evidence on Earth's early life. Research teams in Japan, U.S.A., France, and Australia are searching for microscopic and chemical evidence that life existed in a range of ancient depositional environments between 3490 and 2490 Ma. The research is also attempting to resolve the controversy on whether or not Earth's early hydrosphere and atmosphere contained oxygen.

Early results support past suggestions, based on structures interpreted to be fossilized stromatolites and microfossils, that life existed on Earth from at least 3460 Ma. Additionally, there is new evidence to suggest that oxygen may have been present in the atmosphere at 2920 and 2760 Ma.

KEYWORDS: Pilbara, geoscientific drilling, early life.

Pilbara geoscientific drilling

The Geological Survey of Western Australia (GSWA) is a participant of three international geoscientific drilling projects in the Pilbara region of Western Australia. Thirteen diamond drillholes, varying in depth between 100 and 1000 m, were drilled during 2003 and 2004, and intersected sedimentary and volcanic rocks ranging in age from 3490 to 2490 Ma (Fig. 1). Drilling avoids the near-surface chemical and biological contamination in rock outcrops.

In 2003 the Archean Biosphere Drilling Project (ABDP) was jointly conducted with the Pennsylvania State Astrobiology Research Center (PSARC), Kagoshima University (KU), and The University of Western Australia (UWA). GSWA's initial role was to advise on the best drilling locations to obtain the rock types required. GSWA then undertook much of the work required to obtain necessary approvals and permits before drilling. After drilling GSWA provided facilities to cut the core (about 1400 m from 6 holes) at the Perth Core Library, where 50% of all core was retained with the remainder being exported to KU and PSARC.

In 2004 the Deep Time Drilling Project (DTDP) included all members of the ABDP, with the addition of researchers from the University of

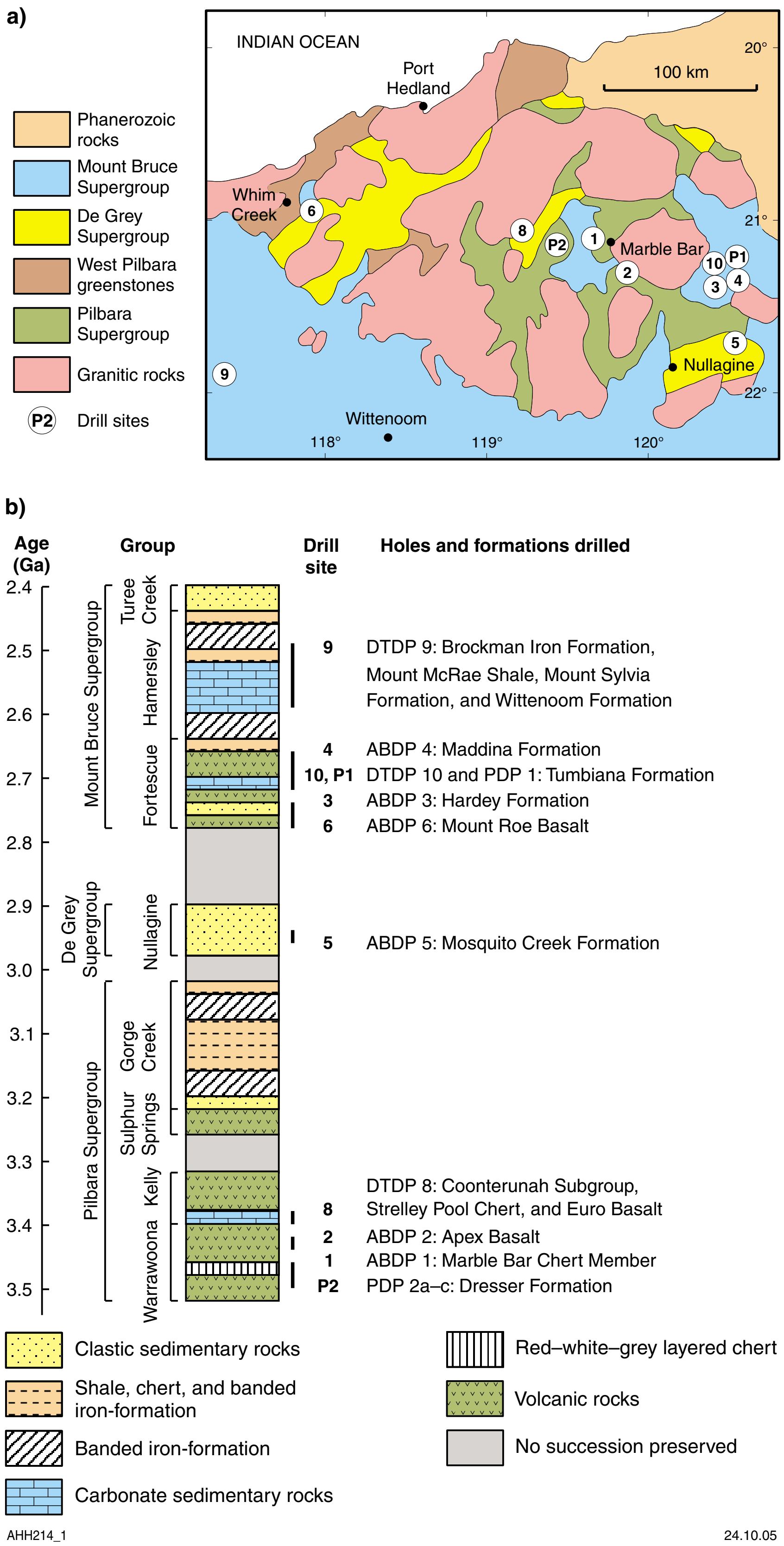

Figure 1. Stratigraphy and locations of the geoscientific diamond drilling projects in the Pilbara Craton, 2003–04: a) stratigraphic positions of the geoscientific drillholes; b) simplified geology of the northeast Pilbara Craton showing locations of the drilling sites. Note: drilling of site 7 was never undertaken

Washington (UW) and Arizona State University (ASU). This project drilled three holes, one almost 1000 m deep. As in 2003, GSWA's main role was advisory and logistical. In the same year the Pilbara Drilling Project (PDP), by GSWA and the Institute de Physique du Globe de Paris (IPGP), drilled four holes, including two through the 3490 Ma Dresser Formation, which is the oldest known fossiliferous unit in the Pilbara region. GSWA is currently assisting with research on the PDP cores.

Project aims

The time that life first appeared on Earth and what forms this life took are currently very controversial subjects. Some geoscientists and biogeochemists believe that life did not appear on Earth until the Paleoproterozoic era (commencing at 2500 Ma), and many believe that Earth's atmosphere was essentially anoxic before c. 2350 Ma (see below). Others maintain that the fossil record is adequate to establish that life was already well developed on Earth at 3500 Ma, and some geochemists have argued that the Earth's atmosphere contained oxygen as far back as 4000 Ma (e.g. Ohmoto, 2004). The level of controversy reflects a lack of data from Archean rocks (older than 2500 Ma). Outside the Pilbara Craton of Western Australia and the Kaapvaal Craton of South Africa, there are few Archean rocks of sufficiently low metamorphic grade to preserve good evidence of ancient life.

The Pilbara drilling targeted particular rock types. Archean life was probably bacterial, inhabiting hot springs, volcanic calderas, freshwater lakes, continental margins, or deep-sea hydrothermal-vent environments. The most prospective rock types are chemically precipitated chert and carbonate sedimentary rocks, which in Proterozoic and Phanerozoic successions contain bacterial fossils, and carbonaceous and sulfidic shales and sandstones, which in post-Archean successions commonly owe their compositions to accumulations of biological organic material.

Archean life

Throughout the post-2500 Ma geological record, bacterial colonies have built structures, termed 'stromatolites', that range from a few millimetres to several metres in height. These structures are biochemical precipitates of carbonate or siliceous minerals that are preserved as fossils. Some 2720 Ma stromatolites from the Pilbara region (e.g. Fig. 2) have morphologies very similar to Proterozoic stromatolites that are universally accepted as biogenic. Much older structures interpreted as stromatolites or fossilized microbial mats have been discovered in the Pilbara region, in rocks as old as

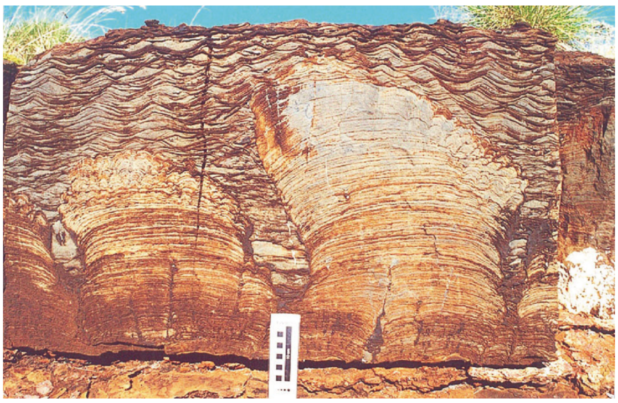

***Figure 2.** Cross-section exposure of columnar stromatolites in carbonate rocks of the c. 2720 Ma Tumbiana Formation of the Fortescue Group, Meentheena, Pilbara Craton. This unit was drilled in ABDP 10 and PDP 1*

***Figure 3.** Wavy-laminated chert (interpreted as fossilized bacterial mats) and domical stromatolites in the c. 3490 Ma Dresser Formation, North Pole, Pilbara Craton. This unit was drilled in PDP 2b and 2c*

c. 3490 Ma (Fig. 3). Although many geoscientists accept the stromatolite-like morphology of these structures as adequate evidence of their bacterial origin, others question a bacterial origin. Likewise, examples of 'microfossils' reported from early Archean Pilbara Craton chert (Schopf, 1993) have recently been reinterpreted as products of inorganic mineral crystallization (Brasier et al., in press). Ratios between the stable isotopes of carbon are generally agreed to be useful in distinguishing biological from nonbiological carbonaceous material in sedimentary rocks of low metamorphic grade. Most workers agree that strongly depleted $\delta^{13}C$ compositions (–15 to –60 per mil) indicate a biological origin.

Astrobiology

The Pilbara drilling projects are not only aimed at uncovering diagnostic proof of early life on Earth. Mars probably had similar environments to Earth during the early Archean, and the two planets may at that time have supported similar life. The rarity and the currently contentious nature of early Archean fossils on Earth highlights how difficult it may be to discover convincing evidence of early Archean Martian life, if it existed. Astrobiologists therefore need high-quality data from Earth to assist their exploration of Mars.

Selected early research results

ABDP Hole 1, Marble Bar Chert Member and Apex Basalt (c. 3460 Ma)

The Marble Bar Chert Member of the Duffer Formation is well known for its distinctive red, white, and grey layering (Fig. 4). This results from different proportions of hematite (in red chert), magnetite (in grey to black chert), and siderite (in rare green chert). The Apex Basalt, which stratigraphically overlies the chert, also contains hematite. ABDP 1 was drilled to determine if the hematite is merely a near-surface alteration product of primary minerals such as siderite or pyrite or if it extends to depths below the effects of oxidation by today's atmosphere.

Red chert typically makes up about 30% of surface exposures of the Marble Bar Chert Member, but is far less common in the ABDP 1 drillcore. This supports hematite formation by near-surface alteration. However, red chert does form part of the chert at depths to about 200 m (Fig. 5a), and hematite fills fractures in the Apex Basalt (Fig. 5b) at deeper levels. Hematite cannot be dated directly, but Kato et al. (in prep.) dated crosscutting pyrite veins at 2762 ± 16 Ma by the Re–Os method. This result indicates that the hematite in ABDP 1 is Archean, although its precise age remains uncertain. Kato et al. (in prep.) argued that their data support Archean oxidation at least 400 million years before the generally accepted date for the development of atmospheric oxygen (c. 2350 Ma).

Figure 4. Red–white–grey layering in the Marble Bar Chert Member at Marble Bar Pool. One of the main reasons for drilling ABDP 1 was to determine if the red chert (containing hematite) persists at depth

ABDP Hole 3, Hardey Formation (c. 2760 Ma)

Watanabe et al. (2004) reported that the mean $\delta^{13}C$ value of samples of black shale over a 60 m intersection in ABDP 3 is –33.4 per mil, and that the mean $\delta^{13}C$ value in a calcareous sandstone stratigraphically above the shale is –30.4 per mil. They interpreted these variations to indicate changing microbial communities as the depositional environment of the Hardey Formation changed.

Sulfur isotope analysis of 18 samples of shale from ABDP 3 (Ohmoto et al., 2005) revealed no evidence of mass independent fractionation (MIF-S). Sulfur is present entirely in finely disseminated pyrite, and averages only 0.04 wt% of the rock. Various workers (e.g. Farquhar et al., 2000; Pavlov and Kasting, 2002; Bekker et al., 2004) have observed that the few Archean sedimentary rocks so far analysed exhibit MIF-S, whereas numerous post-

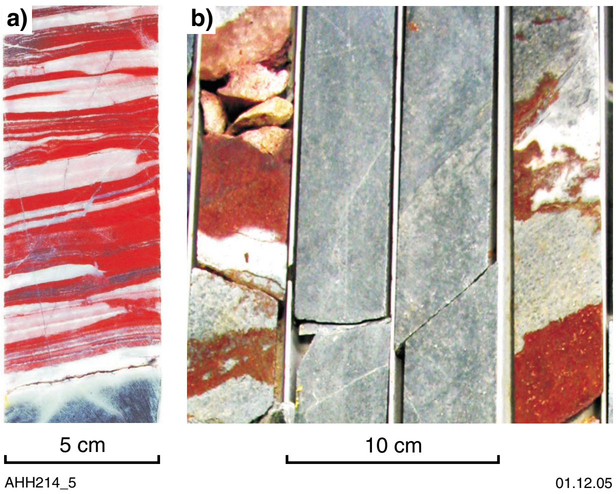

Figure 5. a) Red and white chert in ADBP 1 at the 170 m level, about 200 m below the present land surface; b) hematite and quartz filling fractures in the Apex Basalt at the 213–215 m level (about 250 m below the present land surface). Small veins of pyrite crosscutting the hematite were dated at 2762 Ma

2350 Ma sedimentary rocks do not. Because MIF-S can originate through ultraviolet radiation of volcanic sulfur dioxide in the absence of ozone or oxygen, these previous workers have argued that the MIF-S data provide evidence that Earth's atmosphere changed from anoxic to oxic at c. 2350 Ma. However, the sulfur isotope results from ABDP 3 do not support an anoxic atmosphere at 2760 Ma, and highlight the need for more sulfur isotope studies on rocks older than 2350 Ma.

ABDP Hole 5, Mosquito Creek Formation (c. 2920 Ma)

At Eastern Creek the Mosquito Creek Formation includes black carbonaceous shale and intercalated sandstone metamorphosed only to pumpellyite–prehnite facies (Farrell, in prep.). The shale was deposited in relatively shallow water close to the northern margin of the Mosquito Creek Basin. ABDP research has revealed constant $\delta^{13}C$ values of about –31 ± 0.9 per mil over a 35 m intersection. Ohmoto et al. (2005) determined $\delta^{33}S$ and $\delta^{34}S$ values on bulk-rock sulfur from a total of 40 samples of shale. As in the 2760 Ma Hardey Formation (see above), this work revealed an absence of MIF-S in all but one of the 40 samples.

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The Kimberley gold rush of 1885–86

by P. E. Playford

In the mid-1800s Western Australia was regarded as 'the poor relation' of the other Australian colonies. It envied the wealth generated by the major mineral discoveries, especially of gold, in the eastern colonies. As a result, the Western Australian Government decided in 1872 to offer a reward of £5000 ($10 000) for the discovery of the colony's first payable goldfield. Conditions for payment would be that the field lay within 300 miles (480 km) of a declared port, had produced at least 10 000 ounces (311 035 g) of gold within two years of the discovery, and the gold had been shipped to Great Britain after clearance at a Customs House of the colony.

The Kimberley gold story began with the exploring expedition of Alexander Forrest in 1879 (Fig. 1). He traversed the district from west to east, then continued through to the gold-mining settlement of Pine Creek in the Northern Territory. Forrest commented to the manager of the mine, Adam Johns, on similarities between the rocks at Pine Creek and those seen by his party in the Kimberley. This motivated Johns to mount an expedition to the area, with his mate Phil Saunders as party leader, together with James Quinn and Crawford, an Aborigine (Playford, 1972; Playford and Ruddock, 1985; Clement and Bridge, 1991).

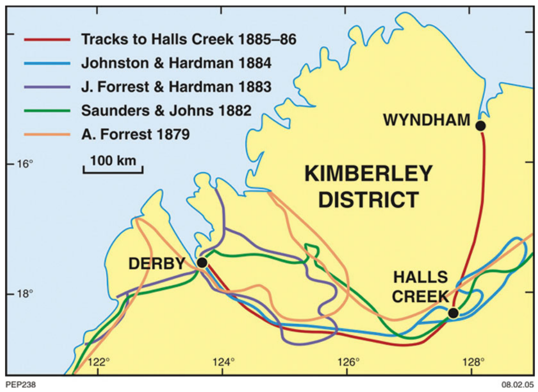
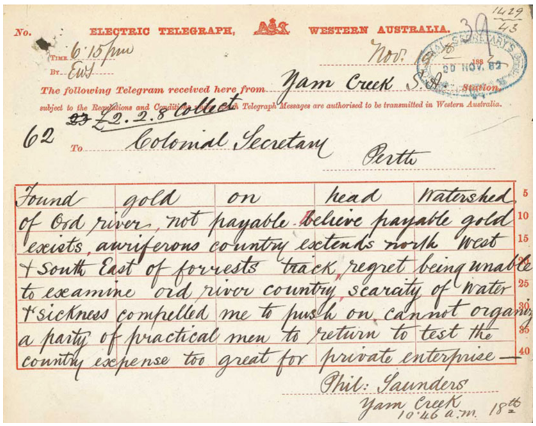


Figure 1. Map showing routes followed by Forrest in 1879, Saunders and Johns in 1882, Forrest and Hardman in 1883, Johnston and Hardman in 1884, and prospectors who joined the Kimberley gold rush of 1885–86


No. ELECTRIC TELEGRAPH, WESTERN AUSTRALIA.

Time 6.15 pm
By EWJ

Nov 19 188

The following Telegram received here from Yam Creek S.A. Station,
subject to the Regulations and Conditions under which Telegraph Messages are authorised to be transmitted in Western Australia.

62 ~~23~~ £2.2.8 collect

To Colonial Secretary Perth

Found gold on head Watershed of Ord river, not payable believe payable gold exists, auriferous country extends north West & South East of forrests track, regret being unable to examine ord river country, scarcity of water & sickness compelled me to push on, cannot organize a party of practical men to return to test the country expense too great for private enterprise —

Phil: Saunders
Yam Creek
10.46 a.m. 18th

Figure 2. Telegram from Phillip Saunders to the Colonial Secretary, 19 November 1886, announcing the discovery of gold in the East Kimberley

The party sailed from Port Darwin to Cossack in the west Pilbara in July 1881, then set out for the Kimberley (Fig. 1). Saunders found traces of gold at several places in the East Kimberley in August–September 1882, especially in the headwaters of the Ord River. However, Johns had become seriously ill and it was imperative for them to push on without delay to the Northern Territory. Consequently there was insufficient time to evaluate the discovery. Saunders reported this in a telegram to the Western Australia Colonial Secretary, indicating his belief that payable gold could probably be found in the area (Fig. 2).

The Legislative Council debated the best way of following up this exciting report. Some members maintained that practical (‘pick-and-shovel’) men were needed to prospect the area, whereas others were in favour of sending a geologist. A decision was eventually made to appoint Edward T. Hardman, a geologist from the Irish Geological Survey, to join John Forrest’s survey expedition to the West Kimberley (Fig. 1). However, no positive signs of gold were found on that expedition (Hardman, 1884).

Hardman accompanied a second Kimberley surveying expedition, led by H. F. Johnston, to the East Kimberley in 1884 (Fig. 1; Hardman, 1885). Hardman* panned colours of gold in several watercourses in that area, especially in the headwaters of the Elvire River, where the Halls Creek gold discovery would be made during the following year (Fig. 3).

Several prospecting parties set off for the East Kimberley soon after Hardman’s 1884 report and map were released. One of these parties, consisting of Charles Hall (party leader), John Slattery, Alexander Nicholson, Joseph McCague, John Campbell, and August Pontt, headed east from Derby to the Elvire River area, where Hardman had reported his best gold showings. On 14 July 1885 they found payable gold at a place they named ‘Halls Creek’ (Fig. 3).

As soon as the find was announced — in August 1885 — the Kimberley gold rush began. Many thousands of men made their way to the Kimberley from other parts of WA, the eastern colonies, and New Zealand. Most

* Some of Hardman’s notebooks with water-colour paintings and sketches made in the field have recently been uncovered in Thirsk, Yorkshire. They show that Hardman was not only a competent and motivated geologist, but also a talented artist. One of the many paintings in his 1883 field book is shown here as Figure 4.

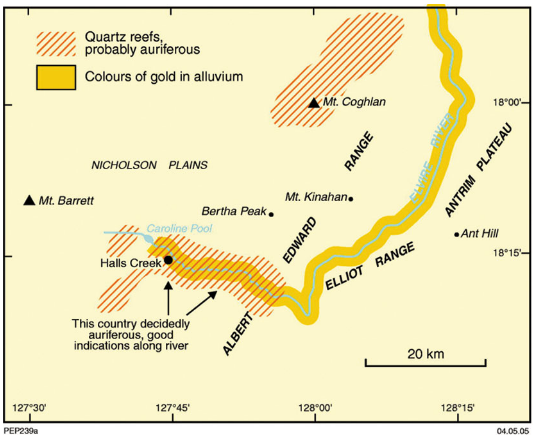


Figure 3. Gold showings and quartz reefs in the Elvire River area, as mapped by Hardman in 1884, showing the location of the Halls Creek gold discovery of 1885 (modified from Playford and Ruddock, 1985)

arrived by ship at Derby or (later) Wyndham, and walked to Halls Creek (a distance of 600 km from Derby or a much rougher 400 km from Wyndham). Others travelled overland from the Northern Territory. Illness and disease were rife at the diggings, and when the first warden, C. D. Price, arrived on 3 September 1886 he found that 'great numbers were stricken down, in a dying condition, helpless, destitute of money, food, or covering, and without mates or friends simply lying down to die'.

A few were lucky enough to locate payable alluvial or reef gold, but most had little or no success. Of those who arrived at the field with possessions, many sold or exchanged them for food within a day or two of arrival, and made their way back to the ports, to escape the misery of Halls Creek. Those who had no possessions were compelled to remain. Warden Price reported that there were about 2000 men at the diggings when he arrived, although the total number who joined the rush is estimated to have been four or five times that number. By the end of 1886 the rush had ended, and in February 1887 only about 600 men remained at the field. In spite of the early promise of several underground mines, Halls Creek never prospered, as ore in the mines petered out at depth and the alluvial gold was soon exhausted.

Applications for the £5000 reward for the gold discovery were lodged by H. F. Johnston, E. T. Hardman, P. Saunders, and C. Hall and party, and

Figure 4. Painting of 'Port Usborne' by E. T. Hardman, May 1883

several others who had found gold in the Halls Creek area during 1885. Johnston based his claim on the fact that he was the leader of the survey party when traces of gold were found in 1884. However, Hardman pointed out that he was the one who had actually found the gold and reported the discovery. He was scathing in his criticism of Johnston, saying that during the survey he had hindered, rather than assisted, in the discovery of gold. Hall and party's claim rested on the fact that they were the first to report the discovery of payable gold at Halls Creek. Saunders did not lodge a claim himself, but a submission from a Justice of the Peace in South Australia, pointing out that Saunders had been the first to report signs of gold in the East Kimberley, was accepted as a claim on Saunders' behalf.

At the conclusion of his temporary appointment as Government Geologist in 1885, Hardman left Western Australia for Ireland to resume his duties with the Geological Survey of Ireland. He died suddenly of typhoid in Dublin on 6 April 1887 at the age of 42 years, leaving a wife and two small children. Had he lived, his ambition to return to Western Australia would soon have been fulfilled. His appointment to the permanent position of Government Geologist (and thereby founder of the Geological Survey of Western Australia) was approved by the Legislative Council on 13 June 1887, before the news of his death two months earlier had reached Perth.

At the time of Hardman's death no decision had been made regarding payment of a reward for the discovery of a payable goldfield. The Government eventually decided, on 31 May 1888, that the full conditions for payment had not been met and therefore the reward would not be paid. The main reason was that the recorded output from the field had been less than the required 10 000 ounces in the two years from 1885. Indeed, total recorded production for the three years from 1886 to 1888 had amounted to only 8668 ounces. However, the Government must have known that the actual production was much larger than this, perhaps more than 20 000 ounces, as claimed by Charles Hall. This is because Western Australia, alone among the Australian colonies, put customs duty on gold (amounting to two shillings and six pence ($0.25) an ounce), and some miners consequently preferred to smuggle their gold out of the colony.

When the reward was withdrawn it was announced that a gift of £500 would be made to Hardman's widow and another £500 to Hall and his party. None of the recipients were satisfied with this — indeed they objected strongly that the full reward had not been paid, to no avail. Over the next four years Hall's party mounted three unsuccessful law suits against the Government. The last word from Hall came in a sad letter to John Forrest, written from Madagascar in 1896. There is no known record of his death, but he is presumed to have died destitute in that country.

The final appeal from one of Hardman's descendants was made in 1956, when his daughter, Bertha, wrote to the then Prime Minister (Robert Menzies) asking whether the Government could assist her, as she was living under straightened circumstances in retirement in Glasgow. She said that her father had died at an early age because his health had suffered as a result of trekking over the Kimberley, living on 'damper and poor food'. Her appeal was unsuccessful, but it did have the effect of reactivating the Mines Department file 'Reward for discovery of the Kimberley Gold Field' (file 10560/96) and thereby preserving it for posterity.

The other prominent applicant for the reward was the prospector Phil Saunders. He was held in high regard and affection by all who knew him, from diggers to politicians. Saunders never pressed his case for the reward, but many people believed that he deserved official recognition and reward as the first person to find gold in the Kimberley. In 1907 he was 66 years old and working a small gold show, with minimal returns, near Mount Ida. The Mount Ida Progress Association wrote to the Minister for Mines asking that Saunders be granted an appropriate annuity by the

Government in view of his many contributions to gold prospecting in Western Australia. The Government reacted slowly to this request, until the Progress Association wrote again, stating urgently that 'the old gentleman is now rapidly declining and almost blind' and he should receive appropriate monetary assistance when 'his life is apparently very near its close'.

This moving appeal had the desired effect, and Saunders was immediately granted a Government pension of £75 per year. If he were indeed close to death in 1907, he recovered well after receiving the annuity. Indeed he lived on for another 24 years, dying in 1931, at the age of 90 years, from the effects of rolling into his camp fire. By the time of his death, Saunders had received far more reward from the Government than the other discoverers of gold in the Kimberley — £1800 compared with £500 to Hall and his party and £500 to Hardman's widow.

There can be no doubt that the discovery of the Kimberley Goldfield and the dramatic rush that followed are important events in the history of Western Australia. They marked the real beginning of the State's mining industry, by drawing world attention to the colony and its gold potential. Some of the experienced prospectors who joined the Kimberley rush soon moved on to make rich discoveries in the Pilbara and Southern Cross districts (1888), the Murchison (1891), Coolgardie (1892), and Kalgoorlie (1893). Those major discoveries captured the imagination of the world, resulting in a flood of immigrants and investment capital that transformed Western Australia from an impoverished colony in the late 1880s to a wealthy State in 1901.

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Postscript

There is a modern postscript to this story. On 25 August 2005 Edward Townley Hardman and Phillip Saunders were inducted into the Australian Prospectors and Miners Hall of Fame, Kalgoorlie. They had been nominated for that honour by the Geological Survey of Western Australia.

Inside GSWA

Neville D'Antoine

Neville D'Antoine is a quiet and unassuming, yet pivotal, member of GSWA. He is the fourth youngest of eleven children, so you can understand where he learnt the value of keeping his head down. He says he enjoyed the advantages of a large family, particularly during his school days when he needed backup on some school-boy prank, or during one of the many family fishing trips when the car became bogged. This was no trouble for such a large crew. The kids would literally pick it up out of the mud (no need for a 4WD — where would you like this dad?).

Neville is a true 'travelling man', which is appropriate when he lives in such a large State as WA. On a daily basis he travels 160 km to and from Toodyay to work, and on an annual basis he returns to the Derby region to see his family (his wife also travels 160 km a day to work, but in the opposite direction!).

Neville is proud to be a member of a family that is well-known in the Broome region for their skills in building pearl luggers. He was born in Broome and spent most of his childhood in Derby, having moved there when he was 12 months old. He attended primary school at Derby, and high school at St Patrick's College in Geraldton where he was a boarder. He then spent some time as a machine operator before commencing tertiary studies at Wembley Technical Collage, receiving his Diploma in Cartography in 1984.

Once he had finished his studies, Neville worked for Fugro (or Associated Surveys as it was known then) as a photogrammetrist. After about five years he decided he needed a change and moved to Cockatoo Island, where he spent six months helping to build the tourist resort. Half his luck! He then moved to Koolan Island for 11 months and worked as a gardener cum garbo. He says Koolan Island has one of the most scenic rubbish tips in the world.

Neville then returned to Perth and started work as an engineering draftsman at Main Roads Department, mainly dealing with realignments of cadastre. He then moved to the Department of Indigenous Affairs (Aboriginal Affairs Planning Authority, as it was then known) as a cartographer. He was instrumental in introducing GIS and spatially enabling his new workplace. He established policy and standards, added a spatial component to the Aboriginal Site Register, and implemented a web-based interface for the Department.

After moving to Toodyay, Neville commenced with GSWA in 2001 as the GIS Manager in the Geoscience Information Products Group. Neville continues to bring his experience to bear in this role, and to build a vibrant and growing team of cartographers and GIS professionals to support the Regional Mapping and Resources projects of the Division.

In his spare time, Neville loves carpentry and building around the home. He also loves fishing, and looks forward to getting amongst the big stuff on his trips north. He fondly remembers times when the family would fish in the Fitzroy River and wake to see crocodile tracks around the campsite. He is quick to point out they never lost anyone during these trips!

Neville is married to Dale and they have two sons, Joel, who followed in his dad's footsteps in the Cartographic/GIS arena (some people never learn — but at least he didn't become a geologist!), and Julian who works in a related discipline as a Computer Technician.

Gaomai Trench

Gaomai is originally from Beijing and graduated with a BSc from Changchun Geosciences University (China) in 1982. She gained a PhD from China Geosciences University (Beijing) for her work entitled 'Dating of carbonate rocks using the Pb–Pb isotope method and its application in stratigraphy'. Upon completion of her doctorate, Gaomai worked at the Chinese Academy of Geological Sciences and prior to coming to Australia was appointed Divisional Director with the Academy, in charge of its technology and research program.

Gaomai came to Perth in 1997 as a student at Curtin University of Technology and she joined the Geological Survey of Western Australia in 1998. Gaomai treats study as a hobby. In Australia she has studied for three degrees part-time — an MSc in Mineral Economics from Curtin University of Technology, a Postgraduate Diploma in Environmental Management from Murdoch University, and a Masters degree in Policy and Technology from Murdoch University.

Gaomai has wide-ranging experience, both in China and in Western Australia, working in the fields of agriculture, the mineral resources industry, with the Chinese Central Government, in the military, in the Chinese Academy, and with the WA Government. Gaomai has been recognized as a bilingual technical Mandarin and English speaker and her language skills are being relied upon for both visits by GSWA staff to China and for reciprocal visits by Chinese dignitaries to this State. At present Gaomai works with the Land Access and Resource Assessment group within GSWA, which entails giving advice to government agencies and companies on land use planning issues, particularly to minimize sterilization of mineral resources.

Gaomai is married to Jim, an engineer who works in the resources sector. Jim and Gaomai love to travel — from the Great Wall of China to the byways of Rome. Gaomai's only daughter, Monica, is graduating in engineering this year. A thoroughly well-qualified family!

Catherine Spaggiari

Catherine Spaggiari has recently joined GSWA, to work in the Geophysics section. Her work has focused on structure and tectonics in Phanerozoic, Proterozoic, and Archean settings to which she adds metamorphic, geochronological, geochemical, and geophysical data. Currently her role is rather unusual in that she is primarily a geologist, and the first to be employed in the Geophysics section. Although her main role is to interpret geophysical data, she is coupling this with regional field work focusing on structural analysis that will allow a geologically reasonable interpretation of geophysical data. Catherine's first task was rather onerous — to produce a 1:500 000 solid geology map covering four 1:250 000 sheets of the northern Murchison domain (Yilgarn Craton); a task she achieved in only a few months.

Catherine's journey into all things geological was born from a rather intriguing upbringing. Born of Italian parents in Melbourne she spent her childhood holidays and weekends enjoying the outdoors, skiing, and bushwalking in the Victorian Alps. At 14, during a family holiday she was introduced to the Italian Alps where she and her sister later moved. She lived there for three years, and still visits her sister on the 'French Alps' side whenever she can.

After experiencing the cold of the Italian Alps Catherine moved to sunny California. For several years she lived between California and Australia working in the hospitality and retail industries. This kind of work allowed her to travel freely. Her extensive travelling has taken her to both the eastern and western U.S.A. and many European countries — to many geologically important and famous regions. She may not have known this at the time but she would become one of but a few geologists who have had a chance to see such significant geological sites.

After years of travelling Catherine decided that it was time for a 'sea change' — but rather than moving to a quiet seaside town on the Victorian coast she moved back to Melbourne and enrolled in a Bachelor of Arts and Science (double degree) at Monash University. In her first year she discovered geology and finally 'the penny dropped' as she thought: Strewth, I've been to those places, so that's how those mountains formed! Needless to say she was well and truly hooked on tectonics and structural geology.

Following her first year she enrolled in more and more geology subjects, finishing her degree with a double major in geology and geophysics. She stayed on at Monash to complete her PhD with Dave Gray and Dave Foster on the 'Structural, metamorphic, and tectonic evolution of Cambrian ophiolites, Lachlan Orogen, southeastern Australia'. Coincidently her PhD fieldwork took her back to the same area where she had spent much of her earlier years skiing and bushwalking in the Victorian Alps. This work included determination of the large-scale geometry of fault slices of Cambrian ophiolite in two major crustal boundaries of the Lachlan Orogen that represent the docking of arc complexes and oceanic plateaus during closure of a backarc or marginal basin. The work showed that the ophiolites in the Lachlan Orogen did not undergo classic 'Oman-style' obduction, but were emplaced as fault slivers by offscraping and underplating processes during underthrusting and closure of the backarc basin. This involved disruption of the upper oceanic stratigraphy, production of serpentinite-matrix mélange, followed by blueschist metamorphism. Her work has provided insight into the mechanisms of ophiolite emplacement, and development of large-scale fault zones in predominantly oceanic settings, as well as helping to constrain a tectonic model that suggests the Lachlan Orogen developed above multiple subduction zones. Catherine's thesis consisted of a series of papers now published in high-quality, peer-reviewed national and international journals. In 2003 Catherine was awarded the Mollie Holman Doctoral Medal for best PhD thesis in the Faculty of Science, Monash University, for 2002.

Upon completion of her PhD Catherine returned to the U.S.A. to take up a position as research scholar at the University of Florida, Gainesville to work on radiogenic isotope geochemistry. Following this she was awarded a two-year position as research fellow at Curtin University with Professors Robert Pidgeon and Simon Wilde to determine the structural and tectonic setting of the Jack Hills Belt (part of the Narryer Terrane and northern Yilgarn Craton margin) of Western Australia.

Catherine's interesting life has somehow brought her to settle in Western Australia, where she enjoys the outdoors (especially cycling and walking), the nightlife of Fremantle, and preparing home-made pasta dishes for a very appreciative 20+ friends.

Obituary
David Frank Blight
(17 June 1947 – 3 October 2005)

Director, Geological Survey of Western Australia 1998 – 2000

David had two periods with the Geological Survey of Western Australia as part of a distinguished career as a geologist and manager in the resources sector, both in Government and private industry. He has left numerous enduring monuments to his work and initiatives, and a very large number of bereft friends, colleagues, and acquaintances across the minerals industry of Australia.

David died suddenly at his home in Nedlands on Monday morning, 3 October 2005, of an unexplained thrombosis. He is survived by his mother Fran, wife Paula, and two adult children, Luke and Claire.

David was born in Melbourne and educated in Adelaide, where he graduated from the University of Adelaide with a BSc (Geology and Geochemistry) in 1968, a BSc(Hons) (Geology) in 1969, and a PhD in 1975 on metamorphic rocks in Antarctica, where he worked with the Australian National Antarctic Research Expeditions at Casey Base. It was probably the Casey experience where he often worked alone, and occasionally in genuinely life-threatening circumstances, which cemented his strong and independent character.

David joined the Geological Survey of Western Australia in 1976 as a petrologist. He moved into regional mapping where he worked on the Barlee and Bencubbin 1:250 000 map sheets, mapping granite–greenstones. He also contributed to the Wyloo 1:250 000 sheet, mapping the Ashburton fold belt before evaluating the mineral potential of the lower Fortescue Group as a mineral resource geologist. He developed a reputation as a very capable geologist, applying his knowledge and skills to a wide range of activities culminating in the production of the mineral deposits map of Western Australia. He quickly joined the cohort of young professionals with a penchant for practical jokes and humorous diversions (the garden gnome stories are still told when groups of (now) old Survey geologists gather). He met and married his second wife Margaret Wenham, another geologist at the Survey.

In 1982 David left GSWA to join Union Oil Development Corporation as the Senior Project Geologist responsible for exploration for ferro-alloy, speciality, and precious metals in WA, NT, and SA, with an emphasis on carbonatite intrusions.

Amongst his geological papers there was one that gave him particular pleasure (and glee!): a co-authored paper with his father, F. G. Blight*, which offered a novel interpretation of the hydrodynamic behaviour of a Devonian fossil, the Spiriferid brachiopod, and was published in a major palaeontology journal.

The resurgence of gold exploration in 1986 attracted David and Margaret and their young family to life in Kalgoorlie where David became Exploration Manager for Hampton Australia Ltd. He was proud to have Luke and Claire attend North Kalgoorlie Primary School, a symbol of the mining industry he loved, and the egalitarianism he espoused. He entered enthusiastically into the Kalgoorlie lifestyle, becoming a member of the Hannans Club and Chairman of the Committee of Management of the Museum of the Goldfields. In 1987 he became Exploration Manager for Mount Martin Gold Mines NL and Noble Resources NL and, in 1993, Director, Exploration and Development. Late in 1993 Mount Martin was taken over by Titan Resources NL and David returned to Perth to continue responsibility for Noble Resources. The sudden death of Margaret left David

* Blight, F. G. and Blight, D. F. (1990), Flying Spiriferids: some thoughts on the lifestyle of a Devonian Spiriferid brachiopod: Palaeogeography, Palaeoclimatology and Palaeoecology, v. 81, p. 127–139.

with the single-parent dilemma as he tried to be both parents to Luke and Claire as well as manage his busy life in industry.

So the government once again beckoned and he joined GSWA in May 1995 as Deputy Director, responsible for the Resources and Organizational Development Branches. During this time he had a major role in managing a significant cultural change in the Survey to an output-focused organization with a much larger budget. Despite his tough exterior and supposed uncompromising stance, stories and gossip gradually emerged from staff who had found David an unexpectedly generous and understanding boss when they were in family or personal difficulties — stories David much preferred didn't get out into the airwaves!

In 1998 David became Director of GSWA, a position he held until 2000. David oversaw the consolidation of a robust, aggressive, and quality GSWA that had embraced rapidly changing technology, particularly in the area of delivery of geoscience data and information as digital spatial datasets. This facilitated the first seamless map at 1:100 000 scale for the eastern Goldfields and the start of systematic mineral occurrence mapping. David promoted the delivery of map products as digital data and ensured that GSWA took advantage of the accuracy now available through the use of GPS. GSWA took the lead in establishing National standards for the delivery of exploration company reports as digital files. Funding for the core libraries in Kalgoorlie and Perth was obtained and construction of this state-of-the-art facility completed in 2000. David also further developed strong links with industry, highlighted by the success of the first GSWA Seminar and Poster Display day, 'GSWA 1998'.

An opportunity arose for David and his wife Paula to return to South Australia where he took on the role of Executive Director, Office of Minerals and Energy Resources at Primary Industries and Resources South Australia (PIRSA). In this role he led a major push to promote the exploration opportunities in South Australia that has resulted in a significant expansion in exploration activity and new discoveries in that State.

The attraction of industry again captured David's imagination and in May 2004 he drove the formation and listing of a new exploration company on the ASX, Abra Mining Limited. As Managing Director of Abra, he relished the challenges of a successful float as well as the technical and scientific aspects and worked determinedly to achieve exploration success. At the time of David's death Abra Mining had embarked on a major drilling program that already had sampled some significant mineralization.

David held GSWA in very high regard and was most concerned to ensure that the Survey maintained its pre-eminent position in geoscience studies in WA — a position firmly established by David's friend and mentor, a previous Director of GSWA, Joe Lord (1961–1980).

We, his friends and former colleagues at the Survey, are deeply saddened by his untimely death and will long remember this fine geologist, highly respected senior manager, a man with an ever-ready sense of humour, and a generous nature.

Staff list (30 June 2005)

GRIFFIN, Tim (Executive Director)

Regional Geoscience Mapping Branch

DONALDSON, Mike (General Manager)
TYLER, Ian (Chief Geoscientist)

Terrane Custodians
HOCKING, Roger (Basins)
MORRIS, Paul (Regolith, Chief Geochemist)
SHEPPARD, Steve (Proterozoic Orogens)
VAN KRANENDONK, Martin (Archean)

Edmund and Collier Basins
MARTIN, David
THORNE, Alan

Tanami
BAGAS, Leon

Gascoyne
FARRELL, Terry
SHEPPARD, Steve

Earaheedy Basin
JONES, Amanda

West Musgrave
HOWARD, Heather
PIRAJNO, Franco
SMITHIES, Hugh

Eastern Goldfields (Kalgoorlie Office)
DOYLE, Chris
GROENEWALD, Bruce
HALL, Charlotte
JONES, Sarah
RIGANTI, Angela

Murchison and Central Yilgarn
CHEN, She Fa
FORBES, Caroline
WYCHE, Stephen

Pilbara Craton
HICKMAN, Arthur
VAN KRANENDONK, Martin
WILLIAMS, Ian

Lennard Shelf
PLAYFORD, Phillip

Geochronology
BODORKOS, Simon
BRZUSEK, Marianna
CLANCY, Lisa
WILLIAMS, John

Geophysics, Remote Sensing and Regolith
HOWARD, David
MARNHAM, Jodi
SHEVCHENKO, Sergey
SPAGGIARI, Catherine
SKWARNECKI, Marian (Swanny)
WATT, John
ZENGERER, Matthew

Publications and CAD
DAY, Lyn
DOWSETT, Suzanne
EDDISON, Fiona

FERGUSON, Andrew
HARTLEY, Gary
HOFFMAN, Arthur
JOHNSTON, Jean
JONES, Murray
KUMAR, Manjeet
LENANE, Tom
MARON, Marcel
MIKUCKI, Jennifer
MULLIGAN, Sue
NASH, Margie
NOONAN, Kath
PIZZI, Trevor
PRAUSE, Michael
QUINN, Matthew
REDDY, Devika
STRONG, Caroline
SUTTON, Dellys
TETLAW, Nathan
THOMSON, Amanda

Map Production and GIS
BANDY, Stephen[1]
BACKHOUSE, Paul
BODEKER, Donald
BRIEN, Cameron
CLAIR, Brett
COGHLAN, Shannon
COLDICUTT, Shaun
D'ANTOINE, Neville
FRANCOIS, Annick[1]
GREENBURG, Kay
HAMILL, Sam[1]
HOGAN-ESCH, Johan
JEFFERYS, Stewart
KIRK, John
KUKULS, Liesma (Les)[1]
LADBROOK, David
LESIAK, Irena
LOAN, Geoff
McDONALD, Tuyen
SIMONETTI, Joseph
TAYLOR, Peter
THEEDOM, Erica
WAGHORN, Clayton
WEITER, Hana
WILLIAMS, Brian
WILLIAMS, Geoff

Data Integration
GOZZARD, Bob

Mineral and Petroleum Resources Branch

ROGERSON, Rick (General Manager)

Petroleum Systems Studies
CARLSEN, Greg
CUNNEEN, Jane
DE LEUW, Lorraine
GHORI, Ameed
HAINES, Peter
IASKY, Robert[1]
MORY, Arthur
STEVENS, Mark

Mineralization and Exploration Assessment
FERGUSON, Ken
HASSAN, Lee
PEIRIS, Elias
RUDDOCK, Ian

Industrial Minerals
FETHERSTON, Mike

Commodity and Industry Analysis
ABEYSINGHE, Pathmasekara (Abey)
COOPER, Roger
FLINT, Don

Mineral Resource Services
ANDERSON, Bill
FREEMAN, Mike
KOJAN, Chris
PAGEL, Jutta
ROBERTS, Ivor
TRENCH, Gaomai

Resource Mapping and Assessment
LANGFORD, Richard[1]

Inventory of Abandoned Mine Sites
ORMSBY, Warren
STRICKLAND, Colin

Paleontology
GREY, Kath

Executive Support
CRESSWELL, Brian
SLATER, Elizabeth
STOYANOFF, Nell

Special Projects
GOSS, Andrew[1]

Carlisle Operations
CLARK, Dean
ELLIOTT, Ian
GREEN, Robert
HOLMES, Mario
LOCKYER, Stuart
MEDDINGS, Garrie
MOORE, Brian

Core Libraries
HITCHCOCK, Wayne (Kalgoorlie)
BONER, Peter
BROOKS, Chris
HOLLAND, Trevor
KUCHEL, Matthew (Kalgoorlie)
WILLIAMS, Gary

Mineral and Petroleum Exploration Information
BELL, Ann
BLOORE, Alan
BRADSHAW, Brian
DODD, Fiona
ELLIS, Margaret
EMMS, Rosie
FITTON, Ann
FREEMAN, Heather
GRZESIOWSKA, Eva
HAWORTH, Jeffrey
IRIMIES, Felicia
JOHNSON, Leanne
KARNIEWICZ, George
MASON, Jan Sandra
MacCORQUODALE, Fiona
McKEATING, Joan
NAGY, Pearl[1]
NOACK, Scott
O'BRIEN, Richard
ORTON, Vergil
PIGOTT, Michele
PIZZI, Robert
SALUNDI, Michael
SUCHODOLSKI, Christine
SZWEDZICKI, Mary
WEBSTER, Jeffrey

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[1] On secondment to other parts of DoIR

Staff movements (1 July 2004 to 30 June 2005)

Internal reclassifications
KARNIEWICZ, George — to Level 2
HARTLEY, Gary — to Level 5
GOSS, Andrew — to Level 6
HASSAN, Lee — to Level 6
RIGANTI, Angela — to Level 6
SHEVCHENKO, Sergey — to Level 6
TRENCH, Gaomai — to Level 6
BAGAS, Leon — to Level 7
VAN KRANENDONK, Martin — to Level 7

Commencements
BACKHOUSE, Paul
BLOORE, Alan
BODEKER, Donald
COGHLAN, Shannon
CUNNEEN, Jane
DOYLE, Chris
FORBES, Caroline
FREEMAN, Heather
GRZESIOWSKA, Eva
HOGAN-ESCH, Johan
JOHNSON, Leanne
KUCHEL, Matthew
McDONALD, Tuyen
NOACK, Scott
ORTON, Vergil
SALUNDI, Michael
SPAGGIARI, Catherine
SUCHODOLSKI, Christine
TETLAW, Nathan
WAGHORN, Clayton
WEITER, Hana
WEBSTER, Jeffrey
ZENGERER, Matthew

Resignations
COLLOPY, Sean
D'ERCOLE, Cecilia
DRAGOJEVIC, Bob
EVANS, David

GOSCOMBE, Ben
HO, Susan
HUGHES, Bernard
LOCKWOOD, Andrew
LOVE, Gary
McCABE, Marian
MARTIN, Sarah
NELSON, David
SIMEONOVA, Anelia
STAPLETON, Gladys
WARD, Brendon
WRIGHT, Gareth

Secondments
BANDY, Stephen — to special project
FRANCOIS, Annick — to Mineral and Title Services Division
GOSS, Andrew — to Corporate Support Division
HAMILL, Sam — to Mineral and Title Services Division
IASKY, Robert — to industry
KUKULS, Liesma — to Department of Environment
LANGFORD, Richard — to Safety, Health and Environment Division
NAGY, Pearl — Mineral and Title Services Division

Transfers out
GREEN, Ellis — to Corporate Support Division

Casual and short-term contracts
BAIRD, Angus
EDMONDS, Tracey
HALLORAN, Kate
HEWSON, Paul
JARLETT, Ben
LOVE, Gary
ROBINS, Justin
WILLIAMS, Kerry

Retirements
DAWSON, Brian

Key staff contacts (from 30 June 2005)

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- ***East Yilgarn***
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- ***Central Yilgarn***
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- ***Earaheedy Basin***
  Franco Pirajno: 9222 3155
- ***Pilbara Craton***
  Arthur Hickman: 9222 3220
- ***Edmund and Collier Basins***
  Alan Thorne: 9222 3335
- ***Murchison***
  Stephen Wyche: 9222 3606
- ***West Musgrave Complex***
  Hugh Smithies: 9222 3611
- ***Lennard Shelf***
  Phillip Playford: 9222 3157
- ***Kalgoorlie Office***
  Angela Riganti: 9022 0408
- ***Gascoyne Complex***
  Stephen Sheppard: 9222 3566
- ***West Tanami***
  Leon Bagas: 9222 3221
- ***Geoscientist Specialist Support***
  - *Geochemistry/Geochronology*
    Paul Morris: 9222 3345
  - *Paleontology*
    Kath Grey: 9470 0302
- ***Geophysics and Remote Sensing***
  David Howard: 9222 3331
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  Neville D'Antoine: 9222 3175
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    Jenny Mikucki: 9222 3568
  - *Publication Drafting and Design*
    Michael Prause: 9222 3854
  - *Geographic Information Systems*
    John Kirk: 9222 3875
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    Shaun Coldicutt: 9222 3894
  - *Data Integration*
    Bob Gozzard: 9222 3594

Reporting to the Executive Director

- ***Chief Geoscientist***
  Ian Tyler: 9222 3192
- ***Terrane Custodians***
  - *Archean*
    Martin Van Kranendonk: 9222 3631
  - *Basins*
    Roger Hocking: 9222 3590
  - *Proterozoic Orogens*
    Steve Sheppard: 9222 3566
  - *Regolith*
    Paul Morris: 9222 3345

GENERAL MANAGER
Rick Rogerson
9222 3170

MINERAL AND PETROLEUM RESOURCES BRANCH

- ***Mineral Resource Services***
  Ivor Roberts: 9222 3204
  - *Mineral Exploration Information*
    Margaret Ellis: 9222 3509
  - *Industry and Community Liaison*
    Mike Freeman: 9222 3502
  - *Mining Act Advice*
    Jutta Pagel: 9222 3173
- ***Industrial Minerals***
  Mike Fetherston: 9222 3322
- ***Commodity and Industry Analysis***
  Don Flint: 9222 3624
- ***Mineralization & Exploration Assessment***
  Ian Ruddock: 9222 3334
- ***Inventory of Abandoned Mine Sites***
  Warren Ormsby: 9222 3571
- ***Petroleum Systems Studies***
  Greg Carlsen: 9327 5409
- ***Petroleum Exploration Data***
  Jeff Haworth: 9222 3214
- ***Core Library Services***
  Gary Williams: 9470 0304
- ***Field Support***
  Brian Moore: 9470 0308

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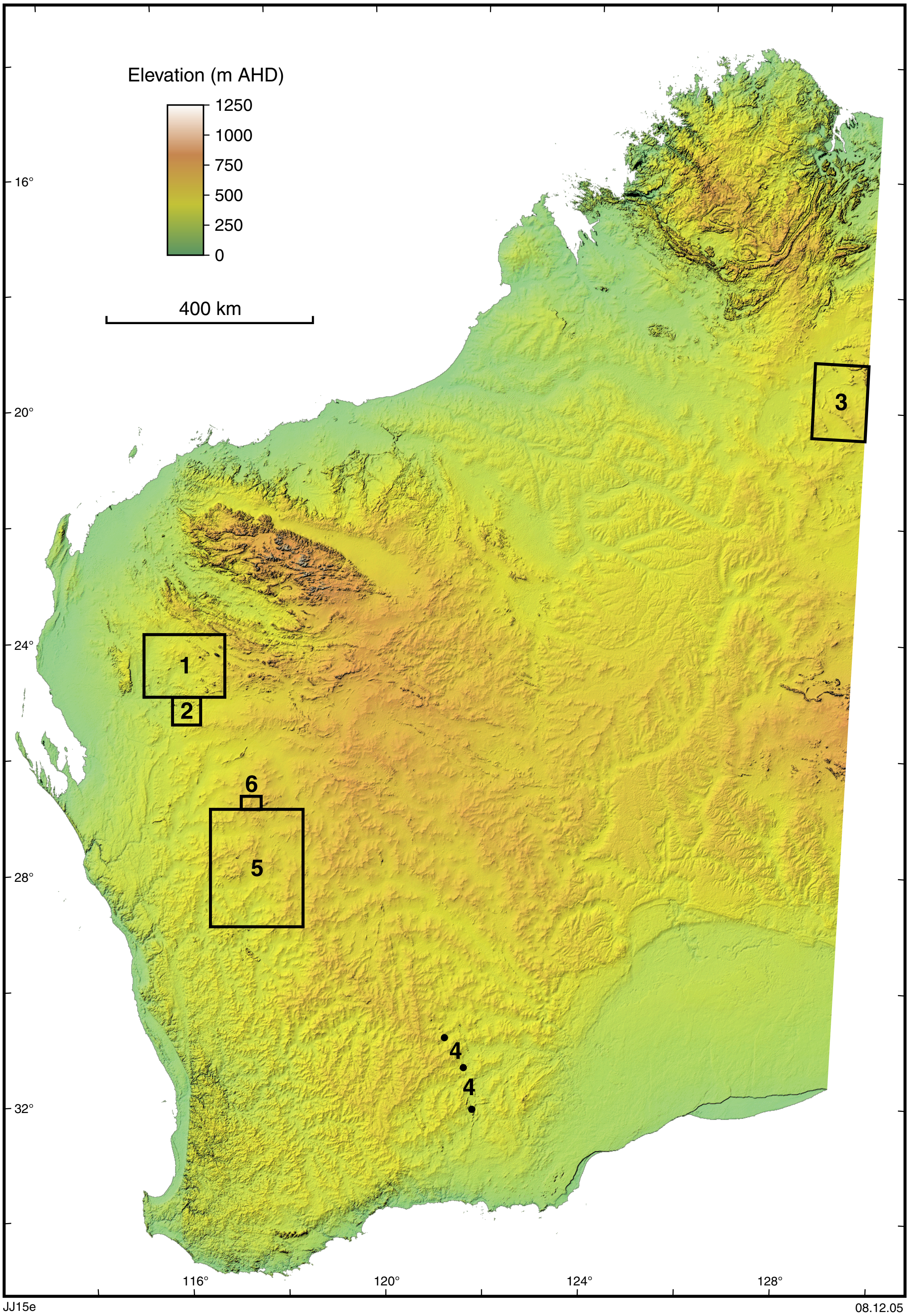

Map of Western Australia showing the locations of the six technical papers listed opposite. Hole-filled seamless Shuttle Radar Topography Mission (SRTM) data from NASA (http://jpl.nasa.gov) and CIAT (http://gisweb.ciat.cgiar.org)

Technical papers

Aegerine–augite bearing meta-leucogabbros in the Gascoyne Complex

by S. Sheppard and T. R. Farrell

Abstract

Numerous small occurrences of metamorphosed leucogabbro, quartz gabbro, and anorthosite outcrop within foliated porphyritic biotite monzogranite in the central Gascoyne Complex. These abstruse mafic rocks contain aegerine–augite, along with abundant titanite, allanite, zircon, and xenotime. The meta-leucogabbros differ from Proterozoic massif-type anorthosites, including alkaline varieties, based on their whole-rock chemistry and the composition of associated granites. The Gascoyne Complex meta-leucogabbros most likely represent a fractionated mafic–ultramafic intrusion, or intrusions, subsequently dismembered during regional deformation and metamorphism. The unusual composition of these rocks may be due to a mildly alkaline parent magma.

KEYWORDS: anorthosite, geochemistry, Paleoproterozoic, Western Australia, Gascoyne Complex, Capricorn Orogen

Introduction

Anorthosites are igneous rocks consisting of at least 90% plagioclase that can be categorized into six basic types: Archean (calcic) anorthosites, Proterozoic (massif-type) anorthosites, anorthosites in layered intrusions, anorthosites of oceanic settings, anorthosite inclusions in other rocks, and extraterrestrial anorthosites (Ashwal, 1993). Probably the most enigmatic are the massif-type anorthosites, which typically consist of large plutonic masses, with only minor associated mafic and ultramafic rock (Ashwal, 1993). Some anorthosites, such as those of the '…Aïr complex, Niger are associated with Paleozoic syenite–granite ring complexes, and may be unique' (Ashwal, 1993, p. 3).

A unit of 'alkaline anorthositic gneiss' in the Gascoyne Complex was described briefly, and partial whole-rock analyses presented for three samples by Williams et al. (1983). These rocks are largely confined to a southeasterly trending belt about 85 km long and about 10 km wide in the central part of the complex (Fig. 1). The rocks are dominated by plagioclase ($An_{10–30}$), but are unusual in that they contain a 'green clinopyroxene', in addition to abundant titanite (up to 5%), and allanite, zircon, and xenotime. These alkaline anorthositic gneisses were thought to be coeval with 'early stage gneissic' granites.

Several anorthositic gneiss occurrences from part of the central Gascoyne Complex are described here. They comprise metamorphosed leucogabbro, quartz gabbro, and minor anorthosite, and are referred to collectively as meta-leucogabbros.

Geological setting and field descriptions

The Gascoyne Complex comprises Paleoproterozoic granitic rocks and medium- to high-grade metasedimentary rocks (Williams, 1986). Extensive U–Pb zircon sensitive high-resolution ion microprobe (SHRIMP) geochronological studies show that the complex was primarily shaped by three orogenic events involving crustal formation and reworking; the 2005–1960 Ma Glenburgh Orogeny, the 1830–1780 Ma Capricorn Orogeny, and the 1680–1620 Ma Mangaroon Orogeny (Sheppard et al., 2005).

The meta-leucogabbros commonly form concentrations 2–10 km^2 in areal extent, although the largest of the individual bodies is only about 0.3 km^2. Williams et al. (1983) noted that the meta-leucogabbros always form elongate bodies that are closely associated with large masses of foliated, coarsely porphyritic biotite monzogranite. There are no minerals in the monzogranite indicative of alkaline affinity. Williams et al. (1983) placed the monzogranite into their 'early stage gneissic' granites, but a preliminary U–Pb SHRIMP date of c. 1660 Ma (Geological Survey of Western Australia (GSWA), unpublished data) shows that it is younger than their 'late stage' granites that make up the bulk of the Minnie Creek batholith to the north, which has been dated at c. 1790 Ma (GSWA, in prep.).

The meta-leucogabbros outcrop as knolls or low ridges, and are

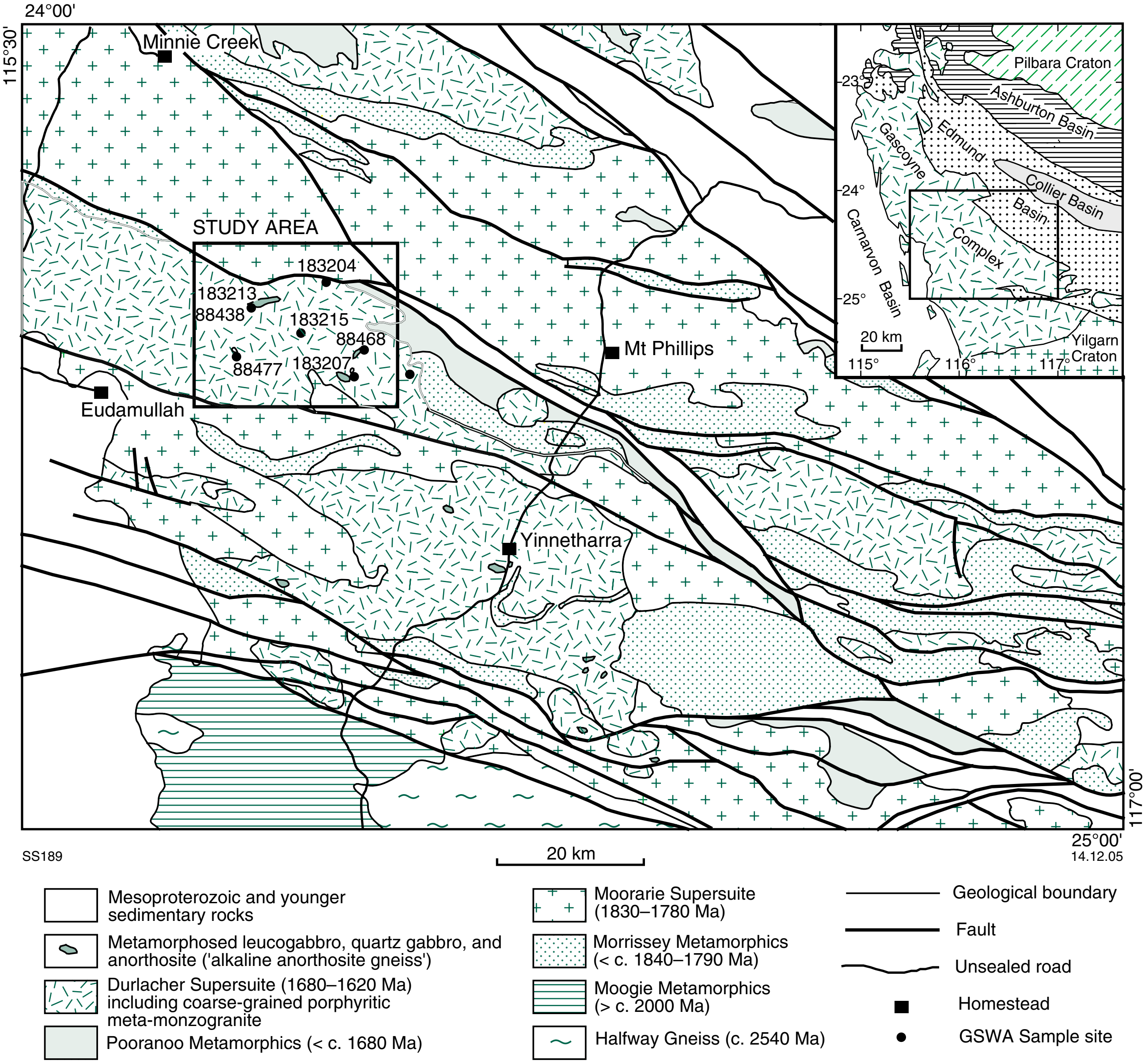

Figure 1. Sketch map of the Gascoyne Complex showing distribution of meta-leucogabbros. Inset shows outline of the Gascoyne Complex and location of the Mount Phillips 1:250 000 map sheet area. Box in main map shows study area, along with GSWA sample numbers in Table 1

commonly difficult to distinguish from the surrounding monzogranite. The meta-leucogabbros, and surrounding monzogranite, were metamorphosed at amphibolite-facies conditions, and all have the same moderate to strong tectonic foliation or L-tectonite fabric. Contacts between the meta-leucogabbros and monzogranite are typically tectonic. However, at one relatively low-strain locality 5.5 km northwest of New Well (MGA Zone 50, 392922E 7297584N), field relationships suggest that the meta-leucogabbros are older than the monzogranite; monzogranite apophyses in meta-leucogabbro are finer grained and less porphyritic than the monzogranite away from the contact, and the margins of the meta-leucogabbros are altered to epidote, whereas the adjacent monzogranite is fresh.

The meta-leucogabbros are medium to coarse grained (Fig. 2), and range from leucogabbro through quartz gabbro (all with 10–25% pyroxene or amphibole), to anorthosite (>90% plagioclase) in minor segregations. Plagioclase phenocrysts are preserved in places (Fig. 2a). Locally, the rocks contain magnetite crystals 5–10 mm in diameter. The meta-leucogabbros commonly have a weak centimetre-scale compositional layering, defined by variations in the proportion of plagioclase to the mafic silicates and oxides. A subtle compositional layering on the scale of a few metres is also present in some exposures.

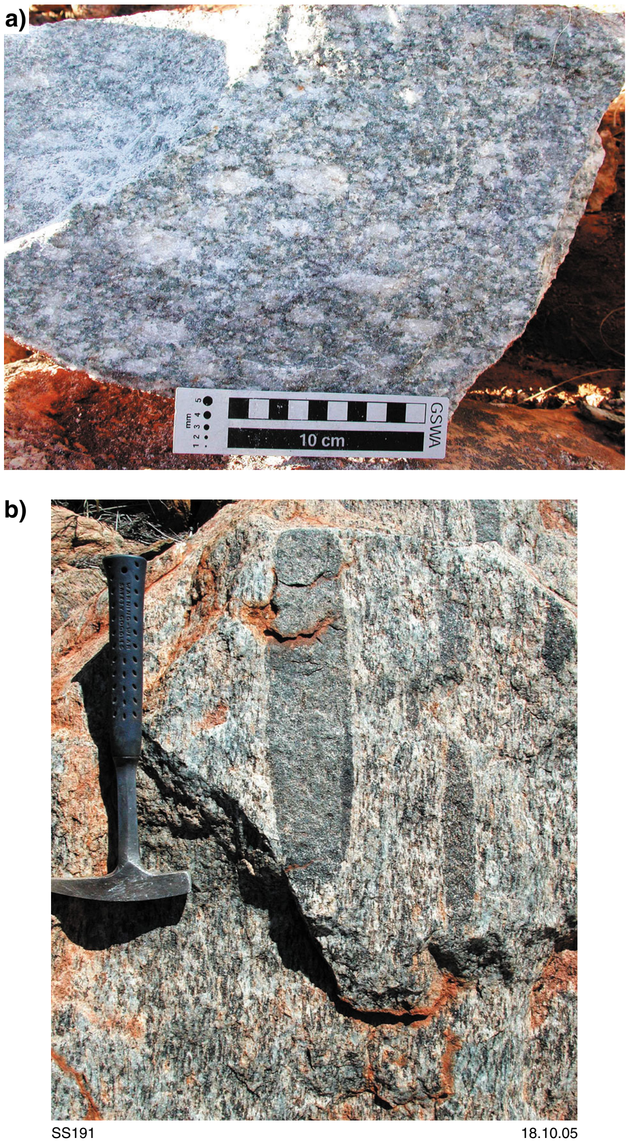

Figure 2. a) Schistose, coarsely porphyritic meta-leucogabbro with pale green aegerine–augite (MGA Zone 50, 381621E 7307421 N); b) Coarse-grained meta-leucogabbro with inclusions of amphibolite and meta-quartz diorite (MGA Zone 50, 393379E 7299597N). All rock types have a well-developed L-tectonite fabric. Hammer is 33 cm long

Meta-leucogabbro locally contains elongate inclusions of amphibolite and fine- to medium-grained metamorphosed quartz diorite (Fig. 2b). At one locality about 20 km east-northeast of Eudamullah Homestead (MGA Zone 50, 377686E 7299747N), metamorphosed leucogabbro and anorthosite, along with minor amphibolite and coarse-grained hornblendite, define a horizon about 3–4 m thick within metasedimentary schist and gneissic medium-grained monzogranite. The metamorphosed leucogabbro and anorthosite contain a centimetre- to decimetre-scale crude banding defined by layers and lenses rich in hornblende. About 200 m to the north, a foliated anorthosite layer about 10 m thick (with locally abundant epidote), is bordered by a thin band of amphibolite.

Petrography

The meta-leucogabbros comprise plagioclase (oligoclase to andesine), subordinate aegerine–augite or amphibole, and lesser amounts of quartz (5–12%), epidote, titanite, and allanite. Other minerals present include grossular, titanomagnetite, zircon, and apatite. Accessory allanite and zircon are present even in samples of amphibolite (metamorphosed gabbro).

Most of the meta-leucogabbros have an anhedral granular or granoblastic texture, but some samples (e.g. GSWA 183213) contain remnants of a subhedral granular igneous texture. In rocks with a granoblastic texture, aegerine–augite has straight grain boundaries with epidote and fine-grained titanite, and sharp boundaries with plagioclase. In some samples aegerine–augite forms oikocrysts with small inclusions of hornblende, quartz, and plagioclase. Amphibole ranges from hornblende to a sodic hornblende with deep bluish-green pleochroism. Epidote, titanite, and grossular may form fine-grained clots up to 10 mm in diameter with blebby quartz inclusions. Titanite, which constitutes about 1–5% of the rocks, forms idioblastic 1–2 mm long crystals with blebby inclusions of quartz, as well as fine-grained xenoblastic crystals. Allanite is typically partly or wholly altered and is mantled by epidote or, less commonly, titanite. Titanomagnetite has straight grain boundaries adjacent to titanite and allanite.

Whole-rock chemistry

Five leucogabbro and three associated monzogranite samples were analysed at Geoscience Australia for major and trace element compositions (Table 1). Analytical procedures are outlined in Morris and Pirajno (2005).

The meta-leucogabbros from the Gascyone Complex are characterized by high SiO_2 (60–66 wt%) relative to most anorthosites (48–54 wt%; tables 3.5 and 4.2, Ashwal, 1993), as well as much lower Sr, Ba (Fig. 3a), and Al_2O_3 contents. The Gascoyne rocks are distinguished from other

Table 1. Whole-rock analyses of leucogabbros and spatially associated biotite monzogranite

Sample ID	*183213*	*183207*	*88438*	*88468*	*88477*	*183204*	*183215*	*183216*
	Leucogabbro					*Monzogranite*		
				Oxides (wt%)				
SiO_2	59.94	63.18	60.89	60.17	65.73	70.22	67.16	68.19
TiO_2	1.21	1.10	1.18	1.37	0.40	0.48	0.74	0.41
Al_2O_3	18.47	15.28	17.88	17.49	19.04	13.65	13.95	14.93
Fe_2O_3	0.53	3.23	0.60	1.44	2.45	1.09	2.01	1.42
FeO	0.89	1.19	0.92	1.58	0.59	1.88	2.31	2.47
MnO	0.02	0.06	0.03	0.03	0.05	0.08	0.11	0.13
MgO	2.18	1.01	2.33	2.25	0.06	0.66	1.00	1.27
CaO	9.87	8.53	9.93	6.60	4.08	1.99	2.60	3.35
Na_2O	5.69	4.93	5.48	7.40	7.14	2.34	2.09	2.94
K_2O	0.15	0.33	0.13	0.28	0.18	5.65	5.58	3.64
P_2O_5	0.35	0.31	0.33	0.41	0.21	0.14	0.21	0.15
MLOI	0.45	0.55	0.05	0.66	-0.09	1.41	1.73	0.60
SO_3	0.02	0.02	0.03	0.02	0.03	0.02	0.03	0.02
O-S	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.01
Rest	0.19	0.19	0.20	0.20	0.11	0.23	0.27	0.24
Total	**100.06**	**100.07**	**100.07**	**100.09**	**100.03**	**100.06**	**100.06**	**100.03**
				Trace elements (ppm)				
As	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	0.5
Ba	102	40	102	41	2.7	853	1 031	982
Be	9.8	3.2	7.9	9.2	0.2	3.0	3.3	4.0
Cr	22	19	26	21	30	10	10	28
Cs	0.18	0.09	0.11	0.10	0.23	4.00	5.19	16.83
Cu	-1	-1	-1	-1	-1	3	10	11
F	812	876	764	1 307	308	1 672	2 354	1 302
Ga	12.0	19.2	13.6	16.0	16.8	14.4	16.1	15.4
Hf	10.8	11.5	11.1	11.3	4.1	5.3	7.4	4.6
Mo	0.6	0.5	0.7	0.2	0.2	0.5	1.2	1.0
Nb	28.3	25.3	27.1	27.7	19.0	16.7	20.4	11.0
Ni	6	3	6	7	-2	-2	3	4
Pb	10.6	16.9	12.7	11.3	9.0	43.0	45.0	28.0
Rb	1.9	3.1	2.0	1.9	2.7	244.3	257.5	149.4
Sb	3.0	7.5	1.4	0.3	0.3	2.7	2.4	9.2
Sc	21	18	22	23	18	10	13	9
Sn	5.2	5.8	5.4	6.2	8.2	4.2	4.4	3.7
Sr	386.4	350.3	352.5	249.9	244.7	108.5	143.3	254
Ta	1.8	1.6	2.0	2.1	1.5	1.0	1.4	1.1
Th	37.0	50.2	55.6	52.5	25.2	53.1	42.9	22.2
U	2.83	4.56	2.78	4.78	4.62	2.06	3.25	3.91
V	90	132	80	138	86	33	60	46
Y	48	48.8	48.9	52.8	27	34	44	21
Zn	4	11	6	12	4	34	51	47
Zr	350	332	334	351	108	190	234	161
La	91.55	101.50	116.60	130.30	38.07	86.07	71.92	41.77
Ce	169.9	189.0	222.9	262.4	92.5	149.2	137.9	77.8
Pr	19.50	21.61	25.28	27.40	8.73	18.04	16.17	8.39
Nd	76.12	87.54	98.77	104.40	32.09	68.66	62.91	31.87
Sm	13.72	14.94	16.66	17.96	5.51	11.75	11.30	5.51
Eu	2.118	2.624	2.482	3.072	1.435	1.608	1.861	1.314
Gd	11.14	12.61	12.63	14.37	4.37	8.23	8.55	4.11
Tb	1.62	1.76	1.78	2.05	0.81	1.13	1.26	0.59
Dy	9.93	10.73	10.29	11.94	4.98	5.87	7.31	3.44
Ho	1.88	2.03	1.95	2.22	0.83	1.06	1.40	0.65
Er	5.43	5.71	5.65	6.52	2.15	3.00	4.17	2.01
Yb	4.62	4.97	4.88	5.29	1.43	2.50	3.83	1.98
Lu	0.65	0.67	0.69	0.73	0.17	0.35	0.55	0.29
Na_2O/K_2O	39.2	14.8	41.2	26.0	39.9	0.4	0.4	0.8
La/Nb	3.2	4.0	4.3	4.7	2.0	5.2	3.5	3.8
Nb/Th	0.76	0.50	0.49	0.53	0.75	0.31	0.48	0.50

183213 metamorphosed leucocratic quartz gabbro or quartz diorite: oligoclase(An_{27}) –aegerine augite–quartz–titanite–allanite–hornblende
183207 metamorphosed leucogabbro: plagioclase–quartz–aegerine augite–epidote–titanite–grossular–allanite–hornblende–titanomagnetite
88438 metamorphosed quartz gabbro: labradorite (An_{55})–clinopyroxene–quartz–epidote–titanite–allanite
88468 metamorphosed quartz diorite or quartz gabbro: plagioclase–?sodic hornblende–quartz–titanite–allanite–epidote
88477 metamorphosed leucogabbro: plagioclase–quartz–titanomagnetite–titanite–allanite–apatite–zircon–garnet
183204 weakly schistose, coarse-grained porphyritic biotite monzogranite
183215 massive, coarse-grained porphyritic biotite monzogranite
183216 schistose, medium-grained porphyritic biotite monzogranite

meta-leucogabbros by their extremely high Na_2O/K_2O values (15–42 vs <7 for other leucogabbros and anorthosites in Fig. 3a), primarily due to their very low K_2O contents (Table 1). However, what really sets the Gascoyne meta-leucogabbros apart from other anorthosites and leucogabbros are their high Hf, Nb, Ta, Th, U, Y, and Zr abundances (Fig. 3a). The trace element abundances, particularly for the rare earth elements (REE), Zr, Hf, and Y, are similar to ocean island basalts (Fig. 3a). Nevertheless, there are some important differences, particularly the presence of negative Nb–Ta anomalies for the Gascoyne rocks (Fig. 3a).

The high REE abundances, and lack of a positive Eu anomaly on chondrite-normalized plots for the Gascoyne Complex meta-leucogabbros contrasts with anorthosites and most other leucogabbros (Fig. 3b), including anorthosite and leucogabbro from the Ofoud anorthosite of the Aïr region in Niger, which are associated with alkaline syenite and granite (Demaiffe et al., 1991). Figure 3 shows that the Gascoyne Complex rocks have similar trace element and REE patterns to some leucogabbros and anorthosites from the Panzhihua intrusion of southwest China (Zhou et al., 2005), although the latter usually have lower absolute abundances.

Discussion

Plagioclase in the Gascoyne meta-leucogabbros is much more sodic than in most other anorthosites (Ashwal, 1993), but the presence of epidote, titanite, and grossular in many samples suggests that the plagioclase may have recrystallized to a more sodic variety during regional metamorphism. The presence of aegerine–augite in the meta-leucogabbros makes them unique amongst anorthosites. The aegerine–augite appears to be in equilibrium with plagioclase, epidote, and fine-grained titanite, indicating it formed before or during regional metamorphism.

In igneous rocks aegerine–augite is essentially a crystallization product

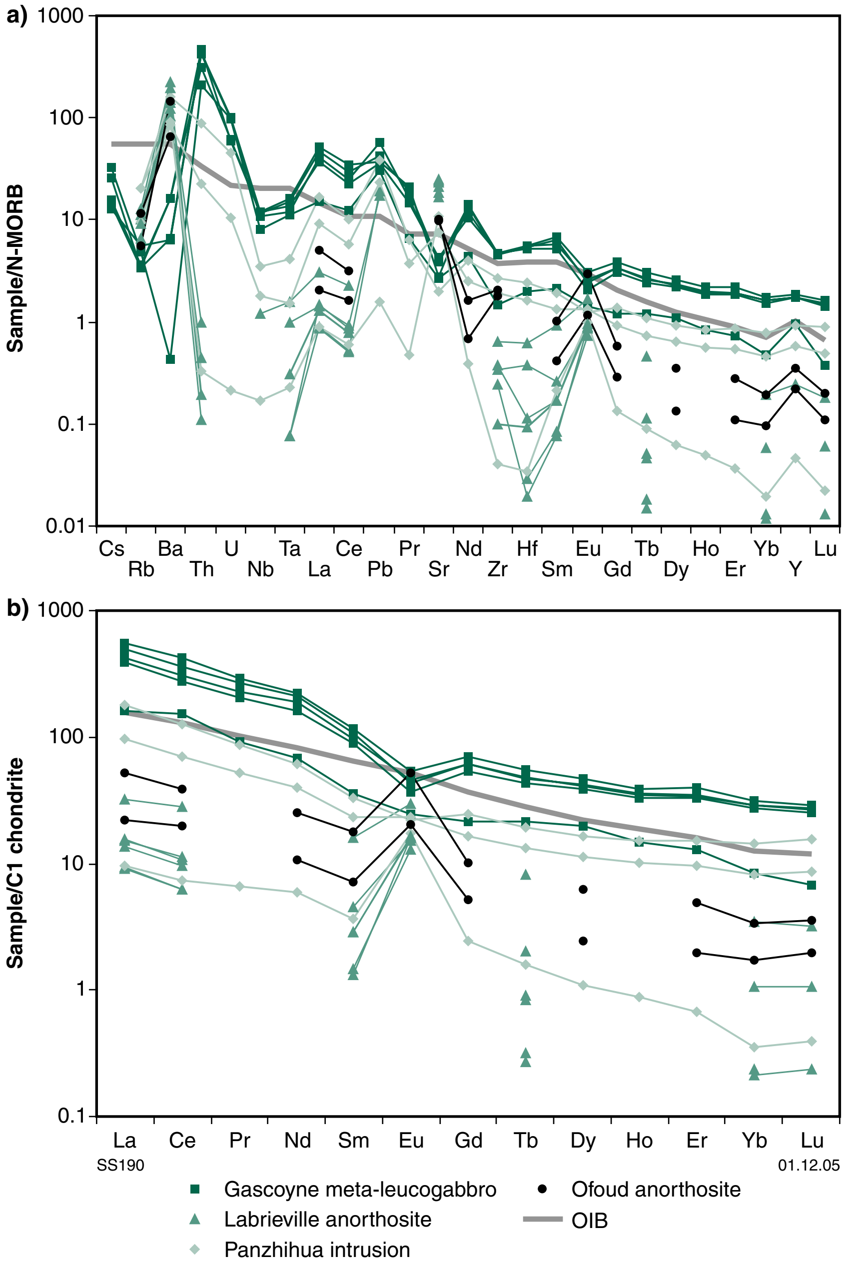

*Figure 3. **Compositions of meta-leucogabbros from the Gascoyne Complex compared with anorthosites and leucogabbros from a massif-type anorthosite (Labrieville, analyses 35, 106, 89 and 218: Owens and Dymek, 2001), a layered mafic–ultramafic intrusion (Panzhihua intrusion, analyses Lj-15, Lj-29 and Lj-40: Zhou et al., 2005), and the Ofoud anorthosite in the Aïr region of Niger (analyses OF2.2 and OF100b: Demaiffe et al., 1991). Also shown is the average ocean island basalt of Sun and McDonough (1989). Normalizing values for N-MORB in (a) and chondrite in (b) are from Sun and McDonough (1989)***

of alkaline magmas. Although there are alkaline massif-type anorthosites (e.g. Roseland and Labrieville), they lack aegerine–augite, and they have much higher K_2O contents (1.0–3.2 wt%, Herz, 1968; Owens and Dymek, 2001) than the Gascoyne meta-leucogabbros. Furthermore, most massif-type anorthosites have an areal extent of hundreds to thousands of square kilometres, and, in the associated granites, the mafic silicates '…are dominated by pyroxenes and/or olivines…' (Ashwal, 1993). Anorthosites associated with alkaline rocks of the Aïr region also do not resemble the Gascoyne meta-leucogabbros, as Aïr region anorthosites contain olivine and clinopyroxene as the main mafic silicates (Demaiffe et al., 1991).

Aegerine–augite is uncommon in metamorphic rocks, being largely restricted either to rocks that have been metasomatized before metamorphism, or to metamorphosed alkaline igneous protoliths (Deer et al., 1997). The low K_2O (and Ba) contents and extreme Na_2O/K_2O values of the Gascoyne meta-leucogabbros could be related to metasomatic alteration. It is also conceivable that the high Zr, Y, Nb, Hf, Ta, and REE contents in the meta-leucogabbros are related to alteration by a F-rich hydrothermal fluid, but this is unlikely given that the F values of the meta-leucogabbros (<1300 ppm) are lower than many igneous rocks in the Gascoyne Complex (Geological Survey of Western Australia, unpublished data).

The association of metamorphosed leucogabbro with amphibolite and hornblendite at some localities, suggests that the meta-leucogabbros may belong to the fractionated parts of a dismembered mafic–ultramafic intrusion (or intrusions). The chemistry of Gascoyne Complex meta-leucogabbros most resembles leucogabbro from the fractionated Panzhihua intrusion from southwest China, which is part of the Late Permian Emeishan Large Igneous Province. The mafic rocks in this province are interpreted to be derived from an enriched lithospheric component, similar to the source for ocean island basalt (see Zhou et al., 2005). Gabbros in the Panzhihua intrusion have positive Ti anomalies, and lack negative Nb and Ta anomalies, consistent with this interpretation. However, anorthosites in the intrusion, like the meta-leucogabbros in the Gascoyne Complex, have negative Nb–Ta (Fig. 3a) and Ti anomalies. Similarly, meta-leucogabbros in the Gascoyne Complex may have been derived from fractionation of a mildly alkaline basaltic magma.

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The origin of tourmaline nodules in granites; preliminary findings from the Paleoproterozoic Scrubber Granite

by D. Shewfelt[1*], K. Ansdell[1], and S. Sheppard

Abstract

Tourmaline nodules, also termed clots, clusters, and orbicules, are found in numerous granites worldwide. Nodules are typically spherical, 2 to 50 cm in diameter, and comprise tourmaline and quartz(–feldspar) cores surrounded by leucocratic haloes. Tourmaline nodules in the Paleoproterozoic Scrubber Granite of the southern Gascoyne Complex exhibit a greater diversity of morphologies and textures relative to other nodule localities, and some nodule morphologies, including starburst and rosette textures, are unique to the study area. Tourmaline nodules in the Scrubber Granite probably crystallized from pockets of volatile-rich fluid exsolved from the host granitic magma.

KEYWORDS: granite, tourmaline, orbicular, Paleoproterozoic, Western Australia, Gascoyne Complex, Capricorn Orogen, Moorarie Supersuite

Introduction

Although tourmaline nodules have been documented since the early 1800s, the physical and chemical parameters that govern their formation have yet to be resolved. Distinctive in appearance, nodules consist of tourmaline and quartz(–feldspar) clots surrounded by a halo of leucocratic granite. There are two main hypotheses for the origin of the nodules. The first suggests that nodules result from post-magmatic metasomatic–hydrothermal replacement of previously crystallized granite by externally derived, boron-rich fluids (e.g. Rozendaal and Bruwer, 1995). The other asserts that nodules are magmatic–hydrothermal features related to the separation and entrapment of immiscible B-rich fluids from coexisting granitic magma (e.g. Sinclair and Richardson, 1992).

Tourmaline nodules are a distinctive feature of the Paleoproterozoic Scrubber Granite of the Gascoyne Complex, Western Australia. Nodules are morphologically diverse and are randomly distributed throughout massive to tectonically foliated regions of the host granite. Although sparse groundmass tourmaline occurs in discrete regions of the Scrubber Granite, tourmaline crystals are typically restricted to nodule cores within the study area. In contrast, biotite is present throughout the host granite, and locally within halo material, but is absent in nodule cores.

Tourmaline nodules in the Scrubber Granite were investigated as part of a Master of Science project at the University of Saskatchewan. This paper focuses on detailed field-based nodule descriptions that were completed during the 2003 field season. Complementary petrography, whole rock and tourmaline crystal chemistry, tourmaline fluid inclusion microthermometry, as well as stable and radiogenic isotope studies were completed on representative nodules from the Scrubber Granite (Shewfelt, 2005). Although some tourmaline nodules are spatially associated with Sn–W mineralization (e.g. Rozendaal and Bruwer, 1995), no such association is recognized in the Scrubber Granite.

Geological setting

The 1800 Ma Scrubber Granite is part of the Moorarie Supersuite, a group of granites intruded into the southern Gascoyne Complex during the Capricorn Orogeny (Occhipinti and Sheppard, 2001; Occhipinti et al., 2001). The granite intrudes the Archean to Paleoproterozoic Halfway Gneiss and the Paleoproterozoic Dumbie Granodiorite. A 3.5 km elongate exposure of the Scrubber Granite, centred approximately 5 km west-southwest of Mooloo Downs Homestead, was chosen for this study as it contains abundant nodules of diverse morphologies combined with excellent exposures. This intrusion is

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superficially divided into three lobes by colluvium and alluvium (Fig. 1).

Field observations

Tourmaline nodules in the Scrubber Granite range from 2 to 30 cm in diameter and are randomly distributed throughout the study area (Fig. 1a). There is no direct relationship between nodule abundance and location within the intrusion; regions containing abundant nodules are in close proximity to regions devoid of nodules (Fig. 1b).

The host granite typically contains 50% quartz, 20% plagioclase, 15% alkali feldspar, 10% biotite, and 5% muscovite. Biotite forms elongate clots 1 to 2 mm in length that define a weak to moderate foliation. The leucocratic halo material surrounding nodules typically comprises 60% quartz, 20% plagioclase, 12% alkali feldspar, and 3% muscovite (±5% biotite). Although core zone mineralogy varies between and within nodule types, it typically comprises 60% tourmaline, 30% quartz, and 8% plagioclase (±2% alkali feldspar).

The Scrubber Granite contains a myriad of nodule morphologies (Fig. 2). Approximately 60% of nodules observed in the field are spherical (Fig. 2a). Nodules in foliated regions of the host granite are typically elongate parallel to the foliation and locally exhibit aspect ratios up to 1:5. These observations indicate that nodules pre-date the dominant episode of deformation affecting the Scrubber Granite.

'Tourmaline rosette nodules' contain dense rosettes comprising thin, prismatic tourmaline crystals that locally extend up to 1 cm in length. Rosette are surrounded by tourmaline-rich cores that are texturally similar to spherical nodules (Fig. 2b). The rosettes are randomly located within the tourmaline-rich cores, and there is no direct relationship between the size of the nodule and the size of the rosette.

Nodules containing prismatic tourmaline crystals up to 1 cm in length that radiate outward into the

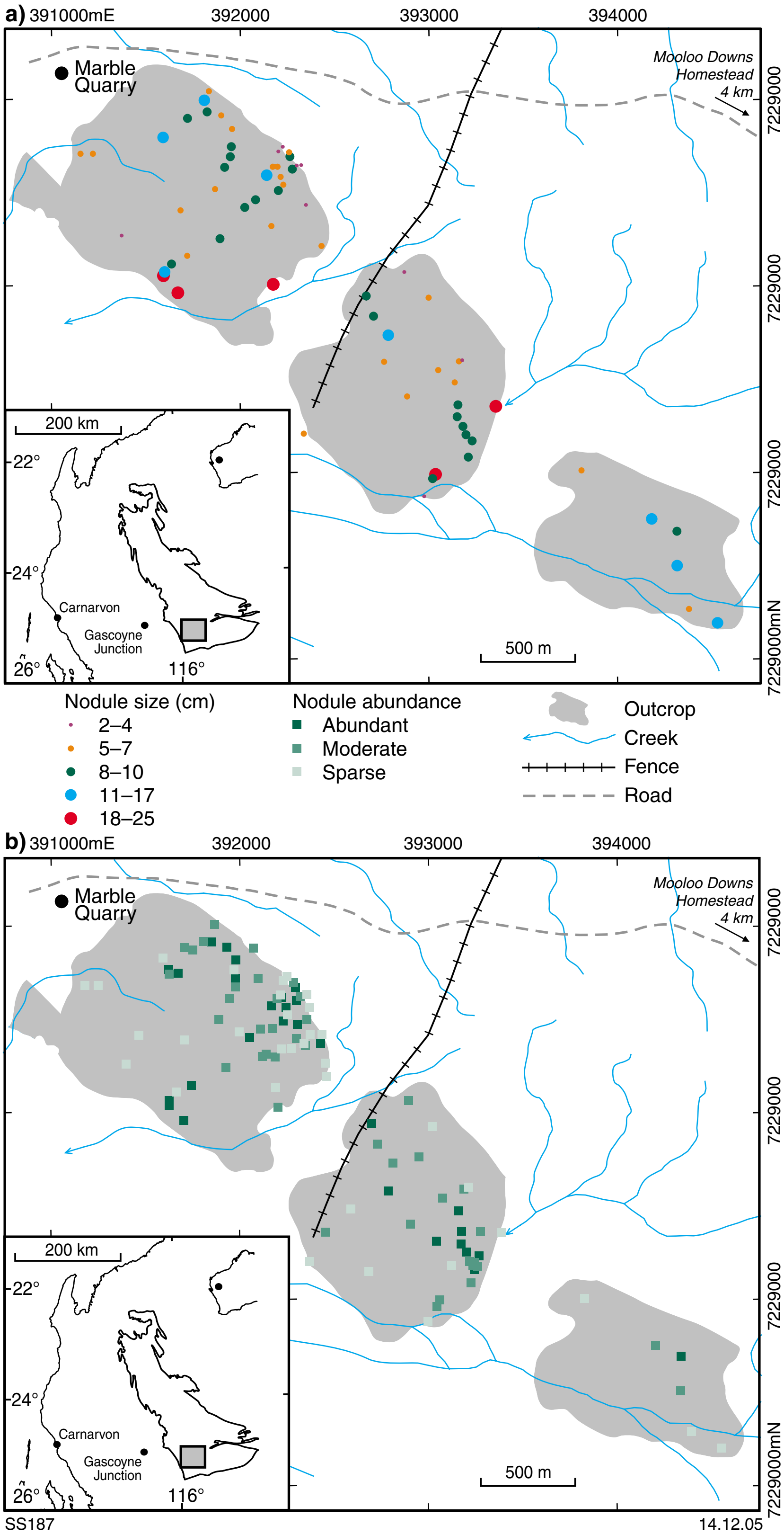

Figure 1. Outline of the three lobes of the Scrubber Granite and field locations where the following data were collected: a) nodule size variations across the three lobes; b) variation in nodule abundance across the three lobes (abundant = >8 nodules/m²; moderate = >4 nodules/m²; and sparse = <4 nodules/m²).

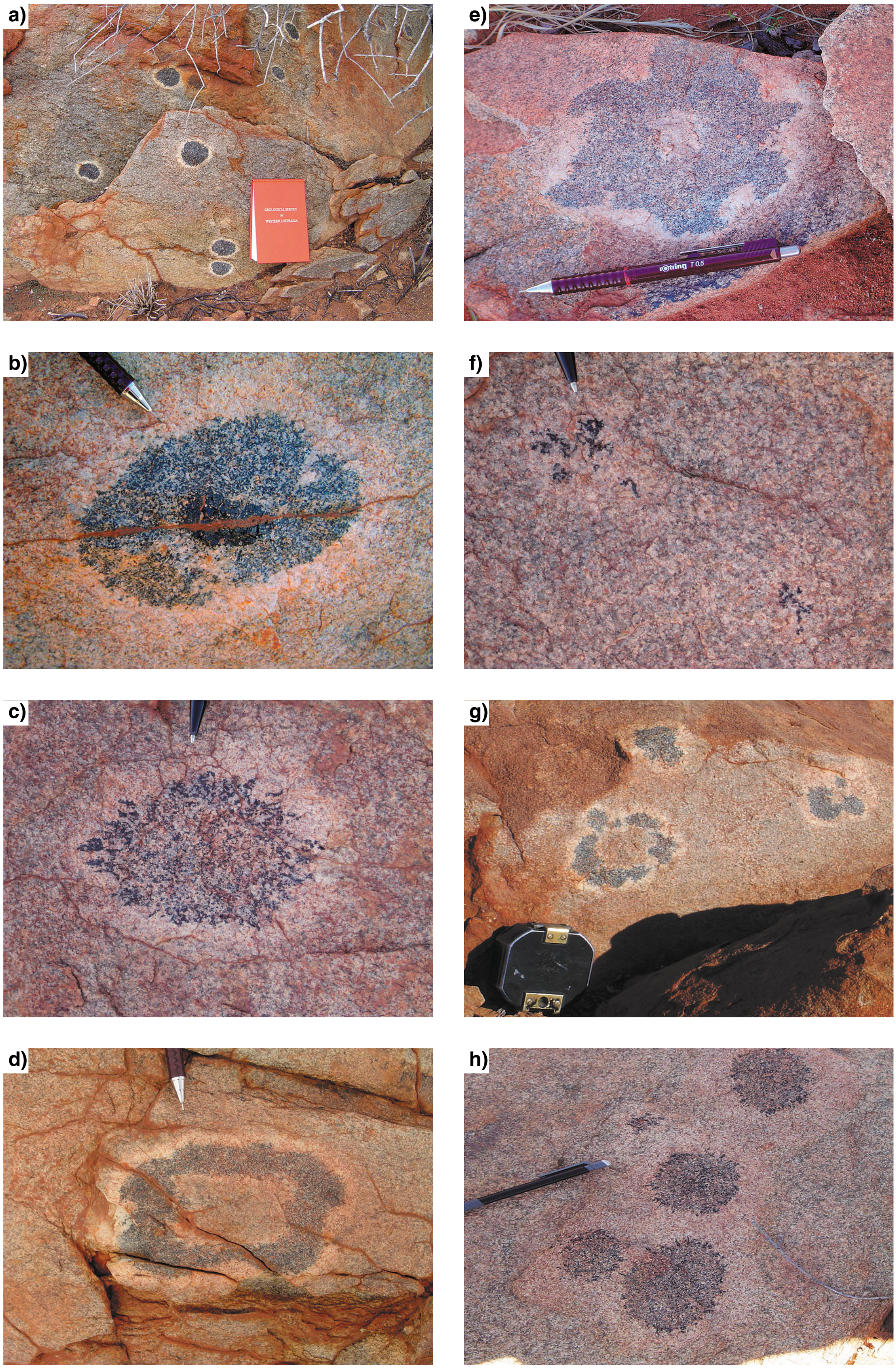

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Figure 2. Various tourmaline nodule morphologies in the Scrubber Granite: a) spherical nodules; b) tourmaline rosette nodule (fracture is a later feature); c) starburst nodule; d) ring-shaped nodule; e) flower nodule; f) proto-nodule; g) telephone dial nodules; and h) swarm of five starburst nodules contained within merged haloes

halo material are termed ‘starburst nodules’ (Fig. 2c). These nodules are typically coarser grained relative to other nodule types.

‘Ring-shaped ’ nodules completely enclose an inner granitic zone and are characterized by the presence of an additional halo zone that separates the tourmaline-rich core from the inner host granite (Fig. 2d). Related to this morphologic type are nodules that resemble stylized flowers and also enclose an inner granitic zone (‘flower nodules’; Fig. 2e). ‘C-shaped nodules’ (not illustrated) are similar to ring and flower nodules, but do not completely enclose the inner host granite.

Nodules typically less than 2 cm in diameter are termed ‘proto-nodules’ (Fig. 2f), due to their small size and general absence of surrounding halo material. These nodules are perhaps small precursors to larger, more developed nodules.

Aggregates of four or more nodules were observed throughout the Scrubber Granite. Small nodules arranged in a circular pattern are termed ‘telephone dial nodules’ (Fig. 2g). Randomly arranged nodule swarms locally display merged haloes (Fig. 2h).

Nodules of various shapes and sizes lacking a specific morphologic character were termed ‘irregular nodules’. These nodules typically comprise splays and blebs of tourmaline(–quartz–feldspar) surrounded by leucocratic haloes.

Other features observed in the Scrubber Granite include nodule tubes, tourmaline veins, quartz–tourmaline patches, small pegmatite pods, and sparse xenoliths. ‘Nodule tubes’ are sparsely distributed throughout the host granite, typically adjacent to spherical nodules. Locally extending up to 4 m in length, nodule tubes are characterized by rounded terminations and leucocratic haloes. Tourmaline veins of varying widths are similar in mineralogy and texture to nodules, and locally crosscut nodules of all morphologic types. In a discrete region of the central lobe of the Scrubber Granite, coarse white quartz and prismatic black tourmaline crystals form quartz–tourmaline patches. Devoid of the leucocratic haloes that surround adjacent spherical nodules, these patches are physically different from nodules and from discrete pegmatite pods that are sparsely dispersed throughout the Scrubber Granite.

Xenoliths within the host granite include a 10 cm-long gneissic inclusion and a 5 cm-long muscovite-rich pelitic inclusion. Although some proponents of the replacement theory suggest that nodules may represent xenoliths that have been replaced by tourmaline-rich fluids (e.g. LeFort, 1991), the sparse xenoliths observed in the Scrubber Granite do not exhibit evidence of alteration to tourmaline, and are not spatially associated with nodules. Additionally, nodules throughout the study area lack evidence of such replacement. A key observation relevant to this discussion is the lack of replacement textures in proto-nodules, as these nodules may represent the early stages of nodule development.

Discussion

Nodules of the Scrubber Granite are strikingly similar to tourmaline nodules in other localities, particularly those documented in South Africa. Nodules observed in the Cnydas Granite (Jankowitz, 1987) and the Cape Granite Suite (Rozendaal and Bruwer, 1995; Rozendaal et al., 1995) are typically spherical in shape, but also form ring-shaped and tube-like morphologies. These authors proposed that nodules are post-magmatic replacement features, and that the nodules are genetically related to tourmaline veins which acted as ‘feeders’ for nodule development. Although this ‘vein-based’ replacement theory may explain the spatial association of nodules and Sn–W mineralization in the region, it does not explain the various nodule morphologies observed in these areas. It remains difficult to envision how spherical and ring-shaped textures could be generated from planar or linear fluid injections. Rozendaal and Bruwer (1995) stated that ‘…the mechanism responsible for their spherical shape is not fully understood, but could relate to point nucleation at the end of dendritically arranged micro-fractures’.

Sinclair and Richardson (1992) focused on explaining nodule morphology and texture when considering the origin of tourmaline nodules of the Seagull Batholith in the Northwest Territories of Canada. Several features of this batholith argue for a magmatic–hydrothermal origin: nodules are typically spherical in shape; nodules are concentrated in the roof zone of this batholith and decrease in abundance with depth; miarolitic cavities, features typically associated with late-stage volatile fluid exsolution, are present in some roof zone nodules and are locally lined with tourmaline and quartz(–topaz); and there is a lack of planar structural features (i.e. veins) related to nodule development. Based on these features, Sinclair and Richardson (1992) proposed that a ‘pocket-based’ fluid exsolution theory best explained the formation of nodule morphologies and textures observed in the Seagull Batholith.

Likewise, several features of the Scrubber Granite tourmaline nodules argue for a synmagmatic crystallization origin, and are not consistent with post-crystallization replacement theories: nodules are typically spherical to globular, which is the preferred shape for pockets of immiscible fluid to decrease surface tensions; nodule formation pre-dated, and appears to be unrelated to, deformation in the Scrubber Granite; there is no evidence that nodule formation involved the replacement of the host granite or sparse xenoliths, even in the proto-nodules; and there is a general lack of structural features related to nodule development. Tourmaline veins are sparse, and typically overprint nodules. Additionally, good three-dimensional exposures show that nodules are not spatially associated with tourmaline veins or fracture fill.

Based on the field observations summarized above, it is proposed that tourmaline nodules of the Scrubber Granite represent the solid product of immiscible B-rich fluid pockets that separated from the crystallizing granitic magma. Pre-solid state fluid exsolution better explains the formation of the multitude of nodule morphologies and textures observed in the Scrubber Granite (and other nodule localities discussed here), as opposed to post-crystallization replacement. Leucocratic haloes may represent the difference between the initial size of the volatile-rich fluid pocket and its resulting size upon cooling and contraction. Ferromagnesian components in this region may have contributed to the formation of tourmaline that became concentrated in the core.

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Debbie Shewfelt, co-author

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Debbie Shewfelt completed this study to fulfill part of the requirements for a Master of Science degree in Geology. She is currently employed as a Research Geologist at the Saskatchewan Research Council in Saskatoon, Saskatchewan. She is involved in the petrography of Archean and Proterozoic basement rocks, mostly in conjunction with uranium and gold mineralization.

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The Bald Hill gold deposits in the Paleoproterozoic Tanami Group, Western Australia

by L. Bagas and D. Huston[1]

Abstract

The Bald Hill Member of the Killi Killi Formation in the western part of the Granites–Tanami Complex of Western Australia (Tanami region in the Northern Territory) contains significant gold deposits over a 15-km strike length. Preliminary geological, geochemical, and structural data from the area suggest that gold was localized early in the tectonic history, during the c. 1835–1815 Ma Tanami Orogeny. This early timing of mineralization is atypical for other parts of the Tanami region, where mineralization is associated with c. 1790 Ma granitic intrusions. Gold localization was controlled by a number of factors. These include structures that focused fluids into depositional sites, where fluid–rock interaction in chemically receptive rocks and structural opening caused fluctuations in fluid pressure, which enhanced gold deposition.

KEYWORDS: Paleoproterozoic, Granites–Tanami Complex, Killi Killi Formation, Tanami Orogeny, gold deposits.

Introduction and regional setting

The Granites–Tanami Complex (Tanami region of Crispe et al., in prep.) of Western Australia and the Northern Territory (Fig. 1) contains mostly Proterozoic rocks (Table 1), which are largely covered by Cenozoic regolith. Over the last two decades more than 280 t of gold has been mined, making this region one of the pre-eminent Paleoproterozoic gold provinces in the world. The locations of significant gold deposits in the western part of the Granites–Tanami Complex are shown in Figure 2.

This paper documents a study of oriented diamond drillcore from the Sandpiper and Kookaburra gold deposits in the Bald Hill area of Western Australia carried out by the Geological Survey of Western Australia (GSWA) and Geoscience Australia. Characteristics of the deposits and JORC-compliant resource estimates are presented in Table 2.

Deposits of the Bald Hill area

The Bald Hill area includes prospects over a 15-km strike length in the c. 1835 Ma Killi Killi Formation of the Tanami Group (Fig. 3). Many of these prospects are hosted by the 200 m-thick Bald Hill Member of the turbiditic Killi Killi Formation. The Bald Hill Member contains a succession of tightly folded and faulted iron-rich siltstone, graphitic and carbonaceous shale, banded and nodular chert, siltstone, turbiditic sandstone, basalt, and dolerite sills (Bagas et al., in prep.).

The eastern contact of the Bald Hill Member with the interbedded turbiditic sandstone, siltstone, and shale of the Killi Killi Formation (Fig. 3) is a layer-parallel fault, which may represent an early structure (D_{B1}*; Table 1). In outcrop, folds formed during D_{B1} are tight to isoclinal with an S_{B1} cleavage, and have been refolded by F_{B2} and later folds (Fig. 4). F_{B2} folds are typically asymmetrical, angular, tight, and have a wavelength of less than a kilometre (Fig. 3). The folds are locally overturned, inclined, verge south, plunge moderately towards the east, and trend around 120°, consistent with north-northeast–south-southwest compression. The folds also have an S_{B2} axial-planar spaced cleavage that dips steeply to the north-northeast. Both the S_{B1} and S_{B2} surfaces are defined by flattened quartz, and aligned sericite and chlorite, indicative of greenschist-facies metamorphism. D_{B2} faults may develop on overturned F_{B2} fold limbs. Mineral occurrences in the area are in D_{B2} faults, in axial-planar zones of F_{B2} folds where they intersect southeast-trending faults or fractures, and along lithological boundaries.

Subsequent deformation resulted in open folding with a moderate plunge to the north-northeast (around 60°),

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* 'B' refers to deformation events in the Bald Hill area

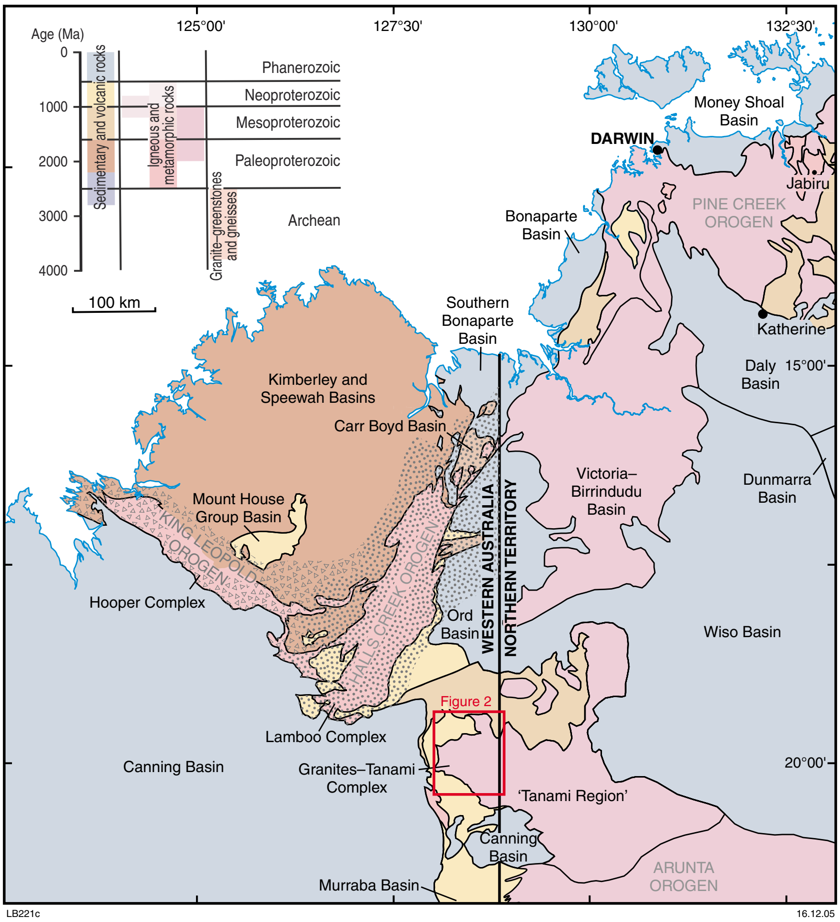

Figure 1. Regional tectonic sketch showing the locality of the Granites–Tanami Complex

Table 1. Early geological events in the Granites–Tanami Complex (modified after Huston et al., in prep.)

Rock types	*Deformation and metamorphic events*
Frederick Suite (c. 1815–1790 Ma): magnetic peraluminous biotite monzogranite to syenogranite **Grimwade Suite** (c. 1820–1790 Ma): nonmagnetic, peraluminous biotite monzogranite to syenogranite	D_3 and ?D_{B3}^*: northeast- to east-trending angular folds with 100 m wavelength (?c. 1810–1800 Ma) D_2: Open, angular, north-northwest- to northeast-trending folds (?c. 1815–1800 Ma, may be correlated with the Stafford Event in the Arunta Orogen)
	Tanami Orogeny (1835–1815 Ma): D_{B1}^*: low-angle faulting and isoclinal folding D_1–M_1 and D_{B2}: asymmetric, disharmonic folds with wavelengths up to 1 km; greenschist- to middle amphibolite-facies metamorphism with highest grades to the southeast. Prolonged period of deformation that affects the Tanami Group
Tanami Group (c. 1840): Killi Killi Formation (c. 1835 Ma): interbedded metawacke and pelite Dead Bullock Soak Formation: interbedded pelite and sandstone (Ferdie Member, c. 1840 Ma) fining up into graphitic pelite and banded iron-formation (Callie Member) Dolerite sills intrude the Tanami Group	

NOTE: * 'B refers to deformation events in the Bald Hill area

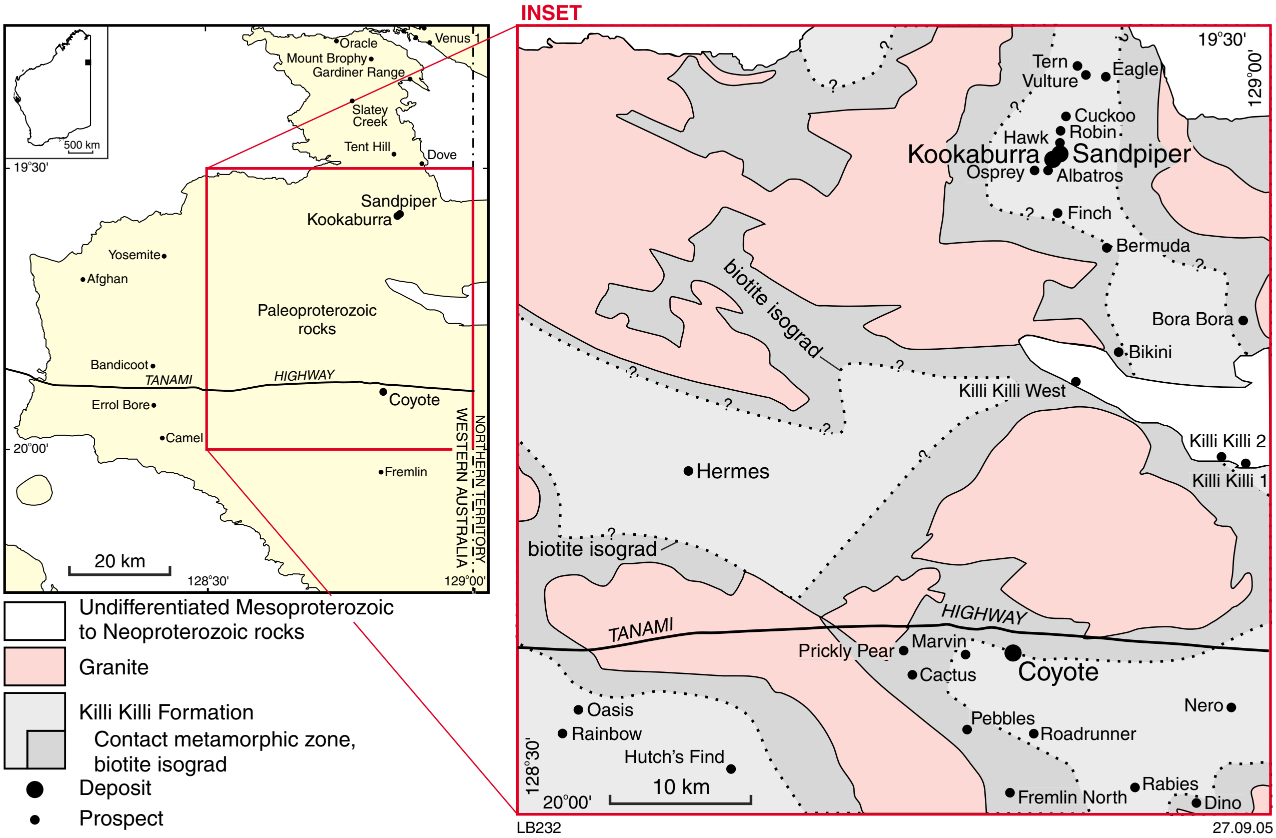

Figure 2. Mineral deposits and prospects in the western Tanami region

and was accompanied by development of a vertical cleavage (Fig. 5). These folds and the cleavage are interpreted as post-D_{B2}, and are referred to as F_{B3} and S_{B3} respectively. The orientation of later F_{B3} folds indicates compression in a northerly to northwesterly direction. A late spaced cleavage (S_{B4}) that dips about 60° towards 220–230° is also recognized in the area.

The Kookaburra and Sandpiper gold deposits

The Kookaburra and Sandpiper gold deposits (Figs 2 and 3, Table 2) were discovered in the Bald Hill Member in the mid-1990s during a geochemical survey by Glengarry Resources NL and Tanami Gold NL. The Kookaburra deposit is in the hinge of an overturned F_{B2} syncline and the Sandpiper deposit is on the southwest limb of an overturned F_{B2} anticline. Both folds trend southeast and plunge about 50° towards the east. A southeast-trending D_{B2} fault at Kookaburra separates the eastern side of the syncline from the Sandpiper deposit to the northeast (Fig. 3). The Sandpiper deposit is largely unexposed, except for auriferous quartz veins, and was discovered following investigation of geochemical anomalies in the area (English, L., 2005, written comm.). At the prospect RAB drillhole cuttings include sericitic, graphitic, and silicified pelite, metachert, and metawacke, and probably also represent the Bald Hill Member of the Killi Killi Formation.

Vein paragenesis and alteration assemblages

The Kookaburra and Sandpiper gold deposits have different structural settings, but are characterized by similar vein parageneses and alteration assemblages. The earliest veins within the Kookaburra and Sandpiper ore zones contain quartz(–pyrite–arsenopyrite) or quartz–carbonate (Table 3). These vein types are commonly anastomosing, form saddle reefs, are locally folded by F_{B2}, and are sheared by the dominant fabric (S_{B2}) within altered wallrock, suggesting that they developed pre- to syn-kinematically with respect to D_{B2}. The veins are typically 3–10 mm thick, and are cut by thick (up to 500 mm), planar, massive quartz veins. Assay results suggest that only the earlier veins carry ore-grade gold mineralization.

The Sandpiper deposit also contains minor carbonate–galena(–sphalerite) veins. Although quartz is absent, the veins have a similar structural timing to veins containing gold mineralization, suggesting contemporaneity.

Quartz(–pyrite–arsenopyrite) veins in the ore zones at both deposits are associated with quartz–mica(–sulfide) schist, with the schistosity defined by sericite and biotite. This fabric is

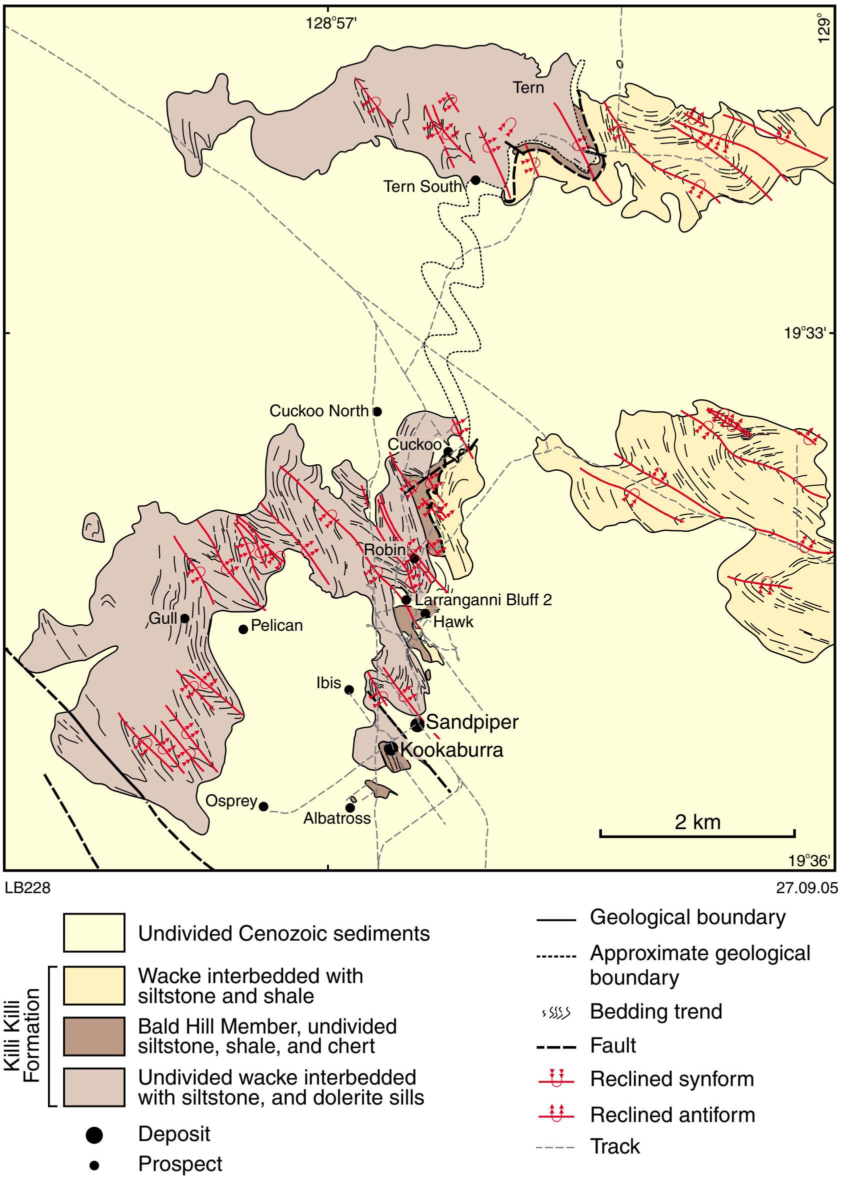

Figure 3.** **Geological map of the Bald Hill area (modified after T. Beardsmore, 2005, written comm.)

Table 2. Characteristics and resource estimates of the Kookaburra and Sandpiper gold deposits

Deposits	*Combined indicated and inferred resource estimates*	*Host rock and structures*	*Vein paragenesis and alteration*
Kookaburra	1.44 Mt at 2.02 g/t Au	Bald Hill Member. Auriferous veins in a synclinal hinge zone	Gold associated with silica–carbonate–sericite–chlorite alteration. Bleached and decarbonized host rocks
Sandpiper	1.21 Mt at 2.92 g/t Au	Bald Hill Member. Auriferous veins in east- to southeast-trending faults	Gold associated with silica–carbonate–sericite–chlorite alteration. Bleached and decarbonized host rocks

SOURCE: Resource estimates after Tanami Gold NL (2005)
Geology after Bagas et al. (in prep.)

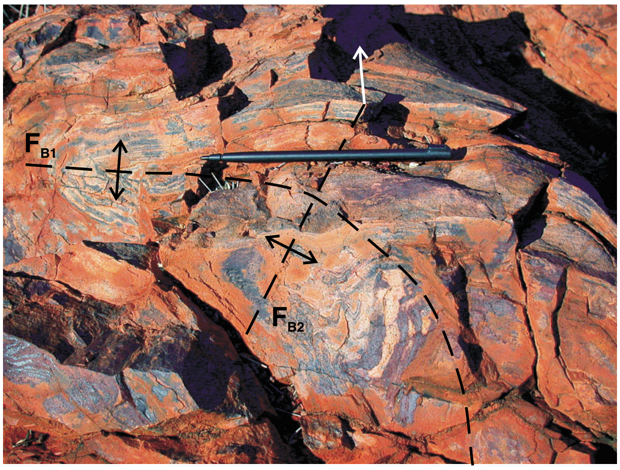

Figure 4. ***Photograph showing the relationship between a tight to isoclinal F_{B1} fold and angular F_{B2} fold plunging 25° towards the east (105°). The rocks are laminated, ferruginized pelite interbedded with metachert in the Killi Kill Formation (MGA 499998E 7835559N)***

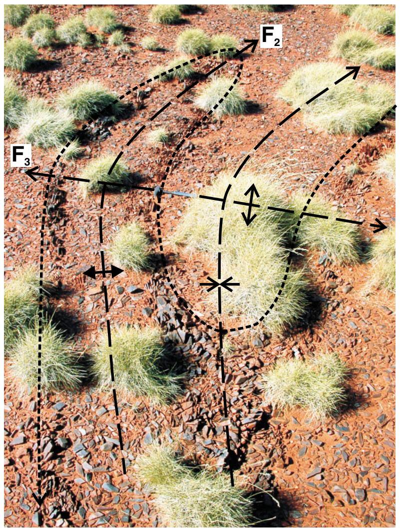

Figure 5. ***Refolded early (F_{B2}) fold hinges in the Bald Hill area (MGA 487124E 7840210N). The F_{B2} folds are upright and plunge moderately to the southeast. The F_{B3} fold hinge plunges steeply to the east-northeast. The hammer is parallel to the F_{B3} fold axis. The photograph was taken facing south, and the area was first reported by T. Beardsmore (2005, written comm.)***

Table 3. Characteristics of veins sets in the Bald Hill area

Vein set and host rocks	*Characteristics*	*Structures*	*Comments and interpretations*
Early veins			
Chloritized mafic igneous rocks	Abundant 1–3 mm, irregular to folded carbonate veins	Veins are folded and crenulated (F_{B2}), and also form disrupted fragments within D_{B2} shears	Carbonate also fills amygdales in basalt, suggesting that the veins and chloritic alteration may be the result of spilitic alteration
Metasedimentary rocks	Carbonate veins associated with a purplish carbonate–(?)hematite wallrock assemblage		
Syn-ore veins			
Dolerite, metawacke, and pelite	Layer-parallel quartz veins, up to tens of metres thick	Saddle reefs, steeply inclined veins in F_{B2} fold axial planes, or subhorizontal veins perpendicular to the direction of maximum D_{B2} extension (σ_3; Fig. 6)	Formed during various stages of D_{B2}
Post-ore veins			
Dolerite, metawacke, and pelite	Planar, 1–10 mm quartz–carbonate–pyrite–chalcopyrite veins	Located along or cut the D_{B4} spaced cleavage; associated with sericitic alteration selvedges that commonly pick out the S_{B4} fabric	This assemblage is similar to late (regional D_{6+}) quartz–carbonate–base metal sulfide veins that cut auriferous veins at the Callie deposit (Wygralak et al., 2005)

parallel to the axial-planar S_{B2} cleavage and D_{B2} faults. Disseminated sulfides within quartz–mica(–sulfide)-bearing rocks commonly form lenticular aggregates parallel to this schistosity. Sulfides include pyrite, marcasite after pyrrhotite, galena associated with native bismuth, chalcopyrite, and sphalerite. Arsenopyrite typically forms euhedral porphyroblasts with common quartz and muscovite pressure shadows. The pressure shadows contain pyrite and, in some cases, marcasite. The fabric commonly wraps around arsenopyrite porphyroblasts, suggesting an early kinematic timing for arsenopyrite introduction. The sulfide and phyllosilicate assemblage in the vein wallrocks appears to have formed syn-kinematically, and is contemporaneous with vein formation.

Massive quartz veins cut the fabric in the quartz–mica(–sulfide) schist, suggesting a post-D_{B2} timing. These veins have a simple mineralogy, with only minor carbonate and pyrite, and very rare arsenopyrite and pyrrhotite.

Conclusion: towards a genetic model for the Bald Hill deposits

Data collected in this study place some constraints on models for the genesis of gold in deposits in the Bald Hill area. Gold deposition occurred early in the tectonic history of the area (i.e. during the c. 1835–1815 Ma Tanami Orogeny), contemporaneous with regional greenschist-facies metamorphism. This timing is atypical for the majority of gold deposits in the Tanami region, which are considered to have formed at c. 1790 Ma (Huston et al., in prep.), broadly coeval with the emplacement of granites (Table 1). Gold deposition in the Bald Hill area was localized along structures that focused fluids into depositional sites, and by fluid–rock interaction in chemically receptive rock types, such as at or near the contacts between mafic igneous rocks, graphitic shale, and sandstone.

Figure 6 summarizes the types of mineralized quartz veins observed in the area. These veins are likely to have been related to the $D_{B1–B2}$ events. The saddle reefs formed in extensional zones at the hinges of folds and continue along bedding contacts where bedding slip was common. These reefs are also generally parallel to the plunge of folds. Other structural controls on veins are fractures parallel to the fold axial plane, and along extensional fractures at right angles to the fold axial surface. Quartz veins in these fractures commonly form en echelon sheets.

The early timing for gold mineralization in the Bald Hill area implies that no single model should be used in exploring for gold in a region, and that gold mineralization can be temporally linked to a number of factors such as tectonism, regional metamorphism, and granite emplacement.

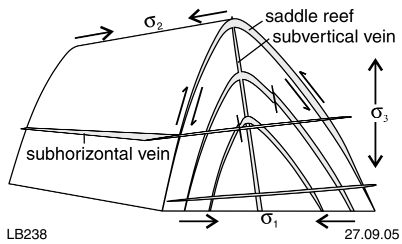

Figure 6. Schematic diagram of quartz veins formed in the Bald Hill area during D_{B2}, showing principal stress directions (σ_1, σ_2, σ_3)

Acknowledgement

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Spatial analysis of gold mineralization information from GSWA's abandoned mine sites database

by W. R. Ormsby, C. D. Strickland, J. A. Robins, and S. D. M. Jefferys

Abstract

Selectively extracted data from GSWA's inventory of abandoned mine sites can be processed to form pseudocolour drapes that portray both bedrock and alluvial–colluvial gold-mineralization patterns. Case studies from Norseman and Widgiemooltha illustrate how these patterns, when combined with historical gold production data, can be used to define exploration targets. The Widgiemooltha example demonstrates how geological attributes that are now routinely recorded can assist in understanding controls on bedrock gold mineralization, and in prospectivity mapping.

KEYWORDS: Western Australia, Norseman, Widgiemooltha, abandoned mines, mineralization, mineral exploration, placer deposits, gold, GIS, spatial data.

Introduction

The Geological Survey of Western Australia's (GSWA's) Western Australian inventory of abandoned mine sites (WABMINES) is a comprehensive digital database, growing by about 25 000 records per annum, that provides baseline data, including photographs, on abandoned mining-related features in Western Australia (Ormsby et al., 2003). Included in this information in recent years are the geological descriptions of all types of former mine workings from small prospecting pits to major shafts and opencuts (GSWA, 2004, 2005).

Overall, about 40% of the known 11 411 abandoned mine sites in Western Australia have been documented, and the vast majority of these sites produced gold. The WABMINES database now aims to include every mining-related feature within the surveyed areas, and currently has more than 138 000 records and 34 000 digital photographs.

Spatial analysis of mineralization trends

Abandoned shallow gold workings and shafts commonly follow bedrock-mineralized features such as quartz veins. They once formed the equivalent of a drillhole for exploration purposes, with the difference being that each working was commonly excavated on the surface outcrop of a vein that produced visible gold from dollying. With continued encouragement, these workings were extended to follow the dip and strike of the mineralization.

The dense number of features in some mineralized areas makes the WABMINES database ideal for spatially analysing 2D mineralization trends using geographic information software. The objective of this analysis is the identification of new exploration targets from the distribution of abandoned mine and prospect workings. This analysis is based on the recently released 'Inventory of abandoned mine sites: progress 1999–2004' digital dataset (GSWA, 2005).

Methodology

To examine bedrock gold-mineralization patterns, field data collected from shallow workings, shafts, collapsed shafts, rehabilitated shafts, open stopes, and former workings located from historical maps and other sources (under infrastructure and some rehabilitated features) were selected from WABMINES for a particular region. Non-gold workings and mechanically excavated features were excluded. Depth ranges estimated in the field were assigned average depths, and original depths for collapsed shafts were inferred from the height of the waste material (bund) that surrounds the feature. Average depths were applied to rehabilitated workings, and to workings that are now either beneath waste dumps or have been removed by opencuts (under infrastructure), where the original depths were unknown. Because the actual depth of any working more than 20 m deep is normally not known (they are recorded as >20 m), all depths in this category were attributed a value of 25 m.

The other main types of abandoned gold workings are those that follow surficial alluvial, colluvial, or eluvial deposits. In the areas covered by the inventory to date, this type of working commonly resulted from panning or dry blower sampling in areas downslope or downstream from bedrock gold mineralization. All workings of alluvial, colluvial, eluvial, or 'deep lead' origin were noted in the 'MINE_NOTE' field, and were selected from WABMINES to examine 'alluvial' gold-mineralization patterns.

Creating pseudocolour drapes

ArcGIS Spatial Analyst software was used to generate raster images of the surface concentration of workings (density), and of working depth via the neighbourhood statistics function. The working density images were produced by calculating the sum of points within a 20 m search radius, with an output cell size of 10 × 10 m. This resulted in both an amplified and smoothed output. The same approach was used for summing the depth of the workings, rather than calculating the mean, so that depth variations were accentuated, yet still reflected a component of working density. Three-dimensional pseudocolour drapes of working depth (in colour) over density (as elevation) were generated using ER Mapper software (Fig. 1).

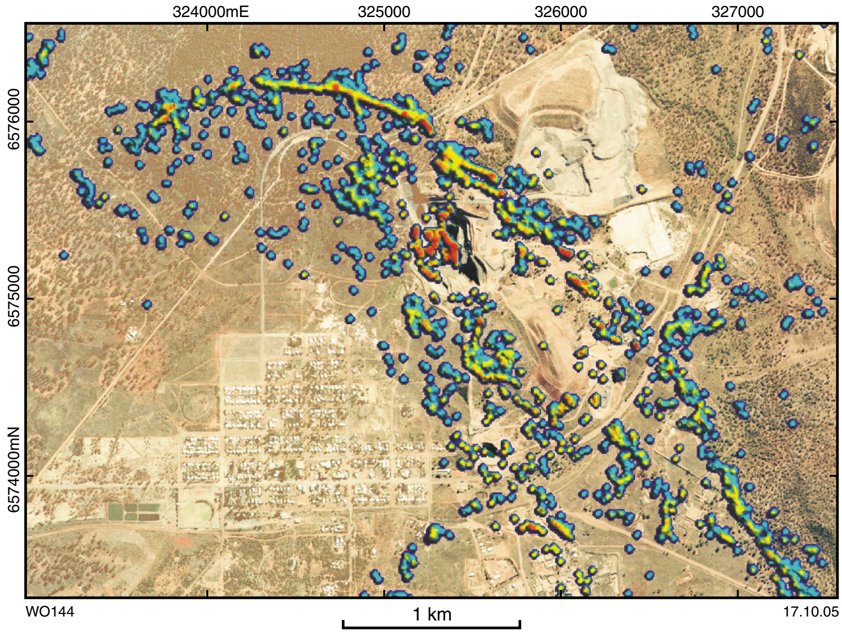

*Figure 1. **Bedrock gold working depth – density drape on an orthophotograph for the Coolgardie region. The deepest workings are shown in reddish tones, and the areas with a higher surface concentration of workings are shown in higher relief***

Exploration target generation

For bedrock gold, mineralization structures were interpreted using the bedrock working depth – density drape. Polylines were created in ArcMap to follow the 'ridge lines' on the drape. Buffers were then created to approximate the width of most of the depth–density drape trend lines, and to encompass the relevant pre-1985 gold production sites from the Western Australian mines and mineral deposits information database (MINEDEX database MH sites). The total historical gold production was calculated for each buffer from the MINEDEX production statistics, and was attributed to that buffer. The buffers now represented bedrock gold mineralization structures, and were colour coded to reflect total cumulative gold production.

Exploration targets can be generated from abandoned mine sites data in a number of ways including:

a) examining the relationships between the major historical production structures and more recent mining activity (e.g. opencuts), and identifying similar patterns in areas with no recent exploration or mining activity;
b) identifying mineralization structures with relatively high historical production, but no recent exploration or mining activity;
c) using targets generated by a) or b) above as templates to identify other areas that share similar characteristics in the WABMINES database;
d) by interpreting geological controls on mineralization structures with known high historical production, and identifying other areas with these controls.

Case study — Norseman

Figure 2 shows the bedrock working depth – density drape for the Norseman region. An area east of the township was selected that covered most of the historical gold production in the district. Mineralization structures were interpreted using the drape, and the surface projections of the major gold-producing reefs (adapted from Thomas et al., 1990). The structures were then given a 60 m-wide buffer to cover the majority of relevant workings and associated MINEDEX MH sites. After attributing the buffers with historical gold production (from MINEDEX and Thomas et al., 1990), it became clear that the most gold has been produced from north-trending structures (Fig. 3). The clear definition of north-trending structures highlighted their intersections with major crosscutting structures and the location of a number of recent opencuts near these intersections. Intersections of these structures were used to define the surface projections of exploration targets at the northern end of the Norseman reef, and along the Mount Barker structure (Fig. 3). A similar process was carried out for the minor

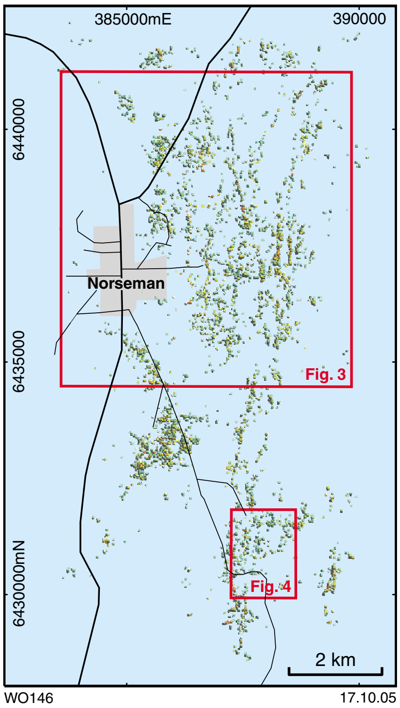

Figure 2. Bedrock gold working depth – density drape for the Norseman region, showing the locations of the areas covered by Figures 3 and 4

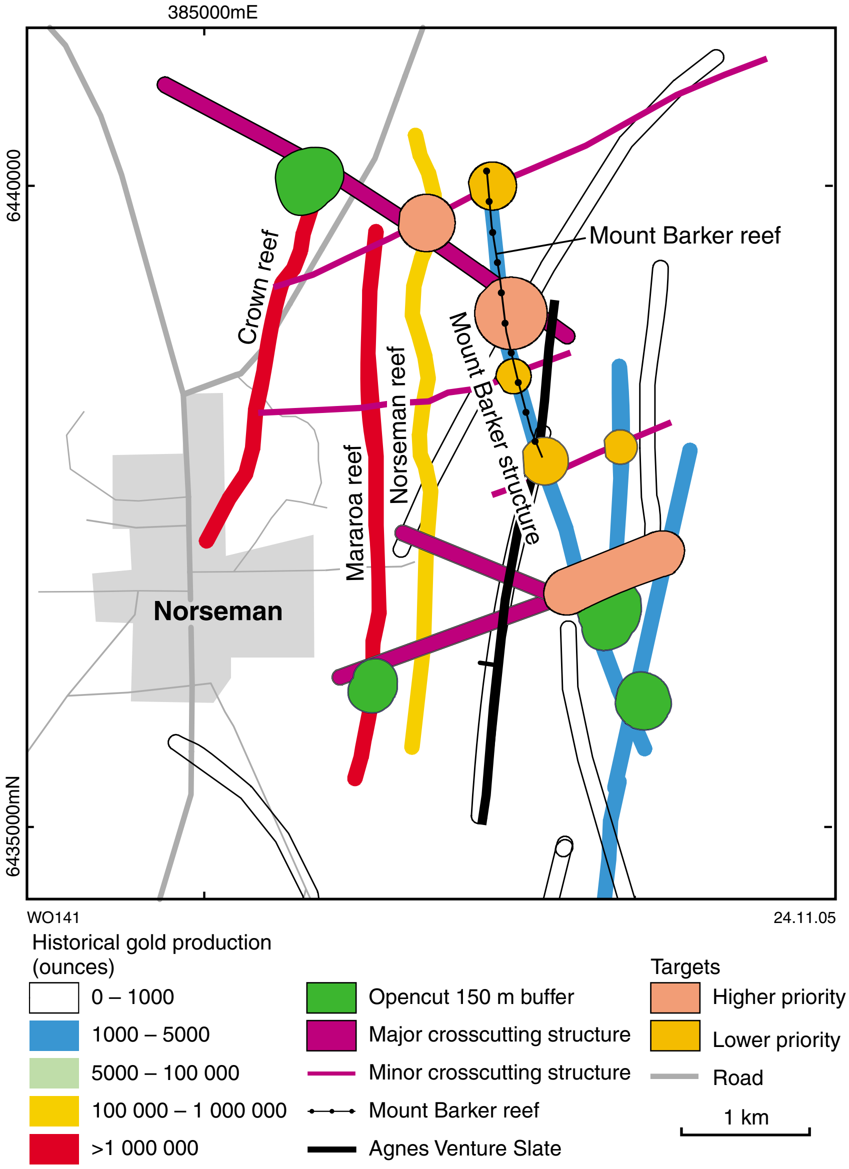

Figure 3. Major bedrock gold-mineralization structures in the Norseman region showing exploration targets

crosscutting structures, with further lower priority targets identified at the intersections of these structures with the major north-trending structures.

The Mount Barker trend was shown to be of similar length to the other major producing reefs, extending about 2.5 km further south of the previously mapped 'Mount Barker reef' (Fig. 3). Historical gold production up to 2.4 km south of the mapped reef suggests the potential for stratigraphically deeper targets beneath the west-dipping 'Agnes Venture Slate' that has been previously thought to mark the eastern boundary of known gold mineralization in this district.

Alluvial–colluvial workings south of Norseman were portrayed as a working depth – density drape (Fig. 4). Like the bedrock workings, many of the alluvial–colluvial workings are along linear trend lines. These trends differ from the bedrock trends in that they reflect areas of downslope redistribution of gold along past and present drainages, rather than primary mineralization structures. The bedrock source of the alluvial–colluvial gold can commonly be inferred from the upslope origin of these lines of workings.

Case study — Widgiemooltha

Like Norseman, bedrock gold mineralization structures were interpreted using the working depth – density drape. In this case, 20 m-wide buffers were generated to cover the majority of associated workings, and associated MINEDEX MH sites. The buffers were again attributed with historical gold production data from the MINEDEX MH sites. Where structures intersect near a MINEDEX site, the production was attributed to the dominant northwesterly structure. Figure 5 depicts historical gold production for both mineralization structures and MINEDEX sites. Three centres of past gold production stood out: Flinders, Cardiff Castle, and Mount. Cardiff Castle and Mount have been

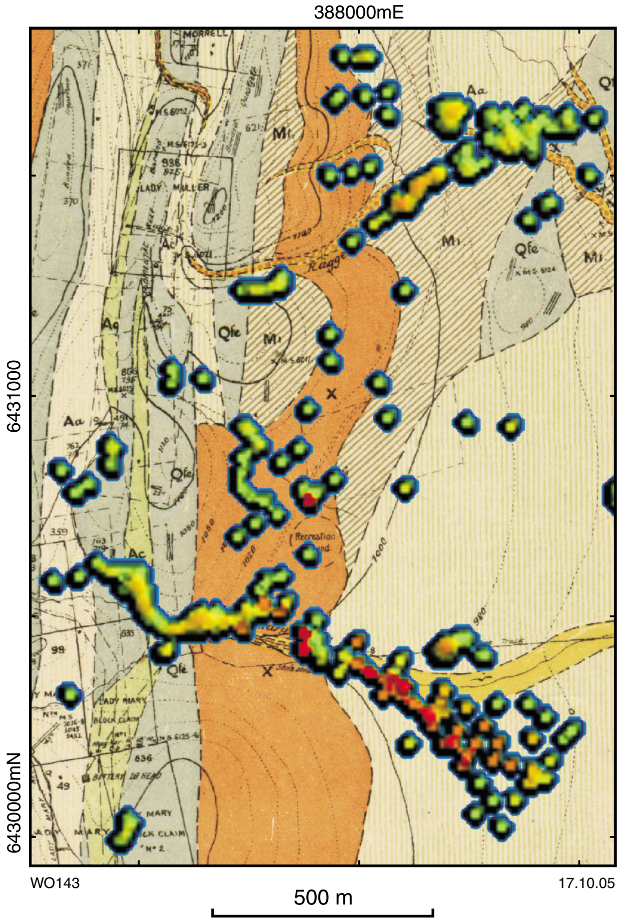

Figure 4. 'Alluvial' gold working depth – density image for the Lady Miller to Lady Mary region, about 7 km southeast of Norseman. The deepest workings are shown in reddish tones, and the areas with a higher surface concentration of workings are shown in higher relief. The base map is from Campbell (1906)

recently explored and mined, but Flinders has received little attention. The majority of gold production in the Flinders area was attributed to a 660 m-long, northwesterly trending 'target' structure.

Specific geological comments in the bedrock gold-mineralization dataset (such as rock type, strike of veins and associated workings, quartz occurrence, foliation, and accessory minerals) were extracted into additional fields and numerically coded for further analysis. Where there were multiple entries such as rock type, a hierarchy was established to ensure that the most relevant lithology (e.g. a marker horizon such as banded iron-formation) was coded. Raster images were then generated using neighbourhood statistics for each of the additional fields (attributes), using the same parameters as for depth and density.

The 'target' structure was intersected with the point layers for each attribute to identify key target characteristics. A selection was made for points both within and outside the 'target' structure, and statistics were examined for each. Natural breaks and various numbers of classes were used to select a threshold value for depth and quartz occurrence that set the target apart from the remainder of the population. Some target characteristics such as rock type, tourmaline occurrence, and foliation were examined visually and have a positive correlation with the target.

Separate binary raster layers were generated for each of the permissive characteristics (e.g. each cell with a depth greater than 12 m was given a value of '1', else '0'), and were added together using the raster calculator in Spatial Analyst. Each layer was given the same weighting. The resultant raster image highlighted other areas with the same permissive characteristics, and hence was a form of prospectivity map. A pseudocolour drape was then created using the same process as for the working depth – density drape, except that 'prospectivity' was shown as colour draped over a 'prospectivity' elevation layer (Fig. 6).

The prospectivity map highlighted a second 'look alike' target area southwest of the previous target at Flinders. Consequently, two areas of exploration interest were clearly defined spatially in the Flinders region. Elevated 'prospectivity' values were also recorded around the Darlek opencut about 1.5 km southeast of Flinders (Fig. 6).

Conclusions

The examples from Norseman and Widgiemooltha illustrate how selective extraction and processing of WABMINES data enables the visualization of both bedrock and alluvial–colluvial gold-mineralization patterns. When combined with historical production information, these mineralization patterns can be used for targeting in areas with significant historical mining activity.

The increased geological information from some of the recent WABMINES data can be extracted and combined to produce prospectivity maps. These data can also provide insights to both regional and local controls on mineralization, as well as providing detailed information on the geological setting at the prospect scale. The extrapolation of regional mineralization controls has the potential to identify targets in areas with surficial cover, especially if used in combination with other detailed proprietary geological, geophysical, and geochemical datasets.

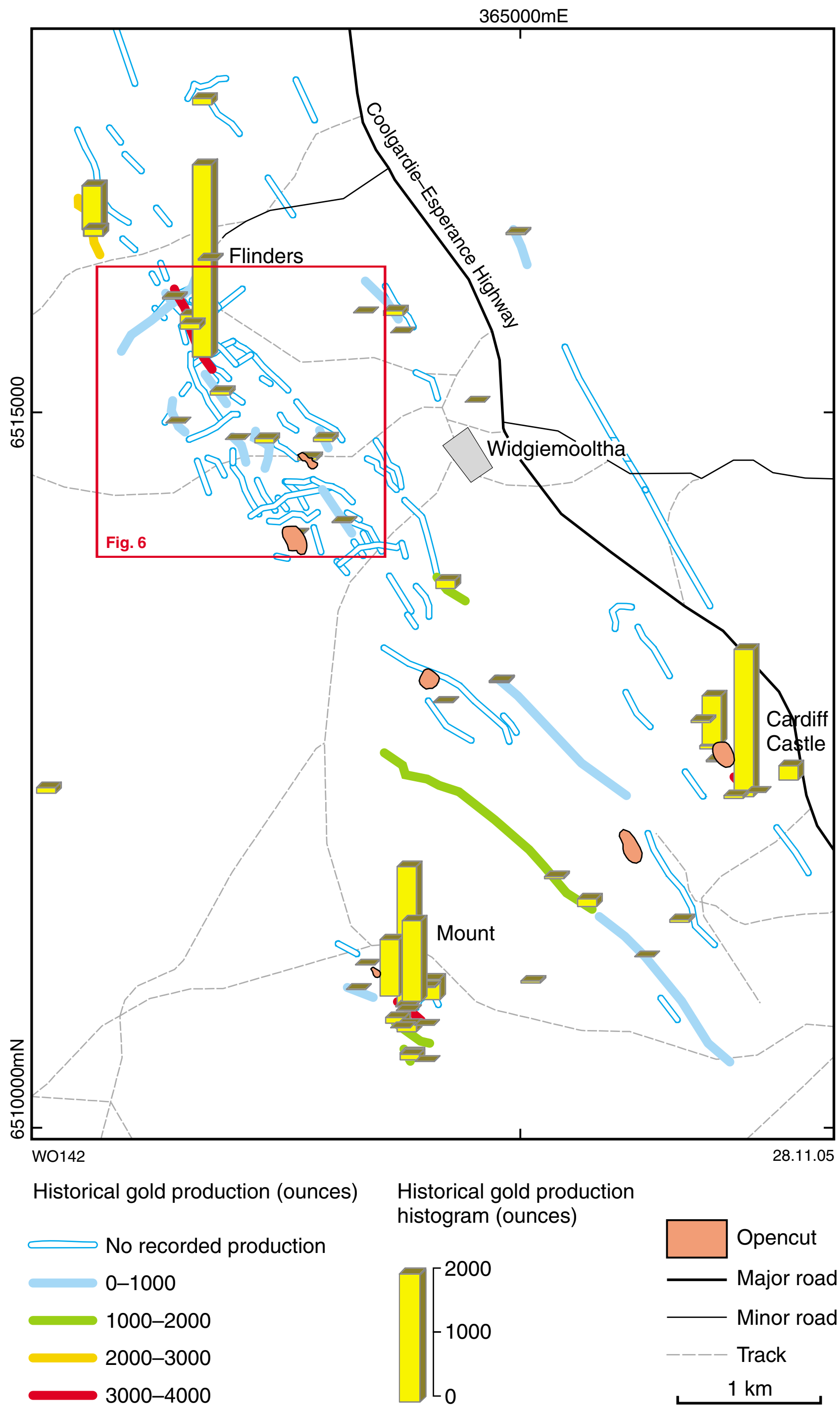

Figure 5. Historical gold production in the Widgiemooltha region shown as coloured mineralization structures, and histograms on MINEDEX MH sites. The Flinders area is highlighted as having had significant previous production and no recent mining development

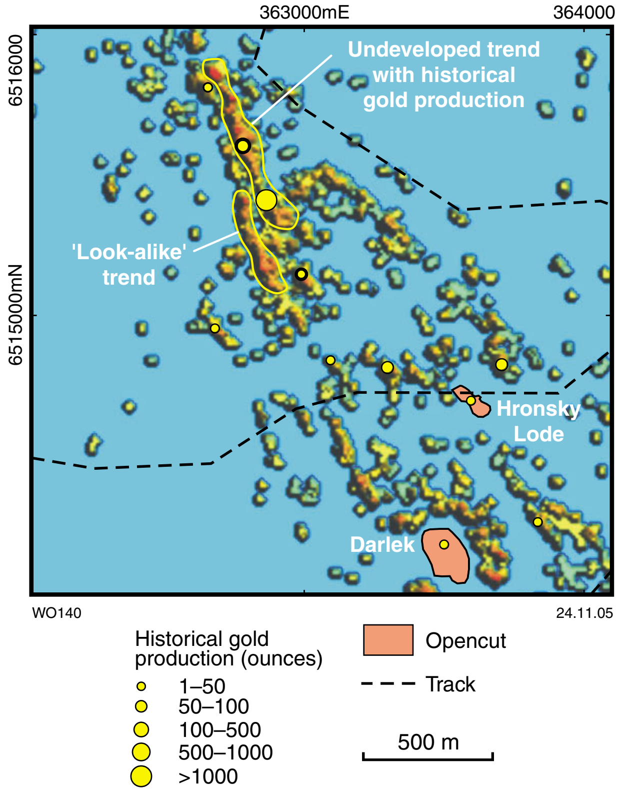

Figure 6. Prospectivity map of the Flinders area, located about 2 km west-northwest of Widgiemooltha. Areas with a high prospectivity are shown in reddish tones and with higher relief

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Mining GSWA's databases — production of exploration leads and targets

by M. Pigott, A. Fitton, and M. J. Ellis

Abstract

There are three major online databases (WAMEX, MAGIX, and MINEDEX) that contain mineral exploration information on Western Australia. Further regional data can be sourced from the Geological Survey of Western Australia's geological exploration packages, geochemical mapping products, the abandoned mine sites database (WABMINES), core library data (in WAPIMS), and geological publications. A significant amount of this information is digital or scanned, available online, and can be downloaded. Two examples are presented to illustrate the usefulness of this material for target generation of mineral deposits.

KEYWORDS: databases, exploration potential, literature reviews.

Introduction

'How can I obtain all the geological and exploration open-file data for my area of interest?' This is an important task for explorers, and this paper aims to answer this question.

Some of the early historic mineral exploration data are only available in hardcopy, but significant amounts of data are available in digital form and online at the Western Australian Department of Industry and Resources' (DoIR's) website at <http://www.doir.wa.gov.au>. The Geological Survey of Western Australia's (GSWA's) publications are also a source of data. These are listed in the Catalogue of pre-1980 Geological Publications and the Catalogue of Geoscience Products 1980–2005 at <http://www.doir.wa.gov.au/gswa/catalogue.asp>.

Databases

Four comprehensive open-file databases (WAMEX, MAGIX, MINEDEX, and WAPIMS) on the DoIR website provide data useful to mineral explorers. These may be accessed directly for a complete search. Alternatively, GeoVIEW.WA can be used as a spatial interface to help the data search. These databases are described in more detail below.

GeoVIEW.WA

GeoVIEW.WA (<http://www.doir.wa.gov.au/aboutus/geoview_launch.asp>) is a free interactive (GIS-based) mapping system that allows the users to make their own geological map (for their chosen area and scale), incorporating other mineral and petroleum exploration datasets including mines and mineral deposits, abandoned mine sites, petroleum wells, live and dead leases, and so on. Users can make a quality PDF plot of their completed map (size A0 to A4) online.

The data available via the GeoVIEW.WA interface are not live, but are uploaded regularly, thus, it may not contain the most recent data captured in the source database.

Figure 1 shows a GeoVIEW.WA screen of the Murchison areas targeted for orogenic gold mineralization as examples of generating exploration leads from the open-file databases.

WAMEX

The Western Australian mineral exploration (WAMEX) database records mineral exploration reports submitted since the 1960s (http://www.doir.wa.gov.au/aboutus/wamex.asp). After a period of confidentiality, now set at five years from submission to GSWA or tenement death if earlier, exploration reports are made publicly available.

Of the more than 40 000 mineral exploration reports available on open file, reports released since 1997 (Item numbers 8600 onwards) are available online and can be viewed, printed or downloaded.

MAGIX

MAGIX (Mineral Airborne Geophysics Information eXchange)

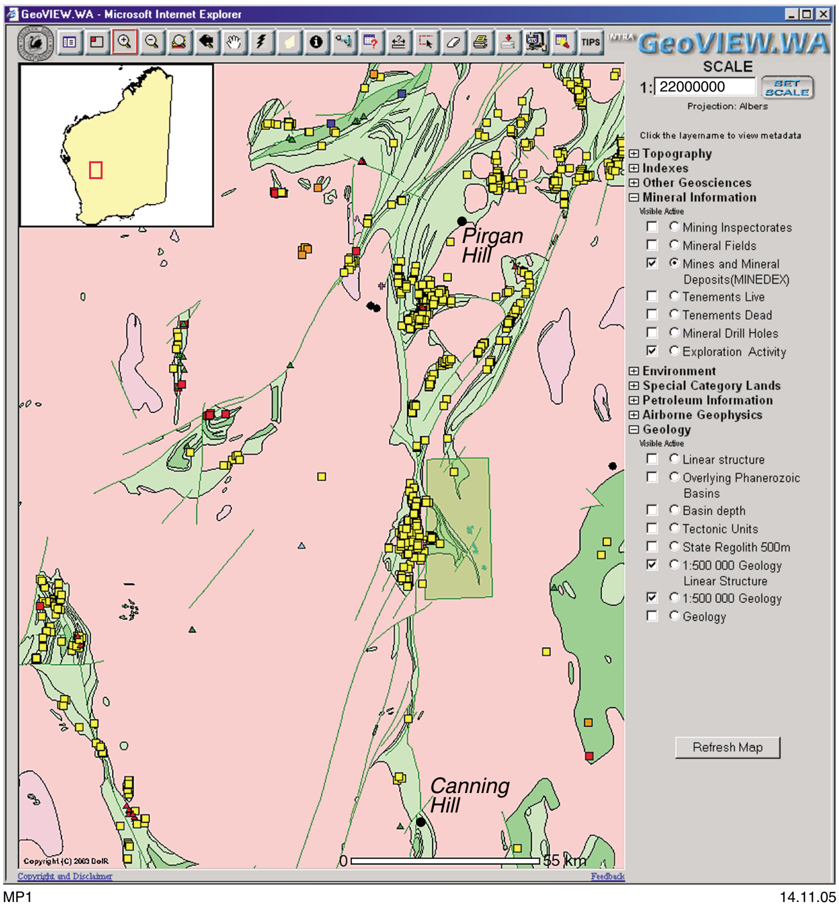

Figure 1. GeoVIEW.WA query of the Murchison study areas with geology, linear structure, MINEDEX, and historic exploration activity layers visible

is a GIS-based register (<http://www.doir.wa.gov.au/aboutus/magix>) of airborne geophysical surveys reported to DoIR under the provisions of the Mining Act 1978. It provides index maps showing the location of surveys available from DoIR and from commercial suppliers, comprehensive details on field recording parameters, and 'thumbnail' images of many of the available datasets.

MINEDEX

The mines and mineral deposits information (MINEDEX) database (<http://www.doir.wa.gov.au/minedex>) contains information on commodities, resource estimates, site type and status, location, corporate ownership, mine operators and contact addresses for mines and mineral deposits of Western Australia.

Abandoned mine sites (WABMINES)

The inventory of abandoned mine sites (WABMINES) provides data on historic mining-related features. The inventory records more than 90 000 mining-related features and includes two-thirds of the highest priority historic mine sites. It is available via GeoVIEW.WA or as a DVD (Geological Survey of Western Australia, 2005).

Geological publications

The GSWA publishes maps, books and digital datasets on the geology of Western Australia. Themes include geology, geochemistry, geophysics, mineralization and mineral deposits mapping, hydrogeology, and urban and environmental geology. Of particular use to explorers are the 1:250 000 regolith geochemistry maps and the 1:100 000 geological maps and Explanatory Notes. Publications can be ordered from the DoIR website (<http://www.doir.wa.gov.au/ebookshop>), which also contains details of all publications produced by GSWA since 1898. GSWA is currently scanning all publications back to 1895, and these will be available online in 2006.

The most recent publications are also available free online at (<http://www.doir.wa.gov.au/gswa/onlinepublications>).

Mineral core collection

Details of collected drillcore and other materials that have been acquired from mineral and petroleum exploration programs are in the Western Australian petroleum information management system (WAPIMS) database (<http://dp.doir.wa.gov.au/dp/index.jsp>). These data are also easily viewed through GeoVIEW.WA.

Geological exploration packages

Geological exploration packages containing topographic, geophysical, and geological legacy data for areas where GSWA geological mapping is underway are currently available for the Northern Murchison, Northeastern Yilgarn, Southeastern Yilgarn, and the West Musgrave areas. A package for the Tanami area is in preparation. Packages include aeromagnetic and radiometric images, satellite imagery, orthophotography, and geological interpretations. The Murchison geological exploration package (GSWA, 2004) includes J. A. Hallberg's 1989–94 Murchison 1:25 000 geology dataset with maps and reports (Hallberg, 2000).

Examples of the generation of exploration leads in the Murchison region

The Murchison region was used to give examples of the generation of exploration leads from data available from GSWA. Two areas were targeted

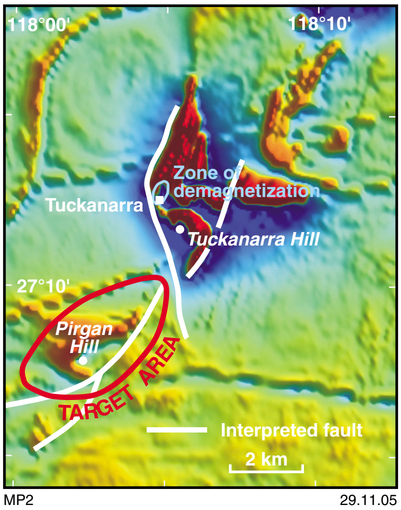

***Figure 2.** Aeromagnetic interpretation of the Pirgan Hill area on the Reedy 2543 magnetic image from the Cue–Kirakalocka GSWA–GA 2004 survey*

for orogenic gold mineralization on the basis of aeromagnetic interpretation, and favourable structural settings and host rocks. Available geological and exploration open-file data were extracted from the GSWA databases and regional datasets.

Pirgan Hill

This target area centred on Pirgan Hill is on CUE*, 10 km south of the Tuckanarra mining centre. It is a structural target interpreted from the aeromagnetic data at the intersection of two faults, one of which is associated with the contact between mafic rocks and granite, and is under cover. Figure 2 shows the aeromagnetic interpretation of part of the Reedy 2543 magnetic image showing the Pirgan Hill area.

Figure 3 shows data extracted from the databases, particularly WAMEX. These data include the aeromagnetic interpretation, Hallberg's (2000) detailed regional mapping (Tuckanarra SW 1:25 000 geological map, 1992) and detailed company geological mapping, grid soil sampling, rock-chip sampling, RAB and percussion drilling, and petrology, from WAMEX Item numbers I155 (Dodds, 1973), I3723 (Freeport Australian Minerals Limited, 1989), I4372 (Grigson, 1990), I4744 (Kelers, 1989), and I7687 (Taylor, 1994). These open-file reports yielded exploration leads such as alluvial workings for both gold and copper, that 'gold had been mined from kaolinised porphyry', surface geochemistry with gold-in-soil values up to 5.45 ppm, anomalous RAB geochemistry, as well as useful regional data including regolith depths from drilling records. There was no evidence of previous exploration at the intersection of the two faults.

Canning Hill

This target area is centred on Canning Hill in the Wydgee area, on KIRKALOCKA, 15 km south-southeast of the Kirkalocka gold mine. The area is a high-prospectivity conceptual target defined by prospectivity mapping (Pigott, 2001) based mainly on structural complexity (faulting and folding) and favourable rock types (banded iron-formations and mafic volcanic rocks).

An aeromagnetic interpretation of the Canning Hill area of the Kirkalocka 2440 magnetic image is shown in Figure 4.

Figure 5 shows exploration leads from aeromagnetic interpretation and the databases, particularly WAMEX, from Item numbers I1484 (Kia Ora Gold Corporation, 1973), I1634 (Aztec Exploration Limited, 1983), I3555 (Cull, 1985; Harvey, 1986a,b,c; Onley and Peters, 1984), I7826 (Davies and Meakins, 1994), I8366 (Hamdorf and Stewart, 1994), I9087 (Ewart, 1996), I9624 (Dalton, 1997), I10923 (Dudfield, 1998, 1999, 2000), I11720 (Westaway, 1999). They include potentially mineralized structures, a central demagnetized zone, and the locations of old workings.

The northern two-thirds of the area is under cover, which may have inhibited effective exploration.

Conclusions

Mining the GSWA open-file databases is an excellent and cost-effective means of exploration targeting. Exploration leads and useful regional data can be obtained. There is a wealth of data available, a significant amount of which is available via the DoIR website or on DVDs, and the databases and regional datasets are continuously being updated.

* Capitalized names refer to 1:250 000 map sheets.

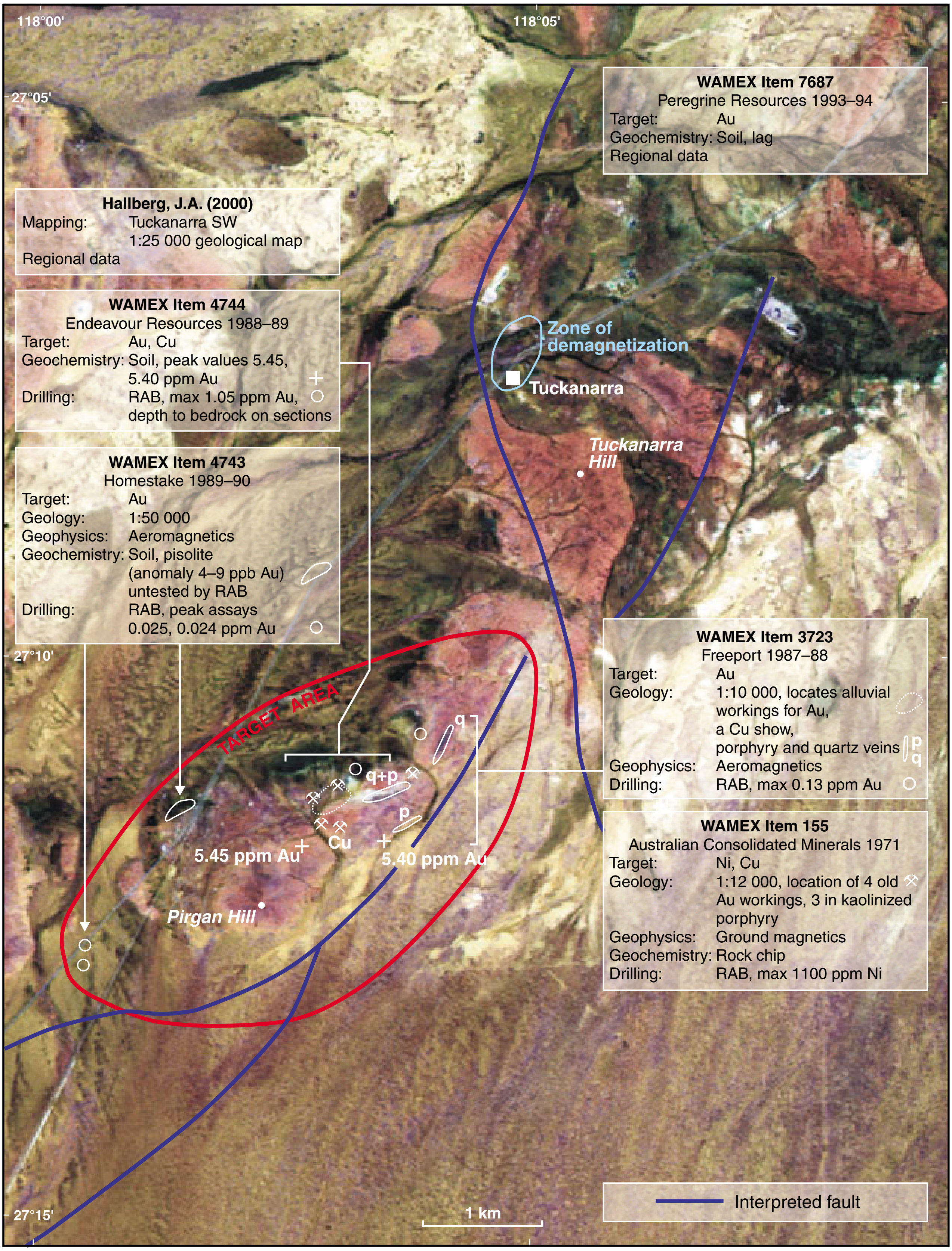

Figure 3. Pirgan Hill target area showing exploration leads from aeromagnetic interpretation, WAMEX, and Hallberg (2000) mapping on a Landsat 7 base

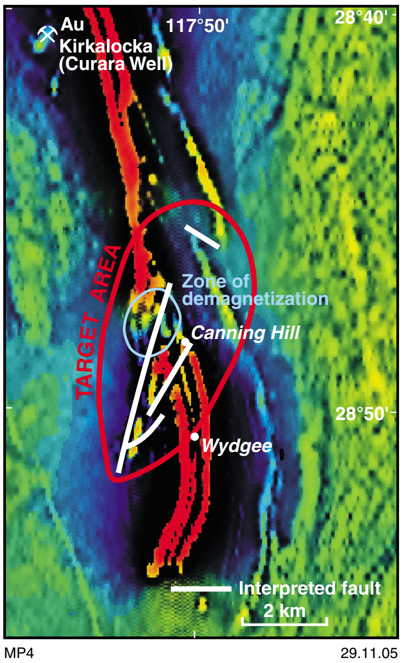

Figure 4. Aeromagnetic interpretation of the Canning Hill area on Kirkalocka 2440 First Vertical Derivative reduced-to-pole magnetic image from the Cue–Kirakalocka GSWA–GA 2004 survey

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Figure 5. Canning Hill target area, showing exploration leads from aeromagnetic interpretation and WAMEX on a Landsat 7 base

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Some unusual gold and bismuth mineralization at Mardoonganna Hill, Murchison mineral field

by L. Y. Hassan and R. M. Clarke[1]

Abstract

A suite of unusual secondary bismuth minerals is associated with gold mineralization in amphibolite at Mardoonganna Hill, 74 km northwest of Cue in Western Australia. These minerals include bismite, mixite, and an unidentified bismuth–iron silicate. A secondary rare earth – copper arsenate intermediate in composition between agardite-(Ce) and agardite-(La) was also identified. Gold is present as electrum in grains 5–35 µm across. The mineralization has similar bismuth levels as the Juno mine in Tennant Creek. It is possibly related to porphyry intrusions or felsic volcanic activity.

KEYWORDS: bismuth, gold, electrum, mixite, bismite, agardite.

Introduction

Samples of poorly exposed amphibolite from Mardoonganna Hill (74 km northwest of Cue; Fig. 1), collected by a prospector, Mr Don Caesar, assayed up to 124 ppm gold. When Mr Caesar dollied and panned the samples he obtained a straw-coloured tail, but could see no gold so he submitted samples to the authors for examination.

In hand specimen the host rock appeared dark green with no obvious sign of mineralization apart from some green secondary minerals along thin veinlets and on fracture surfaces. Polished sections of the specimens were examined using a reflected light microscope and a scanning electron microscope (SEM). An examination of the back-scattered electron image of a polished section under the SEM showed numerous very bright (high average atomic number) grains. Semiquantitative analysis showed that these contained bismuth and Mr Caesar was advised to have the samples assayed for bismuth. The samples assayed up to 8060 ppm bismuth and 5580 ppm copper. Such high bismuth levels are unusual for Western Australia, but are comparable with those at the Juno mine at Tennant Creek in the Northern Territory, where the average grade of ore treated was 76.48 ppm gold; 0.61% bismuth, and 0.42% copper (Large, 1975). Because the mineralization of the sample was so unusual, it was decided to undertake a study of the secondary minerals.

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* Capitalized names refer to 1:250 000 map sheets

Geological setting

The prospect is in an outlier of Archean greenstones northwest of the Weld Range greenstone belt on BELELE* (Elias et al., 1982; Fig. 1) near the contact between basalt and dolerite shown on that map sheet. More recent mapping of the outlier (Battle Mountain (Australia) Incorporated, 1995) identified banded iron-formation units within fine- and medium-grained amphibolites intruded by narrow porphyry dykes. Felsic volcaniclastic rocks were mapped southeast of the prospect.

Host lithology

Petrographic examination of the host amphibolite shows that it consists mainly of blue-green hornblende and colourless to green pleochroic chlorite with anomalous blue interference colours, with minor biotite, ilmenite, and quartz. The rock has been completely recrystallized and no primary igneous textures are evident. In the most strongly mineralized samples, the amphiboles have been almost entirely replaced by chlorite and there are veins and segregations of clinozoisite (both minerals with anomalous blue interference colours). Numerous thin veinlets contain iron oxides and secondary ore minerals.

Nature of the gold

Examination of polished sections under reflected light showed the gold as numerous irregular grains

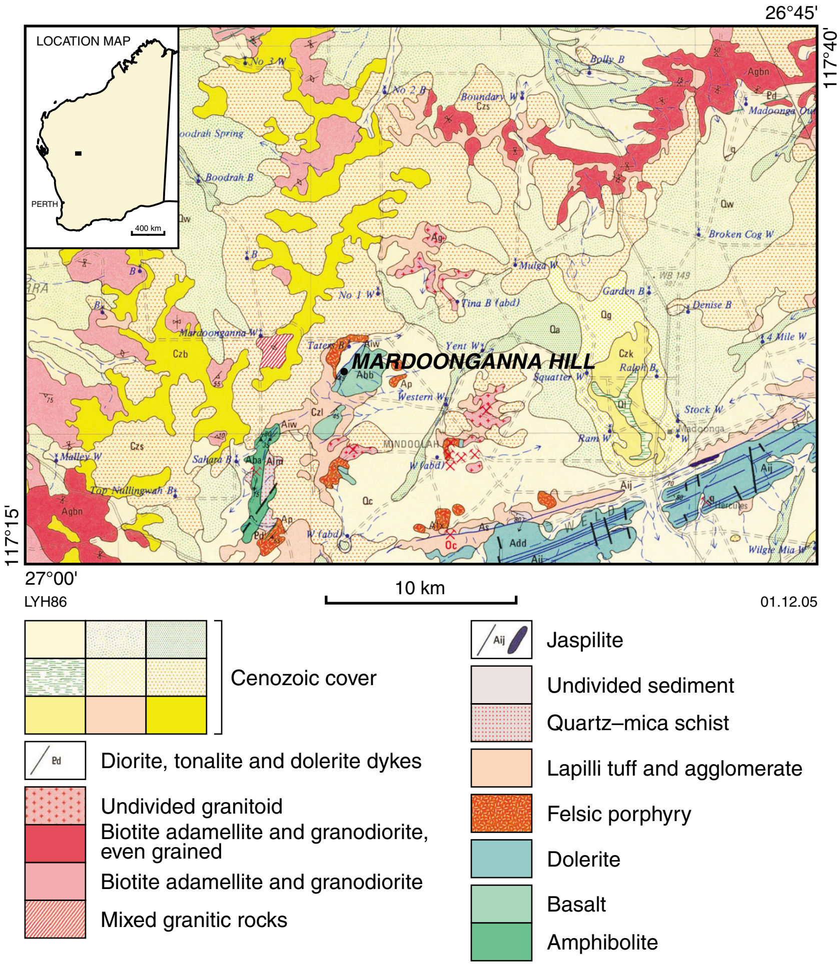

Figure 1. Regional geological setting of the Mardoonganna Hill prospect, northwest of the Weld Range greenstone belt on BELELE *(1:250 000; after Elias et al., 1982)*

ranging in size from 5 to 35 µm across. Most of the grains are associated with thin veinlets of iron oxides after sulfides (Fig. 2) and thin veinlets of secondary bismuth minerals (Fig. 3) in the amphibolite. Some tiny gold grains are also in chlorite and amphibole adjacent to veins of clinozoisite and chlorite. Semiquantitative (SEM) analysis of the gold indicates that it contains 22–25% silver (i.e. electrum).

Nature of secondary minerals

Analytical methods

The samples were examined using X-ray powder diffraction (XRPD) analysis and energy dispersive X-ray analysis (EDXRA) on a scanning electron microscope. The XRPD analyses were performed using Co*Kα* (1.7902 Å) radiation on small amounts (of the order of 1 mg or less) of hand-picked sample, pulverized using glass slides, and mounted on low-background quartz plates. EDXRA was performed on rough grains mounted on carbon tape (semiquantitative) and on a polished thin section (quantitative).

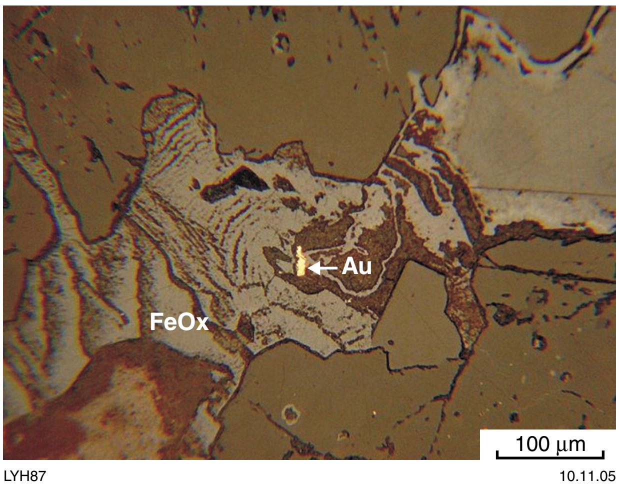

Figure 2. Gold (electrum) grain (Au) associated with iron oxides (FeOx) after sulfides (reflected light)

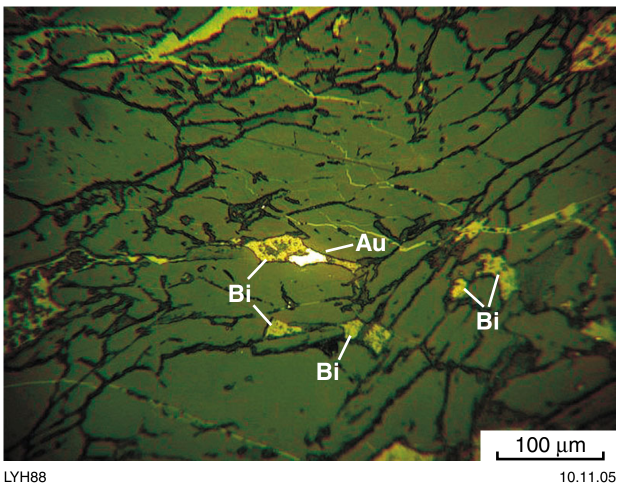

Figure 3. Gold (electrum) grain (Au) with bismite (Bi) along fracture (reflected light)

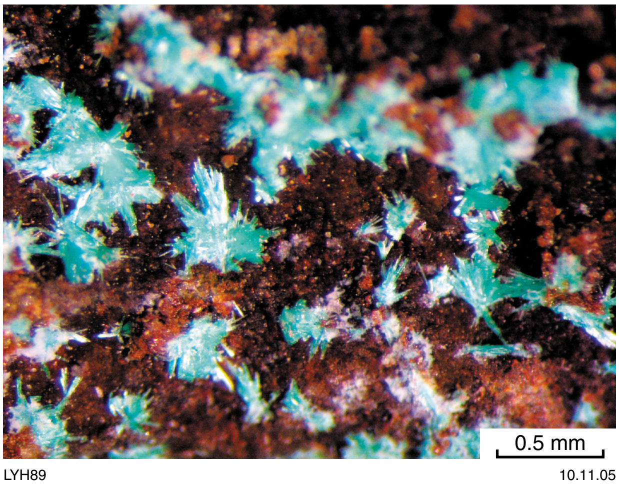

Figure 4. Tufts of fine radiating fibres of mixite on fracture surfaces

Minerals identified

Bismite: Bi_2O_3

Bismite is abundant and forms fracture fillings and interstitial composite grains up to 100 µm across. It is commonly associated with gold–electrum (Fig. 3). A sample assayed 94.6% Bi_2O_3, 0.6% FeO, and 0.5% CaO.

Mixite: $(Bi,Ca)Cu_6(AsO_4)_3(OH)_6.3H_2O$

Mixite forms bluish-green rosettes (up to 0.5 mm across) and tufts of fine radiating fibres on fracture surfaces (Fig. 4). It also forms acicular crystals up to 350 µm long and several microns wide infilling veinlets that are progressively lined by a bismuth–iron silicate and a copper silicate (Fig. 5), indicating that mixite was formed late in the paragenetic succession. EDXRA analyses of the mixite (Table 1) indicate that it is compositionally intermediate between ideal mixite ($BiCu_6(AsO_4)_3(OH)_6.3H_2O$) and záleíite ($CaCu_6(AsO_4)_3(OH)_6.3H_2O$). A back-scattered electron image showed apparent zonation in the mixite crystals, with a brighter core containing the highest Bi_2O_3 and lowest CaO content. The empirical structural formula derived from the average of three analyses of the Mardoonganna Hill material is: $(Bi_{0.60}\ Ca_{0.40})_{1.00}\ (Cu_{5.75}\ Ca_{0.26}\ Fe_{0.06})_{6.07}\ (AsO_4)_{2.93}\ (OH)_6\ 3H_2O$. It is based on the currently accepted ideal formula for this mineral (Anthony et al., 2000) and assumes six hydroxyl ions and three molecules of water with a total of 10 metal cations.

X-ray powder diffraction gave the main lattice spacings (Å) and intensities as follows: 11.8 (100), 2.95 (23), 4.46 (19), 2.57 (19), 2.71 (16), 3.56 (14), 3.27 (13), 2.46 (11). These data agree closely with powder diffraction file card number 13-0414, mixite from the Anton mine from Black Forest in Germany as well as with data obtained from a reference specimen of mixite from Schneeberg in Germany, kindly supplied by Dr. Alex Bevan of the Western Australian Museum (Specimen MDC 5856).

Agardite-(Ce): $(Ce, La, Ca, Bi)Cu_6(AsO_4)_3(OH)_6.3H_2O$

An apple-green coating on a single specimen of amphibolite (Fig. 6) has been identified as agardite-(Ce). X-ray powder diffraction gave the main lattice spacings (Å) and intensities as follows: 11.8 (100), 4.45 (21), 3.56 (20), 2.46 (19), 2.94 (18), 3.27 (14), 2.57 (12), 2.71 (10). The

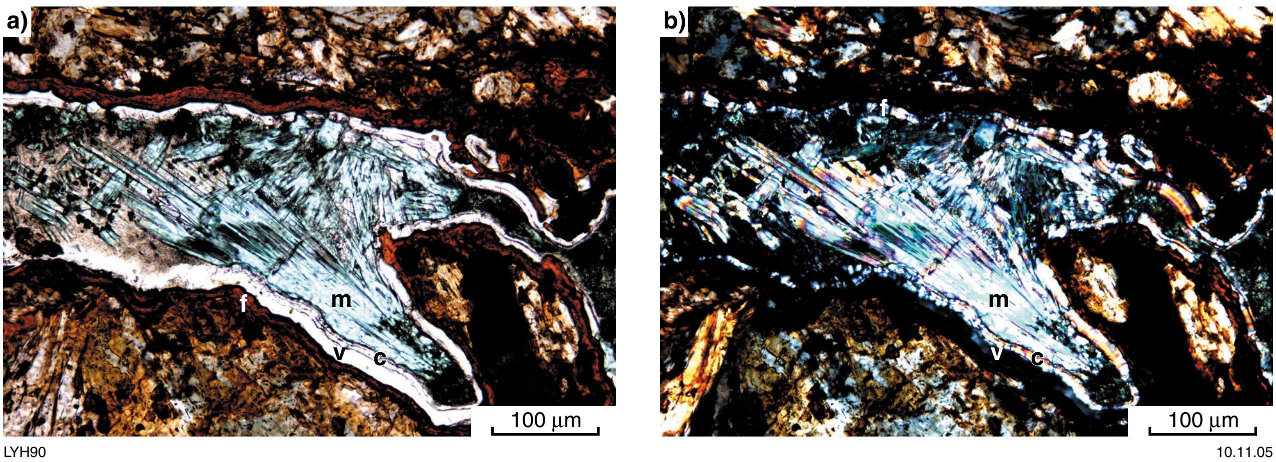

Figure 5. Acicular crystals of mixite (m) infilling veinlets that are progressively lined by a brown bismuth iron silicate (f) and a copper silicate (c): a) plane-polarized light; b) cross-polarized light. Note that there is a void (v), possibly caused during sample preparation, between the copper silicate and bismuth–iron silicate

Table 1. Mixite chemistry

Assay	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
CuO	46.48	44.43	43.58	42.07	42.13	42.48	44.23	41.04
As_2O_5	29.10	27.96	28.01	27.67	26.91	29.17	29.51	29.64
Bi_2O_3	12.03	11.72	17.29	14.13	11.94	19.10	12.25	20.03
CaO	4.24	4.45	2.24	2.53	3.24	1.55	0.83	0.00
FeO	0.53	0.33	nd	nd	nd	0.53	1.52	0.00
SiO_2	nd	nd	nd	0.81	1.51	nd	nd	0.00
P_2O_5	nd	nd	nd	nd	nd	nd	1.05	0.00
H_2O	na	na	na	na	na	na	11.06	9.29
Total	**92.38**	**88.90**	**91.12**	**87.21**	**85.73**	**92.83**	**100.45**	**100.00**

NOTES: Assays 1–3 are separate spot assays on mixite crystal in vein within polished thin section from Mardoonganna (GSWA 116720)
Assays 4–5 are semiquantitative assays on rough grains of mixite from Mardoonganna
Assay 6 is a semiquantitative assay on rough grain of mixite from Schneenberg, Saxony (kindly loaned by the West Australian Museum)
Assay 7 is a published analysis of mixite from the type location at Jáchymov, Czech Republic (Anthony et al., 2000)
Assay 8 is ideal mixite ($BiCu_6(AsO_4)_3(OH)_6.3H_2O$)

nd not detected
na not analysed

X-ray powder diffraction pattern is indistinguishable from mixite, but semiquantitative microanalysis (Table 2) indicates relatively low bismuth content (~1% bismuth oxide) and about 3 and 2%, respectively, of cerium and lanthanum oxides. The agardite is thus intermediate between agardite-(Ce) (ideal formula: $(Ce,Ca)Cu_6(AsO_4)_3(OH)_6.3H_2O$) and agardite-(La) (ideal formula: $(La,Ca)Cu_6(AsO_4)_3(OH)_6.3H_2O$).

Copper silicate (unidentified)

A copper silicate forms 3–5 µm colourless selvedges to veinlets of mixite (Fig. 5a). It has moderate birefringence and cross-fibre structure. Microanalysis at two spots gave MgO (0.5, 0.5%), Al_2O_3 (2.3, 3.3%), SiO_2 (45.9, 54.8%), CaO (1.1, 1.0%), FeO (0.3, 0.5%), and CuO (26.6, 27.9%). The mineral is possibly chrysocolla — a hydrogel that has a wide range in composition. However, the silica content is higher and the copper content lower than that reported by Klein and Hurlbut (1993) for chrysocolla (37.9 – 42.5% SiO_2, 32.4 – 42.2% Cu). Extraction of the mineral for XRPD analysis was not possible.

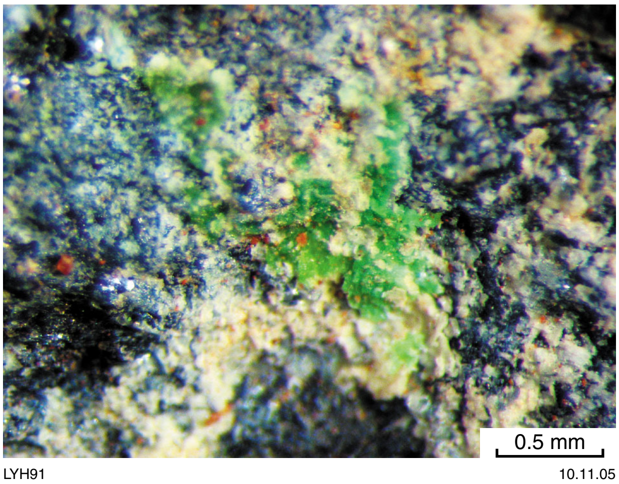

Figure 6. Agardite-(Ce) (apple-green mineral) surrounded by yellow smectite on fracture surface of amphibolite

Amorphous or cryptocrystalline iron–bismuth–copper silicate (unidentified)

A brown colloidal mineral forms selvedges to veinlets of mixite (Fig. 5) and interstitial patches up to 0.5 mm across. The back-scattered electron image showed that the material was zoned with brighter material on the inner and outer edges. Microanalysis of the inner zone gave FeO (57.1%), Bi_2O_3 (3.1%), CuO (4.1%), Al_2O_3 (3.5%), SiO_2 (13.7%), TeO_2 (0.6%), and CaO (0.2%). The brighter zones contained more Bi_2O_3 (5.3%) and TeO_2 (1.19%) and less Al_2O_3 (2.8%) and FeO (54.6%). An X-ray diffraction pattern yielded a single very weak peak with a d-spacing of 8.4 Å. No minerals with these characteristics are known.

Other minerals

Semiquantitative microanalysis led to the identification of tiny blebs of pyrite, chalcopyrite, and bismuthinite within silicates.

Discussion and conclusions

The gold mineralization at Mardoonganna Hill is unusual for Western Australia because it is associated with an abundance of secondary bismuth minerals. Bismite is the most abundant of these minerals and probably accounts for the straw-coloured tail on panning. A small amount of bismite has previously been reported from Western Australia in association with wolframite in a quartz reef at Ora Banda (Simpson, 1948) and in the Londonderry pegmatite at Coolgardie (Cross, 1993). An unidentified bismuth–iron silicate is also common at Mardoonganna.

Mixite was found on fracture surfaces and in veinlets. The only other confirmed mixite in the State is from the Nifty deposit (Downes et al., 2002). Clarke (1979) reported mixite from diggings in black shale in the Widgiemooltha area on the basis of an XRD powder pattern, but noted that samples from the pit assayed less than 5 ppm Bi. Because the XRD pattern of mixite is similar to that of agardite, it is probable that the sample was actually agardite or another member

Table 2. Agardite chemistry

Assay	*1*	*2*
CuO	45.08	45.76
As_2O_5	30.85	42.53
Bi_2O_3	1.19	1.54
CaO	3.61	3.41
FeO	1.80	1.06
SiO_2	13.26	3.61
La_2O_3	2.08	2.81
Ce_2O_3	3.29	4.01
H_2O	na	na
Total	**104.10**	**104.73**

NOTES: 1–2: semiquantitative analyses on rough grains of agardite (some adjacent silicate may be included)

na not analysed

of this family. Elsewhere in Australia, mixite has been reported from the Mount Malvern lead–silver mine in the Mount Lofty Ranges of South Australia (Kolitsch and Elliot, 1999).

Agardite identified in a specimen from Mardoonganna Hill is intermediate in composition between agardite-(Ce) and agardite-(La). Most agardite previously reported from Australia is agardite-(Y), such as as Mount Malvern in South Australia (Kolitsch and Elliot, 1999) and Broken Hill (Birch and van der Heyden, 1997). However, agardite-(Ce) has been reported from Telfer (Downes et al., 2002). Intermediate varieties of agardite, including some containing up to 3.96% bismuth have been recorded from Sardinia in Italy (Olmi et al., 1991).

The bismite was identified in veinlets and microfractures and is probably replacing bismuthinite or another bismuth mineral. The electrum is closely associated with the bismite and appears to be primary. The mixite and agardite are late in the paragenetic succession and have probably resulted from weathering of sulfides, sulfosalts, or tellurides and were deposited along near-surface fractures as described by Kolitsch and Elliot (1999) and Downes et al. (2002).

There is possibly some relationship between the primary mineralization and the porphyry intrusions in the area or with the felsic volcanic rocks exposed to the southeast.

The mineralization is similar to the epithermal Proterozoic Juno gold–bismuth deposit at Tennant Creek (Large, 1975) in its high bismuth content, highly fractured nature, and the presence of chlorite as a major alteration mineral, but differs in the lack of abundant iron oxides.

This style of mineralization would be difficult to recognize in the field due to the dark-green colour of the ore as a result of chloritic rather than the more usual sericitic alteration (bleaching) and the lack of quartz veins. The blue-green mixite along fractures is a guide, however, to high gold content.

In addition, there is a good correlation between gold and bismuth indicating that bismuth would be an excellent pathfinder to gold in this area.

Acknowledgements

We would like to thank Don Caesar for bringing our attention to the mineralization, and providing samples for analysis, and for giving permission to publish this paper. We also thank Alex Bevan of the Western Australian Museum for providing a reference sample of mixite.

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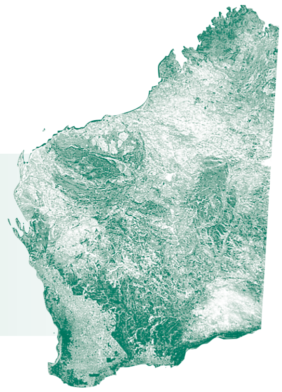
Program review

PETROLEUM SYSTEMS STUDIES AND PETROLEUM EXPLORATION DATA

Basin studies



Objective: *To encourage petroleum exploration within the onshore sedimentary basins of Western Australia by producing original geoscientific reports on the geology and petroleum systems of those areas, utilizing and integrating GSWA data and industry open-file data.*

Highlights and activities 2004–05

The focus of activities during 2004–05 shifted to the Canning Basin as current work programs in the Officer and Perth Basins neared completion. Other basins are under a watching brief. Preparatory studies of the Canning Basin were commenced. Some of the highlights were:

- Analyses to evaluate potential source and reservoir rocks and maturation in the Canning Basin have been completed on 200 selected samples;
- Installation of the Kingdom software (Seismic Micro Technology), and Petroleum System Analysis software (Platte River Associates) has been completed and preparatory work is being undertaken on a two-dimensional seismic interpretation of part of the Canning Basin.

Several papers were presented at the Central Australian Basins Symposium (CABS), covering a range of topics, such as depositional history, petroleum systems, Devonian reef growth, stratigraphy, and biostratigraphy on the Canning and Neoproterozoic basins.

Staff led an excursion for industry personnel to the Southern Carnarvon Basin.

2004–05 publications and products

- Report 86: *A summary of the geological evolution and petroleum potential of the Southern Carnarvon Basin, Western Australia — May 2004 update*;
- Report 89: *Geophysical investigation of the Bernier Ridge and surrounding area, Southern Carnarvon Basin, Western Australia*;
- Report 91: *Hydrocarbon migration and entrapment in potential Lower Cambrian reservoirs, Vines 1, Officer Basin*;
- Report 93: *Lithostratigraphic nomenclature of the Officer Basin and correlative parts of the Paterson Orogen, Western Australia*;
- Report 98: *Seismic mapping, salt deformation, and hydrocarbon potential of the central western Officer Basin, Western Australia*;
- Report 100: *Geology, geophysics, and hydrocarbon potential of the Waigen area, Officer Basin, Western Australia*;
- Record 2004/4: *GSWA Boologooro 1 well completion report (interpretive data), Gascoyne Platform, Western Australia (includes digital dataset)*;
- Record 2004/7: *Depositional facies and regional correlations of the Ordovician Goldwyer and Nita Formations, Canning Basin, Western Australia, with implications for petroleum exploration*;
- Record 2004/8: *Gravity and magnetic interpretation of the southern Perth Basin, Western Australia*;
- Record 2004/10: *GSWA Lancer 1 well completion report (basic data), Officer and Gunbarrel Basins, Western Australia (includes digital dataset)*;
- Record 2004/14: *Western Australia: Isostatic residual gravity anomaly and depth to basement model*;

- Record 2005/4: *GSWA Lancer 1 well completion report (interpretive papers), Officer and Gunbarrel Basins, Western Australia*;
- Record 2005/9: *Geology of the northern Perth Basin, Western Australia — a field guide;*
- *Summary of petroleum prospectivity, Western Australia 2005: Bonaparte, Bight, Canning, Officer, Perth, Northern Carnarvon, and Southern Carnarvon Basins*;
- Annual Review 2003–04 technical paper: *The tectonic history of the Waigen area*;
- Two Specific Area Gazettal data packages (in conjunction with Petroleum and Royalties Division);
- Several external papers were also published.

Future work

Future studies will increasingly focus on petroleum systems analysis of the Canning Basin. Initial products from the Canning Basin studies will consist of basic and interpretative data packages on:

- Potential source rocks and their maturation histories from organic geochemistry, organic petrology, and apatite fission track analysis (AFTA) studies;
- Potential reservoir rocks and their oil and gas occurrences from sedimentology and fluid history investigation by QGF (quantitative grain fluorescence) and QGF-E (quantitative grain fluorescence-extract);
- Basin and petroleum systems formation from integration and interpretation of petroleum geology, geochemistry, and seismic studies of the Canning Basin.

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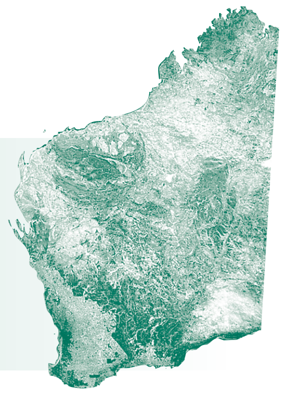
Petroleum exploration reports and data



Objective: *To administer the collection and storage of statutory petroleum exploration reports relating to tenements in Western Australia, and to ensure the efficient dissemination of information in these reports to industry. This work covers all aspects of the submission, management, and release of petroleum exploration data through WAPIMS (Western Australian petroleum information management system).*

Highlights and activities 2004–05

The program of scanning of well completion reports from hardcopy to PDF and TIFF continued, completing the onshore and starting on the territorial seas of the Carnarvon Basin. A total of 671 reports have been scanned and loaded onto the WAPIMS system for online web viewing.

As part of the WAPIMS database program well-log curves for a further 141 wells (giving a total of 881 wells) were loaded into the system, enabling the public to view the data via the web.

Transcription of seismic-field and processed data from the Canning Basin from nine-track reels to 3590 cartridges (23 981 tapes from 46 surveys) continued to reduce the number of 'old' tapes in the archive and move these valuable data to new and more reliable media.

Upgrades to the WAPIMS public interface were completed, with extra features of the database delivered early in 2004–05.

Some 200 GB of data are now available online through WAPIMS.

WAPIMS database

During 2004–05 a total of 20 243 new data items received from industry were loaded into the system.

Data release

During 2004–05, 313 edited and unedited reports were released. Industry requests consisted of 138 requests for loans of seismic and well, digital field, and processed data for 183 seismic surveys and 339 wells. In addition, 115 requests for sampling or borrowing slides from 215 wells were processed.

Future work

- Continue scanning well completion reports to complete the offshore Carnarvon Basin;
- Continue to make well-log data and seismic post-stack data available online;
- Continue the transcription program — working primarily in the western and central Canning and Perth Basins, with some surveys in the Carnarvon and Bonaparte Basins;
- Continue the release of Specific Area Gazettal data packages.

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MINERAL RESOURCES ASSESSMENT AND MINERAL EXPLORATION DATA

Mineralization mapping

Objectives: *To promote prospectivity and encourage mineral exploration within the State for precious metals, base metals, ferro-alloys, and diamonds, particularly in areas where there has been limited sustained exploration activity, by undertaking studies that synthesize and integrate open-file statutory data with existing geological, mineral occurrence, geophysical, geochemical, and remote-sensing data. Products of this work are data packages comprising reports and maps together with GIS-compatible databases on CD-ROM.*

Highlights and activities 2004–05

One mineral prospectivity data package on the Earaheedy area was released during the year. Another data package was nearing completion for the Paterson area. Compilation of databases and digitizing of spatial data for mineral occurrences and mineral-exploration activities continued for the Gascoyne, west Hamersley and Mid-west coast projects. An update CD-ROM with data from the latest WAMEX releases since 2001 was completed for the east Pilbara (Fig. 1).

Each data package contains a Report (in PDF format) that synthesizes information on the mineral prospectivity of an area, a CD-ROM of digital data, and a 1:500 000-scale map that shows mineral occurrences, mineralization styles, commodity groups, and geology.

The CD-ROM for each package contains the following datasets: WAMIN (spatial and attribute database of mineral occurrences); EXACT (spatial and attribute database of mineral-exploration activities); MINEDEX (extract of Departmental database with mine sites and mineral resources); WAMEX (extract of Departmental database with index of open-file mineral exploration reports); TENGRAPH (extract of Departmental database with mining tenements and holders); geology (solid and regolith); Landsat imagery; aeromagnetic images, radiometric images; gravity images; and topographic and cultural features.

2004–05 publications and products

Report 96*: Mineral occurrences and exploration potential of the Earaheedy area;*

CD-ROM update: *2005 update of Report 81, east Pilbara*.

Future work

Three data packages — for the Paterson area (Report 97), the Mid-west coast area, and the west Hamersley area — are in preparation for release in 2005–06. Database compilation and digitizing will continue for the Gascoyne area, and will commence for the north Murchison and Peak Hill areas (Fig. 1).

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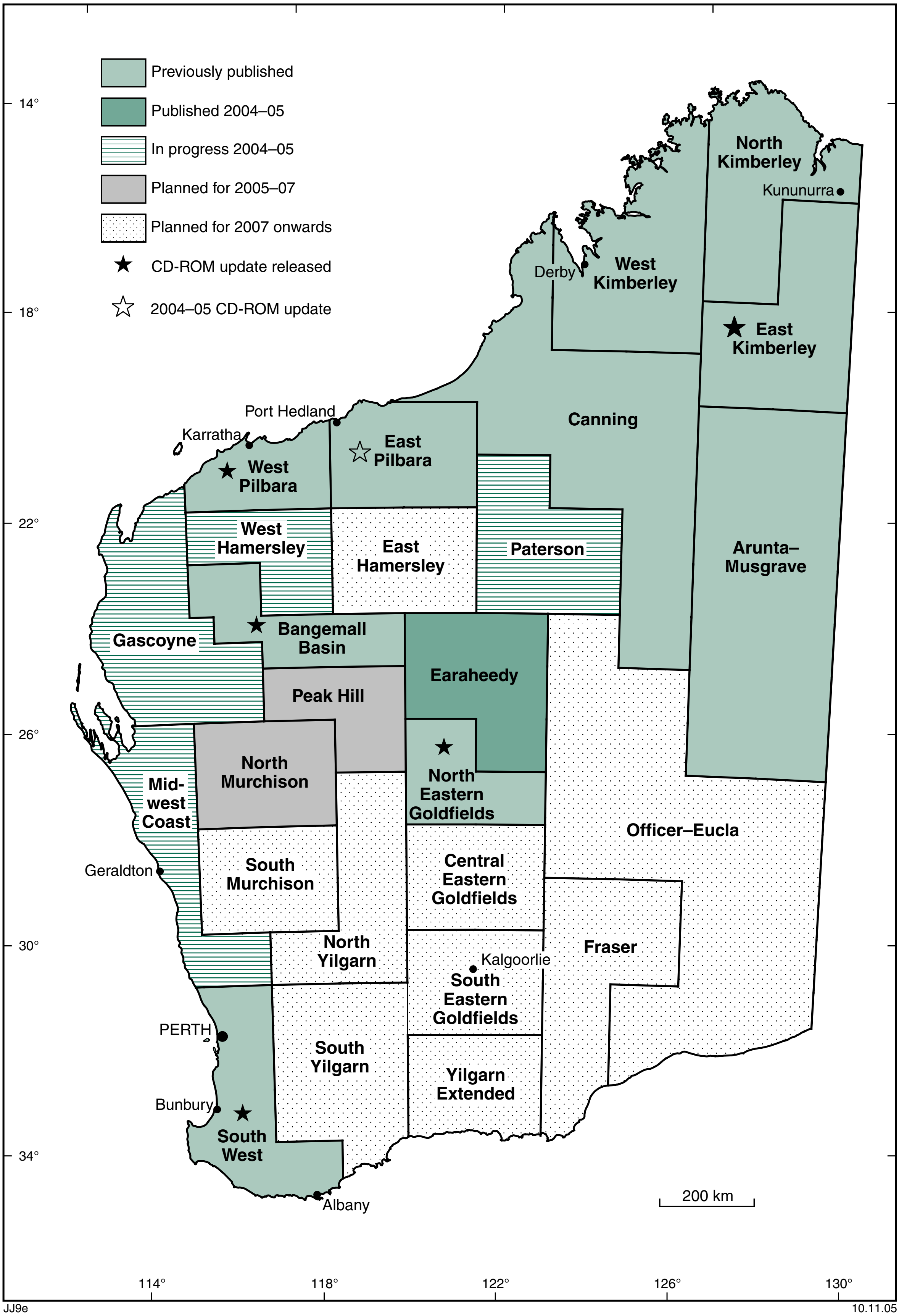
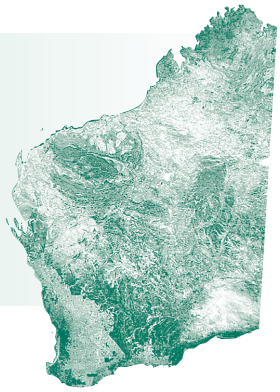


Figure 1. Progress of regional mineralization mapping projects

Commodity and industry analysis

Objectives: *To provide statistics, expert analysis, and authoritative opinion on all commodities in the context of mineral exploration activity, mineral resources and reserves, and mining to a range of customers including: other Divisions of the Department of Industry and Resources, other Government agencies, the minerals industry, and the community at large. All these functions are supported through the maintenance and enhancement of Western Australia's mines and mineral deposits database (MINEDEX).*



2004–05 highlights, activities, and publications

- The ongoing data capture into DoIR's Western Australian mines and mineral deposits database (MINEDEX) formed an important part of the function of this section. A total of about 380 ad hoc inquiries seeking information on mines, deposits, mineral resources, and mineral production were received from industry, the public, other Government agencies, and staff of DoIR.
- Publication of the map *West Australian mines — operating and under development, 2005*; the ever-popular map *Major Resources Projects, 2005*; the *Western Australian atlas of mineral deposits and petroleum fields 2005* (map and A4 booklet); an update on industrial minerals in Western Australia for 2004 (Record 2004/21); a nickel commodity review for 2003 (Record 2005/3), and annual overviews on mineral exploration and development in Western Australia.
- Draft commodity reviews were prepared for nickel; copper–lead–zinc; diamonds; manganese; vanadium; and chromium.
- Fieldwork was completed for the first part of a project covering dimension stone in Western Australia, with compilation and publication intended as a two-part Mineral Resources Bulletin. Several articles on dimension stone in Western Australia were prepared and published.

2005–06 activities and planned publications

Updates and new editions for a suite of publications and maps covering the mineral deposits of Western Australia, the iron ore industry, mineral exploration, and industrial minerals will be published. Work has commenced on integrating three of the Geological Survey's minerals databases (MINEDEX, WAMIN, and WABMINES).

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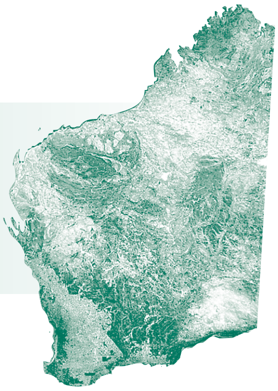
Inventory of abandoned mine sites



Objectives: *To accurately locate mine site features on abandoned mine sites in the State and document factors relevant to the safety and environmental hazards they pose. This will provide a sound basis for future planning of rehabilitation of features at abandoned mine sites.*

Highlights and activities 2004–05

The inventory, which commenced in 1999–2000, has the objective of locating mining-related features within abandoned mine sites in the State and documenting factors relevant to their safety and environmental impact. This information can be used to provide advice on rehabilitation or conservation of abandoned mine sites. The inventory has also recently been demonstrated to assist exploration targeting, and to contribute towards the understanding of controls on gold mineralization.

Data entry in the field is via a hand-held computer that is linked to satellite navigation equipment capable of locating mine site features such as shafts to an accuracy of around 10 m. More than 23 600 mine site features were added to the inventory during 2004–05, resulting in a total of 144 991 features at 30 June 2005 (Fig. 2).

Priority for field inspection is now being given to those sites within 5 km of smaller towns and communities, as well as within 10 km of major towns, and within 1 km of tourist routes and important access roads. About 44% of all abandoned mine sites are in this high-priority category. At 30 June 2005, approximately 74% of these higher priority sites had been inspected during the program.

Fieldwork during 2004 was conducted in the Norseman, Widgiemooltha, and Kambalda regions. Fieldwork commenced along the southern part of the Golden Quest Discovery Trail,

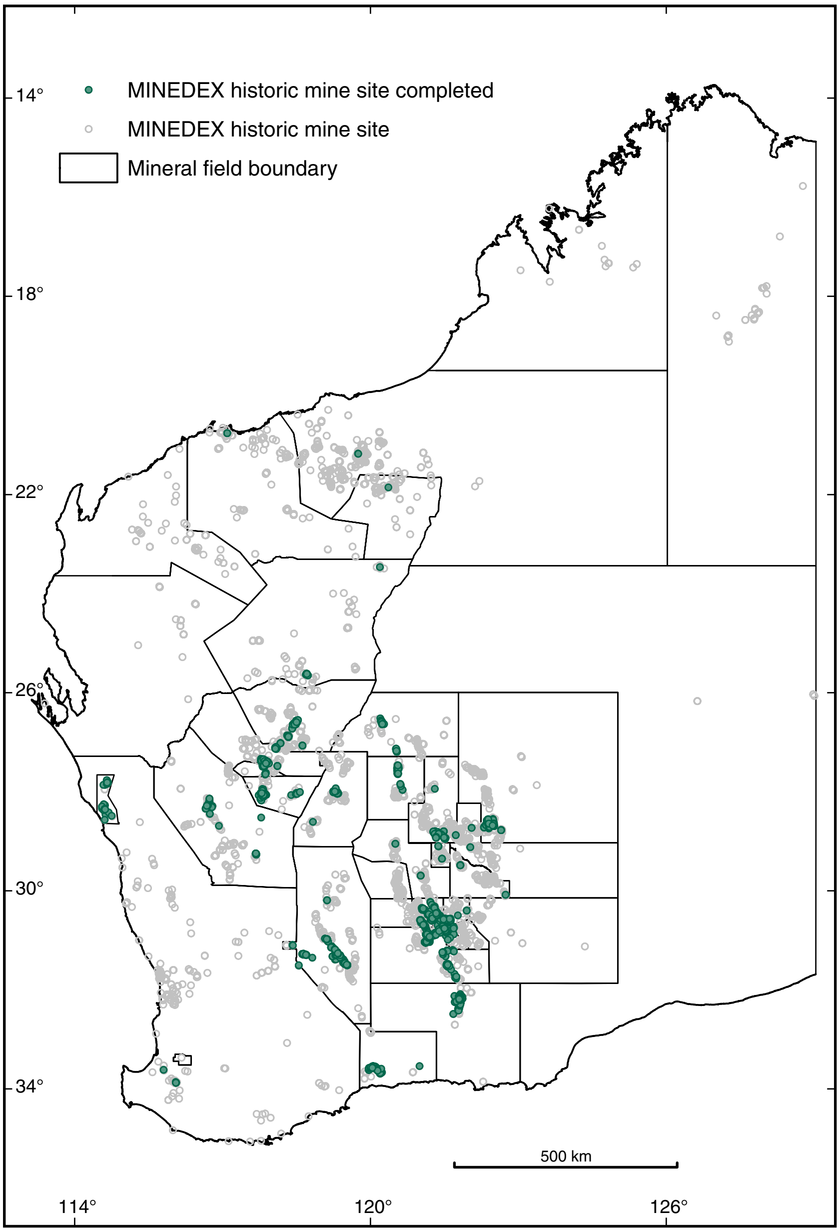


Figure 2. Status of the inventory of abandoned mine sites — MINEDEX sites completed as at 30 June 2005

including Kunanalling and Ora Banda in 2005.

2004–05 publications and products

- Digital datasets on DVD: *Inventory of abandoned mine sites: progress 1999–2004*;
- Extended abstract in Record 2005/5: *Spatial analysis of mineralization information from the abandoned mine sites database*.

Future work

The team will continue work along the Golden Quest Discovery Trail in the Ora Banda and Menzies areas.

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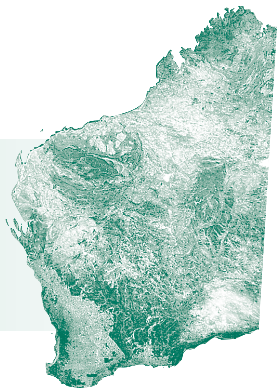
Land access and resource assessment



Objectives: *To provide geological advice with respect to land title and land use changes, and thereby protect access to land for future exploration and mineral resources extraction. This advice is provided to other divisions of the Department, other Government authorities, resource companies, and the community.*

2004–05 highlights and activities

The primary function is to provide geological advice with respect to changes to the tenure and purpose of Crown land and Private land. During 2004–05 advice was given to 1189 requests for land title or land use changes, an increase of more than 30% from 2003–04. This increase in requests is in part due to the buoyant economy in Western Australia and the resulting increase in Perth's urban development and land subdivisions in rural areas, and a significant increase in proposals for national parks, nature reserves, and conservation parks.

Detailed resource assessment studies were carried out on:

- The proposed Pilbara railway to be constructed by Fortescue Metals Group. This involved the assessment of mineral potential of the underlying railway corridor and extensive discussions with tenement holders;
- The proposed Ningaloo Reef–Cape Range World Heritage area. The resource potential for land use planning maps completed in 2003–04 were used to support the Department's position of limiting the World Heritage area to that which has heritage value, thus retaining strategic resources of limestone for future industry requirements and highly prospective areas for petroleum, base metals, and diamonds;
- Local Government town planning schemes and local planning strategies;
- Thirty new national parks proposed for the South West;
- Nature reserve proposals over the iron ore deposits in the Yilgarn, including publishing a 'Resource potential for land use planning' map of the geology and mineralization in vicinity of the Mount Manning Range;
- The area proposed for the Square Kilometre Array — a possible site for a major international radio telescope;
- Construction materials (sand and limestone) north and south of Perth, particularly at Lancelin, Dongara, and Bunbury.

2004–05 publications and products

Resource potential for land use planning maps:

- Mid West region (1:1 000 000);
- Eastern Goldfields (1:600 000);

- Mount Manning Range region (1:500 000);
- Hope Downs railway (1:50 000).

Future work

Work will continue on examining land title and land use changes for potential conflict with land access for exploration or the sterilization of known and potential mineral resources.

Under the Government's SLIP program, and in collaboration with WA Planning Commission, Department of Planning and Infrastructure, and other Government departments, the land referral process is being reviewed with the aim of instigating a more efficient electronic system for referrals and assessment.

The following resource assessment work is continuing:

- assessment of sand and gravel resources in the Kalgoorlie region for the Department of Planning and Infrastructure;
- assessment of the proposed expansion to the Kalgoorlie–Boulder townsite for the City of Kalgoorlie–Boulder;
- assessment of proposed nature reserves;
- assessment of sand resources south of Perth.

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Industry and community liaison

Objectives: *To improve access for exploration and development of mineral, petroleum, and building materials on all lands and marine areas in the State through provision of information and advice to Government authorities, the resources sector, and community groups. The information and advice provided relates to the importance of the sector to the sustainable well-being of our society, to the interaction between resource access and planning processes, and the role of geological information in achieving effective planning outcomes for the State.*

2004–05 highlights and activities

Conservation issues

- The Department of Conservation and Land Management continued to progress its acquisition of lands for the conservation estate. Negotiations were held in relation to their proposals throughout the State and support provided in many cases for creation of conservation reserves. However, in areas of significant mineral or petroleum potential, support was withheld.
- Advice was provided on a draft Biodiversity Conservation Bill released for public comment. CALM requested comment on their World Heritage nomination of the Cape Range area and their Ramsar Wetland nomination for Lake MacLeod. Both include very large surrounding areas.
- Extensions to the Mount Manning Nature Reserve, north of Southern Cross, were announced by the Minister for the Environment, but not progressed following strong community opposition.

Community liaison

- Geological, resource, and tenement information and advice were provided on a broad range of planning initiatives related to Town Planning Schemes and Local Planning Strategies for local Government as well as regional strategies and structure plans for the WA Planning Commission. A number of towns in the Wheatbelt region revised their schemes on the basis of the advice provided.
- The Greater Bunbury Regional Scheme was progressed towards

gazettal by the WA Planning Commission. Revised titanium–zircon mineral resource boundaries were compiled and provided for inclusion into the mineral protection policy that is part of the Scheme.

Planning initiatives

- Mapping of the titanium mineral deposits in the Swan Coastal Plain was continued to ensure resources are protected from conflicting land uses until mining and rehabilitation are completed. Previous mapping of the southern Swan Coastal Plain has been particularly effective in protecting deposits.
- In December 2004, Australia announced that it would nominate the Mileura site, in the Murchison region, as the national bid for the Square Kilometre Array radio telescope. The Geological Survey was instrumental in defining the site because of the need to avoid future conflicts between the telescope operations and mineral activities.
- As future access to building sand in Perth is becoming a planning issue, GSWA has initiated a program to assess future sand needs and potential supplies for the metropolitan area. Sand is readily available but, with likely future urban growth, available deposits will be depleted rapidly and other deposits will be sterilized by encroaching urban and industrial development.

Geological initiatives

- A geoheritage management policy was prepared and will be progressed for Government support in 2005–06. A geoheritage database is being compiled from GSA and GSWA sources for eventual public release.

Future work

Work on the above projects will continue as required, particularly the provision of geological information and advice, and input to regional plans, and urban, rural, and community developments.

Greater emphasis will be placed on community liaison to ensure that the general public are aware of the importance of exploration and resource development to their economic and social welfare.

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Geoscientific advice relating to exploration

Objectives: *To monitor and assess exploration performance on mineral tenements and provide geological advice needed for the administration of, and proposed changes to, the Mining Act and Offshore Minerals Act.*

Highlights and activities 2004–05

Most mineral tenements are held for exploration or prospecting rather than productive mining. Advice on these exploration activities, as gauged from statutory mineral exploration reports and discussions with tenement operators, assists the Department to administer tenements and to ensure that the State is effectively explored.

Exploration performance on 2713 mineral tenements (Table 1) was reviewed during 2004–05 as part of the assessment of applications for exemption from expenditure conditions, applications for extension of term of Exploration Licences, applications for Retention Licences, applications for Special Prospecting Licences, applications for iron ore authorization under Section 111, and applications for Ministerial consent to dealings in Exploration Licences during their first year of tenure.

Due to the strength of the world iron ore market, there has been a continuing increase in the number of applications under Section 111 of the Act to authorize the holder to explore for iron ore (from 90 applications in 2003–04 to 195 in 2004–05). As these applications are routinely supported (provided that the area is prospective for iron ore), the

Table 1. Tenement reviews

Geological advice provided	*Number of tenement actions*					
	1999–2000	*2000–01*	*2001–02*	*2002–03*	*2003–04*	*2004–05*
Expenditure exemption	1 287	1 569	1 962	2 362	2 406	2 146
Extension of term of Exploration Licences	82	394	411	369	323	286
Dealings in first-year Exploration Licences	7	75	42	43	30	67
Iron ore authorization (Exploration Licences)	22	16	32	30	90	195
Iron ore drop offs (Exploration Licences)	22	2	0	0	8	15
Retention Licence applications	3	6	6	5	5	2
Special Prospecting Licence applications	1	4	4	4	6	2
Total	**1 424**	**2 066**	**2 457**	**2 813**	**2 868**	**2 713**

Department is considering whether Section 111 should be repealed.

The number of applications for exemption from exploration expenditure determined by the Department during 2004–05 has decreased by about 35% to 3437 (from 5211 in 2003–04). This is a further indication that exploration activity has increased during the last year.

Most referrals of applications for expenditure exemptions that come to the Geological Survey are those under Section 102(2)(e) and (f) — that the tenement contains a mineral deposit that is currently subeconomic or contains ore required for future operations. Referrals under 102(2)(b) — that time is required to evaluate work done on the tenement — are also common. In these cases, previous exploration data is reviewed to substantiate such claims.

Exemption applications recommended for refusal are referred to GSWA if they require the assessment of a company's submission. Before an exemption application is finally recommended for refusal, a Departmental committee (Exemption Committee) reviews the recommendation. The Geological Survey is represented on this committee to ensure that geoscientific issues are considered in any decision. The committee also considers whether a fine should be imposed in lieu of forfeiture where an expenditure exemption has been refused. The number of exemption applications refused constitutes about 25% of total applications in 2004–05 (up from 13% in 2003–04). This figure includes lapsed applications where tenements have been surrendered before the intent to refuse could be carried through.

The number of granted exemptions still seems high but most are for partial amounts. Also, a large number of applications are made under Section 102(2)(h) — that aggregate expenditure on a project basis has been met. Overall expenditure by industry (exploration and production as claimed on Form 5 Operations Reports) is currently close to sixteen times the expenditure commitment under the Act. Expenditure has increased by about 10% from 2003–04 to about $4.8 billion in 2004–05.

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Mineral exploration reports and data

Objectives: *To administer the collection and storage of statutory mineral exploration reports relating to tenements in Western Australia, and to ensure the efficient dissemination of information in these reports to industry. This subprogram covers all aspects of the submission, management, and release of mineral exploration data through WAMEX (Western Australian mineral exploration database).*

2004–05 highlights and activities

- Deployment of web-delivery software to facilitate viewing, printing, and downloading of digital open-file exploration reports;
- Scanned 7000 reports for release under the 'Sunset Clause' during the year;
- Release of free software to facilitate digital report submission.

Mineral exploration reports

During the year, 1876 mineral exploration reports (3265 volumes) were received, representing industry activity on 8558 tenements. The total number of volumes held is now 87 108. Submission of data in digital form continues to increase, with some 71% of all reports submitted during the year containing some digital data.

During the year 707 volumes were released to open file bringing the total number of open-file mineral reports to 32 845.

Reporting standards

This year has been the ninth full year of required compliance with the 'Guidelines for mineral exploration reports on mining tenements' and the fourth year in which companies could submit data in digital format according to the Department's requirements. The quality-control checking by Departmental staff found that about 19% of the hardcopy reports are not complying with the reporting guidelines. The submission of digital data is voluntary; however, about 71% of reports contain some digital data and about 66% of all reports submitted are totally digital. Compliance with both content requirements as stipulated in the 'Guidelines' and format requirements for digital reporting have improved significantly with only about 13% of reports submitted in digital form requiring some amendments or additional data.

The 'Requirements for the submission of mineral exploration data in digital format', which were developed in consultation with industry groups, have been adopted by the interdepartmental working group as the basis of national reporting requirements for the mineral exploration industry. The Department has released a software program, which is available on our website, to facilitate the generation of metadata (header information) for digital tabular files.

WAMEX database development

During the development of processes and data management systems for the core library, it was recognized that a review of the management and delivery of mineral exploration data was needed. Significant work has been done in developing the new database, which will be deployed in the coming year.

Future work

- Deployment of the redeveloped WAMEX database;
- Continue the implementation and refinement of the 'Requirements for the submission of mineral exploration data in digital format';
- Continue scanning mineral exploration reports prior to release to open file, and scanning of reports previously released to open file in microfiche format. Provide both scanned and generated files of mineral exploration data via the web-based WAMEX interface;
- Progressively capture metadata for digital files submitted prior to the implementation of the 'Requirements for the submission of mineral exploration data in digital format';
- Progressively acquire, in digital format, legacy data previously submitted in hardcopy reports;
- Capture attribute information for legacy mineral core submitted to the core libraries in Perth and Kalgoorlie;
- Continue the three-year program to release 21 000 reports under the 'Sunset Clause' regulation;
- Implement a program for the mandatory submission of exploration reports in digital form.

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REGIONAL GEOSCIENCE MAPPING

Regolith mapping and geochemistry

Objectives: *To document the distribution and composition of regolith over Western Australia, and present these data as digital datafiles and maps to the mineral exploration industry. To acquire and collate geochemical data in a central repository, and disseminate these data, in order to enhance the prospectivity of the State.*

Highlights and activities 2004–05

Regolith–landform mapping, and integration of these data with hyperspectral data, was completed for four 1:50 000-scale map sheets in the Kalgoorlie–Boulder area (Fig. 3). Two dominant regolith–landform domains were identified, and their thickness was constrained using company-generated drilling data. The accompanying digital data published on DVD include existing geological maps, a variety of remotely sensed images (including hyperspectral data), aerial photography, tenement information, and various point datasets (including abandoned mine sites, mines and mineral deposits). Available separately is a plotted kaolin disorder map (derived from hyperspectral data), which can be used to distinguish transported and in situ regolith. The latter product results from a collaborative venture between GSWA and CSIRO to trial the acquisition and use of hyperspectral data (HYMAP) in the Kalgoorlie–Boulder area. This project generated several digital maps, which provide mineralogical information of surface material at a resolution of five metres.

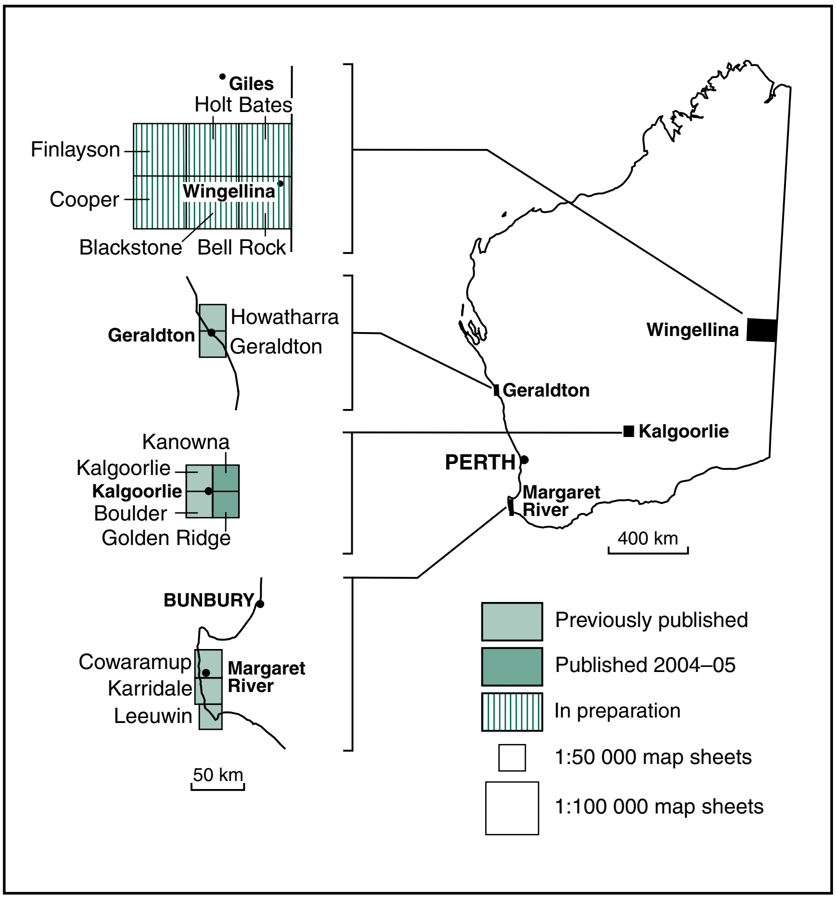

Figure 3. Progress of regolith–landform resources mapping project

Interpretive regolith maps for BATES* and BELL ROCK (west Musgrave) were initiated, as a complement to bedrock mapping. Field validation of regolith maps was commenced.

A pilot study into the suitability of stream-sediment geochemistry in identifying areas of known and potential mineralization was commenced in the State's southwest, involving the collection of 80 stream-sediment samples in the Greenbushes and Manjimup–Pemberton areas.

A report on the Warakurna Large Igneous Province (LIP) was published, discussing the distribution of 1070 Ma igneous activity throughout Western Australia, and parts of South Australia and the Northern Territory. Geochemistry has been used to separate 1070 Ma sills from an earlier (1465 Ma) event, and to assess the potential for magmatic-hosted nickel sulfide mineralization. Sill geochemistry can be downloaded from GeoVIEW.WA.

Re-siting of DataShed software for storage of geochemical data onto an SQL platform has been completed, in conjunction with ISB and an external contractor. The platform change is necessary to align GSWA with future developments of DataShed. The system has been successfully evaluated using a test dataset.

* Capitalized names refer to standard 1:100 000 map sheets.

The collaborative venture with CRC LEME and CSIRO to compile a geochemical map of the Yilgarn Craton (the Yilgarn Geochemical Map (YGM) project), based on laterite chemistry of samples at a nominal spacing of 9 km was 90% completed for the southwest part of the Yilgarn Craton, bordered in the north and east by 30°S and 120°E. Two new laterite reference materials (standards) have been prepared and geochemically characterized by a round-robin analytical program involving seven analytical laboratories. Approximately 900 of a total of 2500 samples have been analyzed for more than 50 analytes by a commercial laboratory.

2004–05 publications and products

- Record 2005/7: *Regolith–landform mapping and hyperspectral data for the Kalgoorlie–Kanowna area;*
- Report 99: *Mesoproterozoic sill complexes in the Bangemall Supergroup, Western Australia: geology, geochemistry, and mineralization potential;*
- *Kalgoorlie–Kanowna kaolin disorder* (map at 1:100 000 scale).

Future work

During 2005–06, GSWA will continue to populate the corporate geochemical database using the DataShed software. Interpretive regolith maps will be completed for BELL ROCK and BATES, and commenced for HOLT, BLACKSTONE, FINLAYSON, and COOPER. Analysis of various grain-size fractions of stream sediments in the State's southwest will form part of the pilot stream-sediment geochemistry program. The remainder of the southwest quadrant of the YGM will be finalized, and sampling and analysis will continue for the northwest quadrant. Results of the study to date will be presented at an international conference on exploration geochemistry. Data collation will commence on a 500 Ma large igneous province, represented by the Table Hill Volcanics and Antrim Plateau Volcanics in Western Australia.

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King Leopold and Halls Creek Orogens project

Objectives: *To increase geological knowledge of the King Leopold and Halls Creek Orogens by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps and supporting publications that integrate field and laboratory studies, including mapping, petrology, geochronology, geophysics, geochemistry, sedimentology, paleontology, remote sensing, and metallogeny.*

Highlights and activities 2004–05

During 2004–05 writing continued for Bulletin 143 on the geology of the King Leopold and Halls Creek Orogens. Writing of Explanatory Notes for TURKEY CREEK* was commenced.

Future work

Bulletin 143 will be completed ready for release the following year. Writing of Explanatory Notes for McINTOSH will commence.

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Lennard Shelf project

Objective: *To prepare comprehensive accounts and maps of the Devonian reef complexes of the northern Canning Basin and their associated terrigenous clastic deposits.*

Mapping and section measuring in the Devonian outcrop belt of the Lennard Shelf, with associated biostratigraphic, sedimentological, and subsurface studies, has been in progress for the present project since 1992, the objective being to increase geological understanding of the Devonian reefal succession and its associated deposits.

The Devonian rocks are regarded as highly prospective for both zinc–lead mineralization and petroleum. The reef complexes form one of the classic features of world geology, and the results of the project will be of widespread interest to geoscientists and the general public.

Seven maps of the outcrop belt, at scales of 1:250 000, 1:100 000, 1:50 000, and 1:25 000, and a Report on the subsurface geology, have previously been published. An eighth map, at 1:500 000 scale, is being drafted.

Highlights and activities 2004–05

Compilation of Bulletin 145 on the Devonian reef complexes of the Canning Basin has continued. The text of most chapters by Phillip Playford, Gil Klapper, Thomas Becker, and Geoffrey Playford has been completed in draft form. Chapters on terrigenous clastic rocks and cyclicity (Roger Hocking), and diagenesis and zinc–lead deposits (Malcolm Wallace) are still in progress. It is expected that these will be written by the end of 2005 and the Bulletin published in 2006–07.

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Pilbara Craton project

Objective: *To increase geoscientific knowledge of the Pilbara Craton by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps and supporting publications that integrate field and laboratory studies including mapping, petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*

The Pilbara Craton project has successfully remapped approximately 70 000 km^2 of prospective Archean granite–greenstone terranes in the northern part of the Pilbara Craton (Fig. 4). Since 2003, when the last of the fieldwork was completed, work has focused on compilation of all remaining 1:100 000-scale and 1:250 000-scale maps and accompanying reports for the project. The last of these maps will be released in 2006. During 2005 work commenced on establishing a digital geoscientific database for the northern Pilbara, and GIS packages are being prepared for release in late 2005 and in 2006.

The project has resulted in a major reinterpretation of the geology and crustal evolution of the northern Pilbara Craton, with important implications for mineral exploration. A succession of different crust-forming events spanned 700 million years, with major differences between the west and east Pilbara. This new information will be used by industry to assist exploration programs and the selection of the most appropriate metallogenic models for individual areas.

Highlights and activities 2004–05

A new interpretation of event stratigraphy in the Pilbara Craton was formulated and published late in 2004. A more detailed account, including formal definitions of all new stratigraphic units, will be prepared as a GSWA Record in 2005–06. The crustal evolution of the northern Pilbara Craton is expressed in terms of discrete thermotectonic events, in which the intrusion of major igneous suites and supersuites is correlated with volcanism and mineralization.

Between July and September 2004, the Pilbara mapping team assisted the satisfactory completion of two international drilling projects — the Deep Time Drilling Project (DTDP) and the Pilbara Drilling Project (PDP). These projects are summarized in a feature article in this Annual Review.

2004–05 publications and products

- COONGAN*, YILGALONG, NOREENA DOWNS, and WARRIE 1:100 000 maps;
- Geology of the Whim Creek greenstone belt: 1:10 000 maps;
- NULLAGINE and LAMIL 1:100 000 Explanatory Notes;
- Geoscientific papers in the Annual Review and external journals.

Future work

The 2005–06 year will see the completion of MOUNT MARSH, EASTERN CREEK V2, and MARBLE BAR, and the PORT HEDLAND and NULLAGINE 1:250 000 maps. Other products to be completed in 2005–06 will include a detailed 1:50 000-scale map of the North Shaw–Tambourah area, a map of the Pilbara Craton showing the distribution of Archean and early Proterozoic meteorite impact deposits, and a special 1:250 000-scale bedrock geology map of the West Pilbara Granite–Greenstone Terrane.

The first release of a seamless digital 1:100 000 Geological Information Series for the Pilbara, covering NOREENA DOWNS, WARRIE, and MOUNT MARSH, will be released on DVD in 2005–06. This will be followed by a second release in mid-2006 that will comprise twenty-three 1:100 000 map sheets covering the East Pilbara Granite–Greenstone Terrane.

Explanatory Notes for MOUNT EDGAR and WODGINA, and for the PYRAMID 1:250 000 map will be finalized in 2005–06. A number of GSWA Reports and Records, some involving collaborative projects with external authors, will also be published in 2005–06.

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* Capitalized sheet names refer to standard 1:100 000 map sheets, unless annotated otherwise.

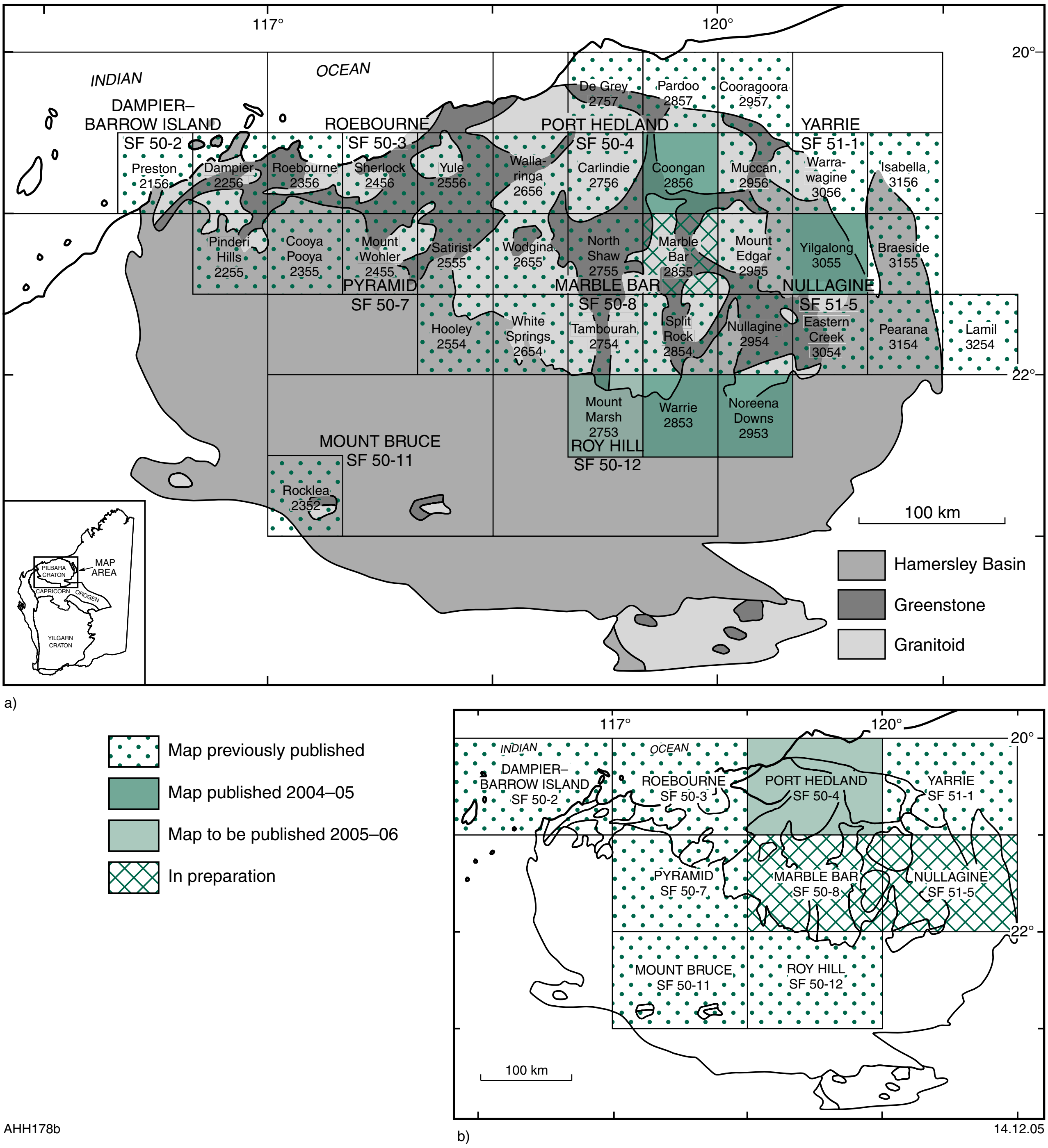

Figure 4. Progress of recent regional mapping in the Pilbara Craton: a) 1:100 000 map sheets; b) 1:250 000 map sheets

Earaheedy Basin project

Objective: *To increase geoscientific knowledge of the Earaheedy Basin and adjacent areas through the collection, synthesis, and dissemination of geological information. This is to be achieved through the production of geological maps and supporting publications that integrate field and laboratory studies including mapping, petrology, geochemistry, geochronology, remote sensing, and metallogeny.*

Fieldwork in the Earaheedy Basin commenced in 1997 and was completed in October 2003. Since 1997, thirteen 1:100 000-scale geological maps have been published (Fig. 5) and five sets of Explanatory Notes.

The Earaheedy Basin contains the Earaheedy Group and lies at the easternmost end of the Capricorn Orogen. Basement to the exposed Earaheedy Basin is the Archean Yilgarn Craton and, to the west, the Yerrida Basin. The Paleoproterozoic Earaheedy Basin contains the Earaheedy Group, a 5 km-thick succession of shallow-marine clastic and chemical sedimentary rocks that is divided into two subgroups — the Tooloo Subgroup and the overlying Miningarra Subgroup. The age of the Earaheedy Group is stratigraphically constrained by the age of the underlying Mooloogool Group (Maraloou Formation, c. 1.84 Ga), and by the Malmac (2.6 Ga) and Imbin (1.99 Ga) Inliers.

Highlights and activities 2004–05

During this period the only activity relating to the project was the initial compilation of VON TREUER*.

* Capitalized sheet names refer to standard 1:100 000 map sheets.

Future work

Work planned for 2004–05 includes new compilations for VON TREUER and COLLURABBIE. A final GSWA Report on the geology and mineralization of the Earaheedy Basin is being written.

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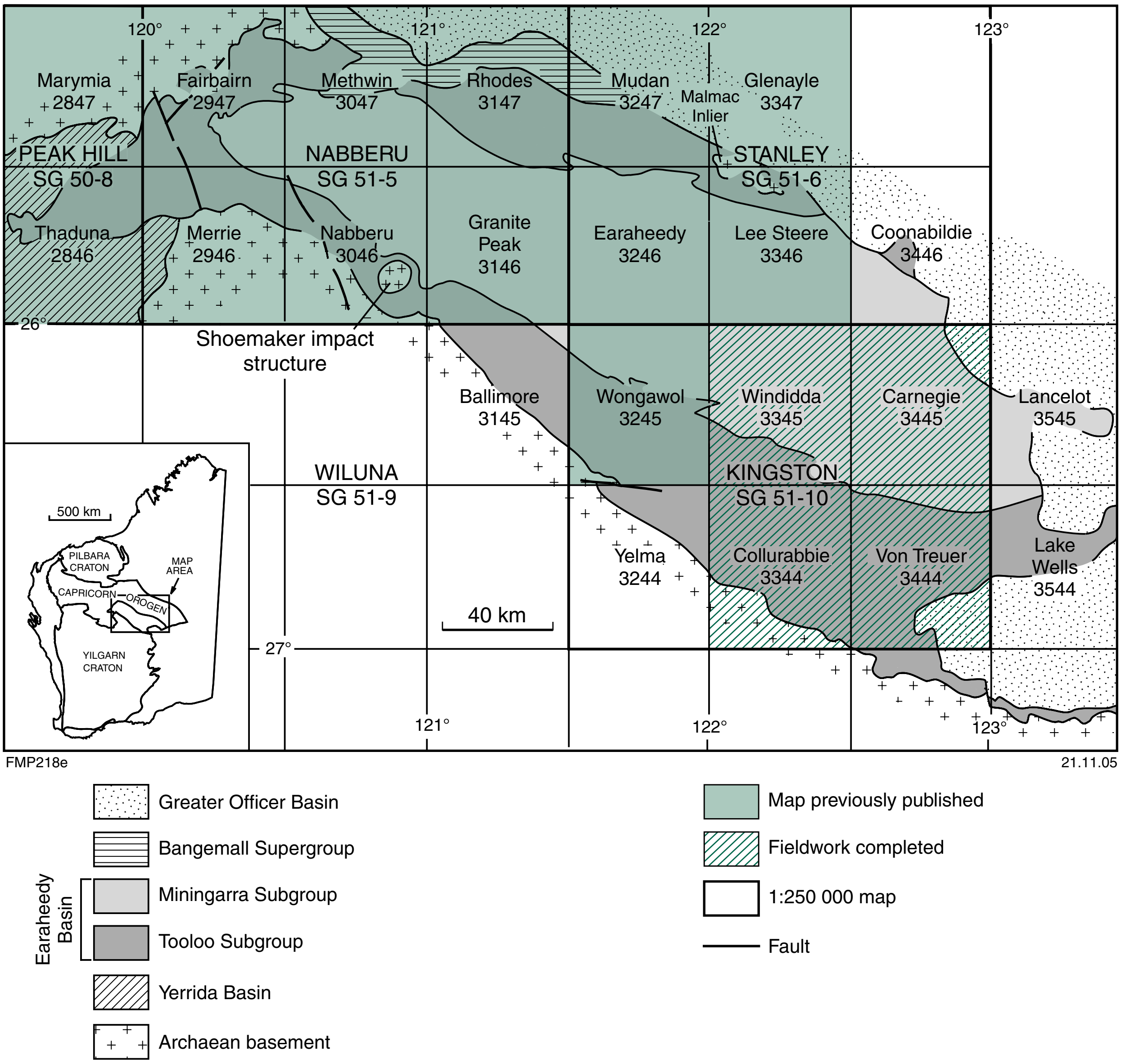
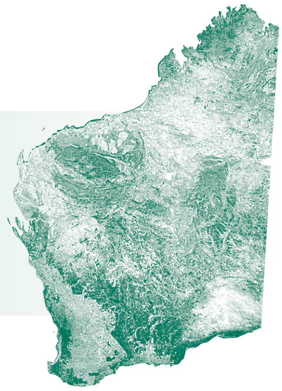


Figure 5. Progress of 1:100 000-scale geological mapping for the Earaheedy Basin project

Edmund and Collier Basins



Objective: *To increase knowledge of the Edmund and Collier Basins (Bangemall Supergroup) through the application of specialist field and laboratory studies, including biostratigraphy, geochemistry, geochronology, petrology, remote sensing, sedimentology, and stratigraphy. This information is to be disseminated through the production of geoscientific maps and supporting publications.*

Highlights and activities 2004–05

Fieldwork carried out in the northwestern part of the Capricorn Orogen during 2004–05 has involved detailed mapping of the Bangemall Supergroup rocks on MOUNT AUGUSTUS*, MOUNT PHILLIPS, and PEEDAWARRA (Fig. 6). In addition, there has been collaboration with staff from the Geological Survey of France (BRGM) and Geoscience Australia (GA).

Within the Edmund Basin, facies distributions are strongly controlled by movement along syndepositional faults and areas of localized basement uplift. On MOUNT AUGUSTUS, MOUNT PHILLIPS, and PEEDAWARRA the principal structures include the faulted southwestern limb of the Wanna Syncline, the Lyons River Fault, and the northwest-trending fault system that bounds the Cobra, and Ti Tree Synclines. These faults have played an important role in controlling the distribution of coarser grained siliciclastic rocks within lower to middle parts of the Edmund Group. Most of the syndepositional faults appear to have been reactivated during the 1070–755 Ma Edmundian Orogeny. A correlation of regolith geochemical anomalies with the major faults suggests some of these structures may have acted as pathways for mineralizing fluids.

A major focus of office activity during 2004–05 has been the update of KENNETH RANGE and the compilation

* Capitalized sheet names refer to standard 1:100 000 map sheets, unless annotated otherwise.

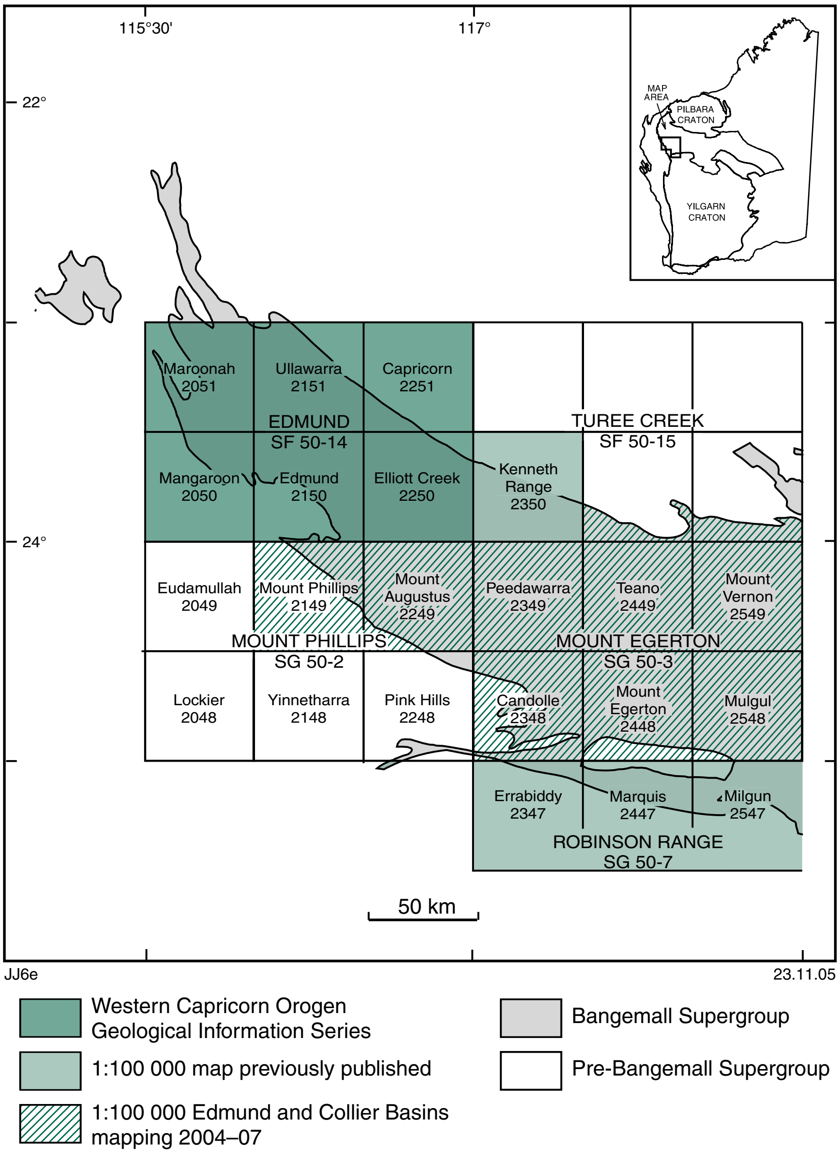


Figure 6. Progress of recent mapping for the Edmund and Collier Basins

of Bangemall Supergroup rocks on Mount Augustus. Digital data from Kenneth Range and Mount Augustus have also been prepared for inclusion in the 2005–06 update of the Western Capricorn Orogen 1:100 000 Geological Information Series digital package. Explanatory Notes for the six 1:100 000 map sheets covering the Edmund 1:250 000 map sheet were also written and released.

A collaborative project with Dr Keith Sircombe of GA has involved a joint geochronological and provenance study of detrital zircon populations taken from sandstone units throughout the Edmund and Collier Groups. The results of this work, together with data from earlier studies, are to be published in a forthcoming special volume of Precambrian Research that will focus on the geological assembly of Australia. Collaborative work has also been conducted with Dr Gabriel Courrioux of the Bureau de recherches géologiques et minières (BRGM). The aim of this project is to test the application of their 3D Geomodeller software to create a 3D model of Bangemall Supergroup and Gascoyne Complex rocks using only surface regional mapping data. Although it was not possible to produce a model of the entire Edmund (1:250 000) geology using the entire geological dataset, it was possible to model smaller areas using a simplified geological framework. These 3-dimensional models are superior to traditional maps and cross sections for viewing and interpreting the geology. The results from this study were presented at the inaugural Australian Geomodeller User meeting held in Perth during June.

2004–05 publications and products

- Kenneth Range 1:100 000 map;
- Western Capricorn Orogen 1:100 000 Geological Information Series update comprising data from Maroonah, Ullawarra, Capricorn, Mangaroon, Edmund, and Elliott Creek 1:100 000 map sheets;
- Maroonah, Ullawarra, Capricorn, Mangaroon, Edmund, and Elliott Creek 1:100 000 Explanatory Notes.

Future work

Work to be carried out during 2005–06 includes mapping and compilation of the Bangemall Supergroup on Peedawarra; and updating the Western Capricorn Orogen 1:100 000 Geological Information Series to include Explanatory Notes and geological linework and data from Kenneth Range, Mount Augustus, and Mount Phillips. An Edmund 1:250 000 map and a 1:250 000 aeromagnetic interpretation of the Western Capricorn Orogen will also be produced.

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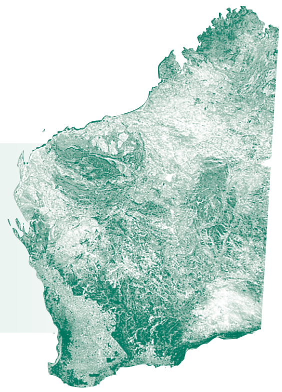
Gascoyne Complex



Objective: *To increase the knowledge of the Gascoyne Complex by the interpretation and dissemination of geological information collected during systematic regional mapping and associated geochemical, geochronological, geophysical, petrological, and metallogenic studies.*

Highlights and activities 2004–05

Fieldwork during 2004–05 was directed towards several objectives: completing the mapping of Gascoyne Complex rocks on Eudamullah* and Mount Phillips (Fig. 7); understanding the metallogeny of the Minnie Creek batholith; and a collaborative 3D-modelling study with the Geological Survey of France (BRGM) and Geoscience Australia.

Geochronological studies supporting the fieldwork have continued to highlight the importance of structures, metamorphic mineral assemblages, and granitic rocks formed during the 1680–1620 Ma Mangaroon Orogeny. This orogeny marks a major episode of intracontinental reworking within the West Australian Craton, and it is the subject of a recent paper published in the Australian Journal of Earth Sciences by GSWA staff. Many of the effects of the Mangaroon Orogeny previously have been attributed to the 1830–1780 Ma Capricorn Orogeny.

Field and laboratory studies were also conducted to understand the timing and nature of previously

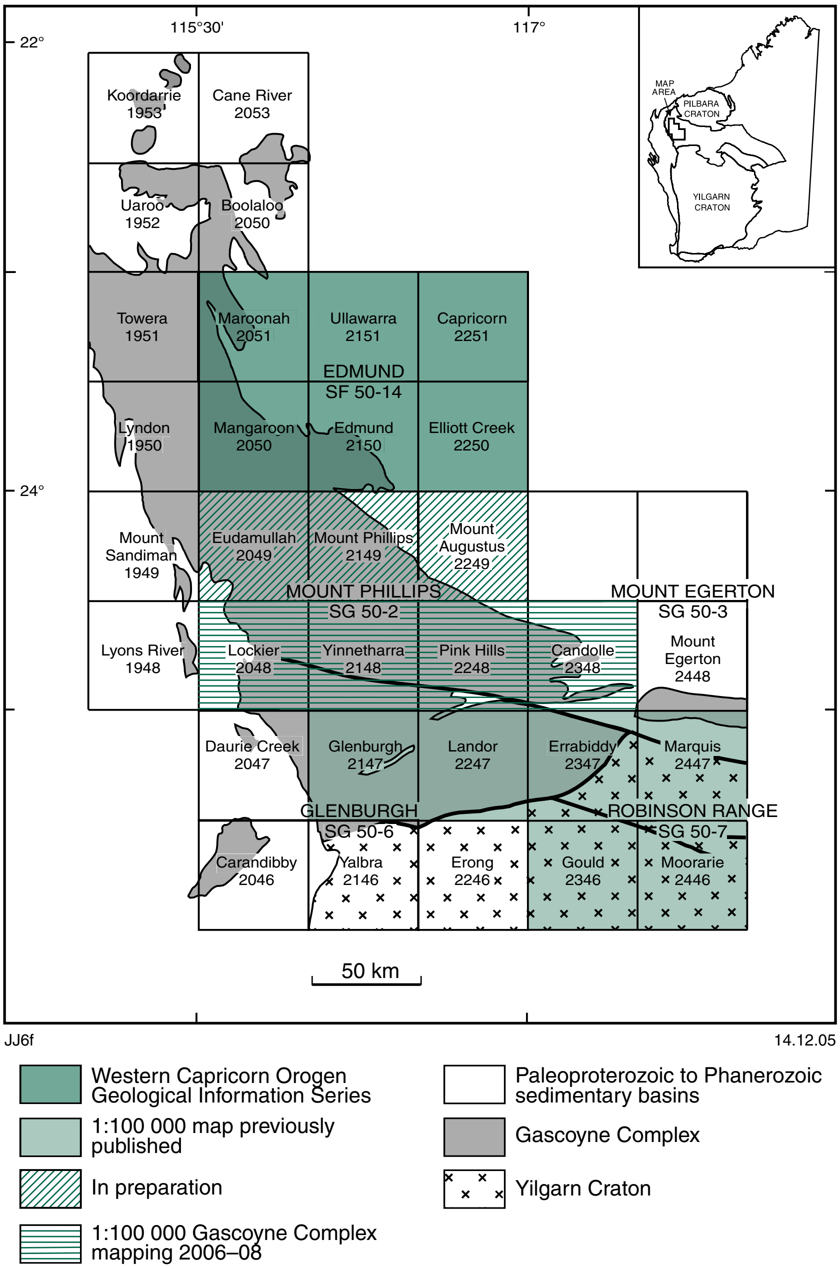


Figure 7. Progress of recent geological mapping for the Gascoyne Complex

identified molybdenum and copper mineralization hosted in the c. 1800 Ma Minnie Creek batholith. Some of the quartz vein-hosted mineralization is probably related to a series of linked structures formed during the Neoproterozoic Edmundian Orogeny, but some disseminated molybdenum mineralization may be older.

During the financial year collaborative work was conducted with Dr Gabriel Courrioux of the Bureau de recherches géologiques et minières (BRGM). The aim of this project was to test the application of the 3D Geomodeller software to create a 3D model of granite plutons in the Gascoyne Complex rocks using only surface regional mapping data. Some success was obtained with the modelling, but geophysical data are needed in order to provide better constrained models for granitic rocks.

Two theses supported by GSWA that examined aspects of the geology of the Gascoyne Complex were submitted. In December 2004 S. A. Occhipinti at Curtin University of Technology submitted her PhD thesis 'Tectonic evolution of the southern Capricorn Orogen, Western Australia'. In early 2005 D. A. Shewfelt at the University of Saskatchewan submitted her MSc thesis 'The nature and origin of Western Australian tourmaline nodules; a petrologic, geochemical and isotopic study'. Aspects of both studies will be published in the GSWA Annual Review or as a GSWA Record.

GSWA staff have been invited to write a paper on the tectonic evolution of the Gascoyne Complex in a forthcoming special volume for Precambrian Research that will examine the assembly of the Australian continent.

2004–05 publications and products

- Western Capricorn Orogen 1:100 000 Geological Information Series update incorporating data on the Gascoyne Complex from MAROONAH, MANGAROON, and EDMUND;
- MAROONAH, MANGAROON, and EDMUND Explanatory Notes for Gascoyne Complex rocks.

Future work

Work to be carried out during 2005–06 includes mapping and compilation of the Gascoyne Complex on EUDAMULLAH, MOUNT PHILLIPS, and MOUNT AUGUSTUS, and updating the Western Capricorn Orogen Geological Information Series to include Explanatory Notes and geological linework and data for the Gascoyne Complex from EUDAMULLAH, MOUNT PHILLIPS, and MOUNT AUGUSTUS. With the Edmund and Collier Basins Project, an EDMUND 1:250 000-scale map and a 1:500 000-scale solid geology interpretation of the Western Capricorn Orogen will be produced.

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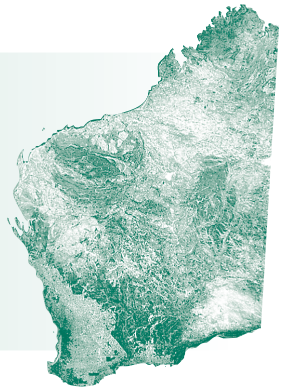
West Tanami project



Objectives: *As part of a cooperative project including the Geological Survey of Western Australia and Geoscience Australia, to increase geoscientific knowledge of the western part of the Granites–Tanami Complex by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps and supporting publications that integrate field and laboratory studies, including petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*

A new field mapping program commenced in the West Tanami during 2005.

Highlights and activities 2004–05

Some of the highlights for the year include:

- Watts (Fig. 8) has been mapped in detail and has been compiled using GIS software;
- A major seismic survey was completed. The survey started in the southern part of Slatey Creek extending south through Watts and Lewis, and then east into the Northern Territory. The data collected is being processed and interpreted.
- A paper on gold deposits in the Granites–Tanami Complex in Western Australia was submitted to Mineralium Deposita for publication.

Publications and products 2004–05

The first edition of the West Tanami Geological Exploration Package, which includes a solid geology interpretation, geophysical data, satellite images, mineral occurrence data, orthophotographs, and 1:250 000-scale geological maps, was released.

Future work

Field mapping and GIS-based compilation will continue on Balwina and Slatey Creek during 2005–06. Seismic sections and interpretations from the seismic reflection survey will be released in 2006.

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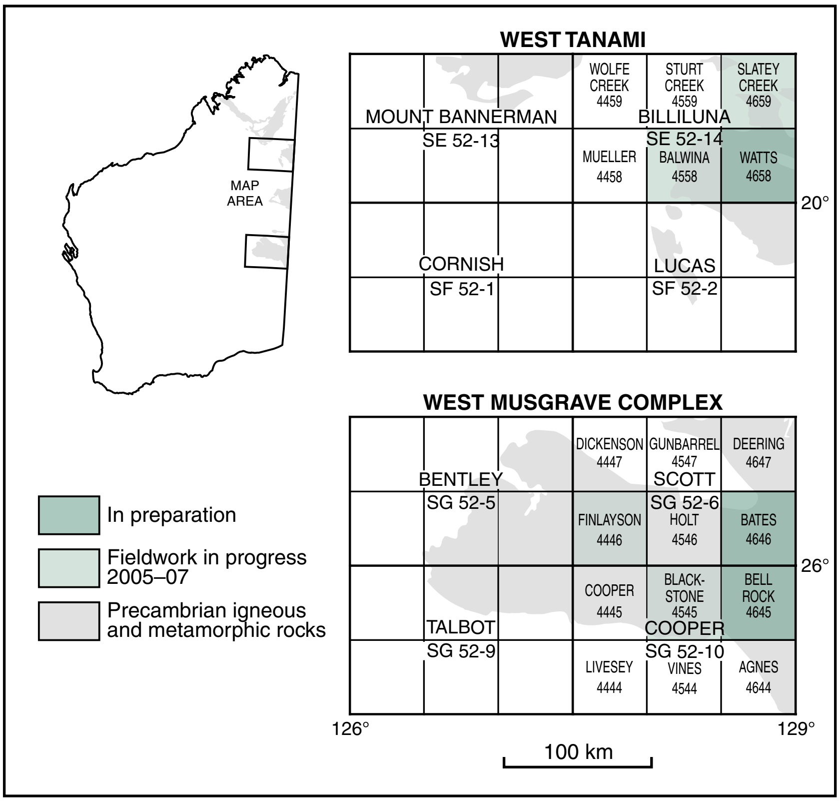
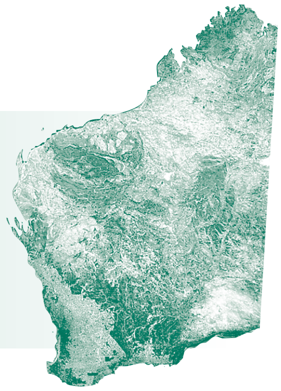


Figure 8. Recent geological mapping for the West Tanami and West Musgrave Complex projects

West Musgrave Complex project



Objective: *To increase geological knowledge of the western part of the Musgrave Complex by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps and supporting publications that integrate field and laboratory studies, including mapping, petrology, geochemistry, geophysics, geochemistry, remote sensing, and metallogeny.*

Highlights and activities 2004–05

Field mapping and map compilation of BATES* and field mapping of BELL ROCK were completed during the 2004–05 period, and mapping of the northern part of BLACKSTONE began (Fig. 8). Several north-oriented gravity traverses on BATES and BELL ROCK were also completed.

* Capitalized names refer to standard 1:100 000 map sheets.

Future work

The 2005–06 period will see the release of BATES and BELL ROCK and the first release of the West Musgrave 1:100 000 Geological Information Series. Mapping of BLACKSTONE will be completed and progress will be made on HOLT.

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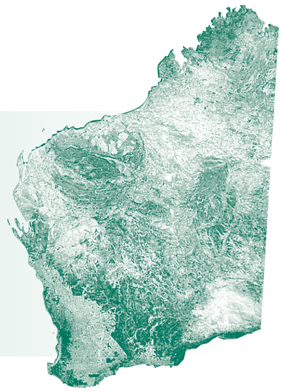
East Yilgarn project



Objectives: *To increase geoscientific knowledge of the east Yilgarn Craton by the collection, synthesis, and dissemination of geological information, particularly through the development of seamless geoscience databases, and production of geological maps with supporting publications based upon integrated field and laboratory studies that include mapping, petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*

The East Yilgarn project covers the highly mineralized Eastern Goldfields Granite–Greenstone Terrane and the southern part of the Southern Cross Granite–Greenstone Terrane that together make up the eastern part of the Archean Yilgarn Craton. The project is based in the Kalgoorlie regional office, which includes the J. H. (Joe) Lord Core Library.

Highlights and activities 2004–05

The East Yilgarn 1:100 000 Geological Information Series was updated and expanded to include recently completed YARDILLA* and a revision of MOUNT MASON (Fig. 9). The area covered now includes fifty-eight 1:100 000-scale geological map sheets as a seamless digital coverage of most of the Eastern Goldfields. Themes include 1:100 000 outcrop geology and structures, mineral

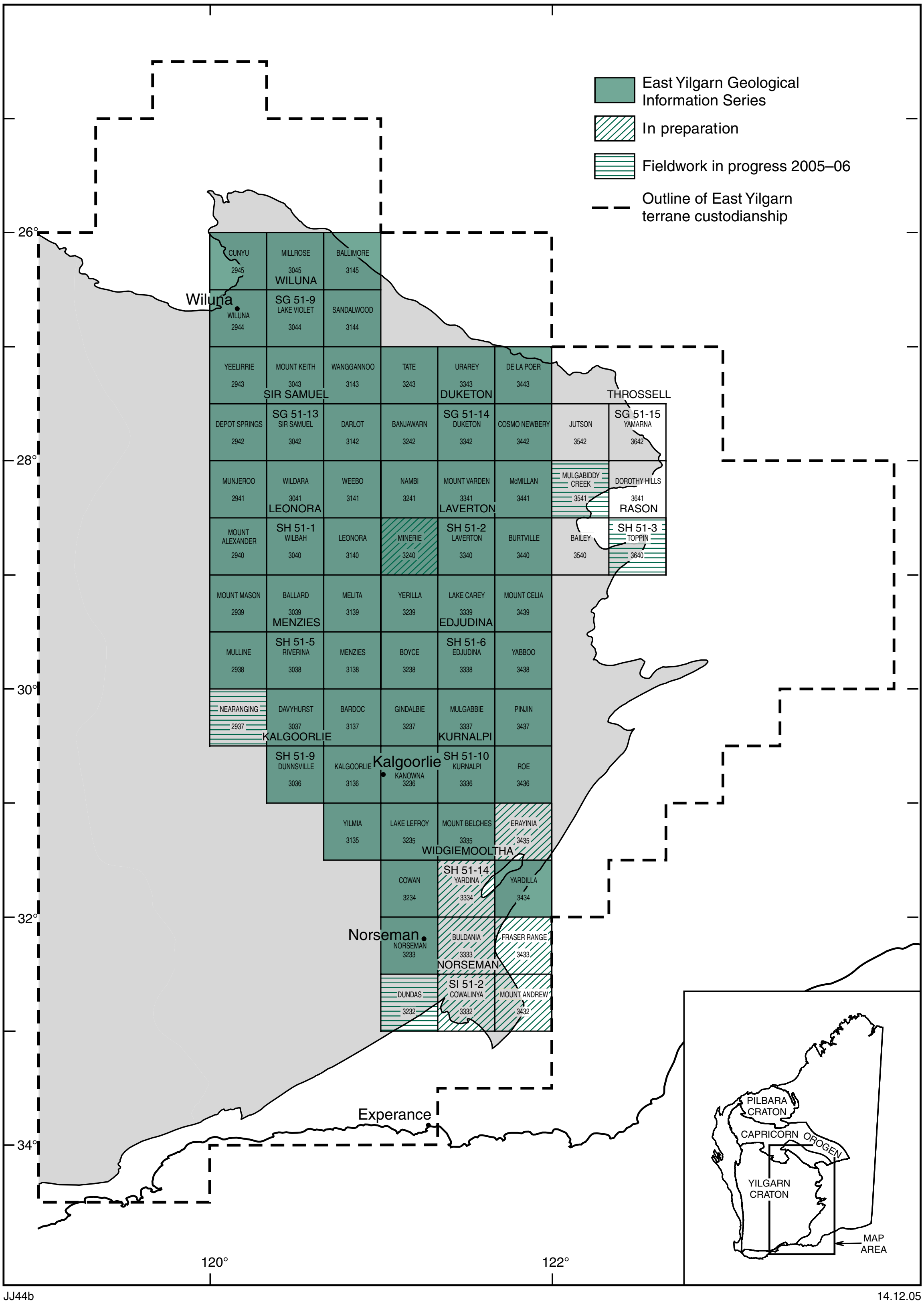


Figure 9. Progress of recent geological mapping in the east Yilgarn region and progress towards the GIS-based seamless digital database

location (from the WAMIN database) and resource data (MINEDEX database), abandoned mine site localities, regolith geochemistry, tenement and geographic information, Landsat images, aeromagnetic and gravity images, 1:500 000 interpretative geology, as well as new hydrological and cultural data. The data are supplied in GIS software-compatible formats, together with GeoVIEWER.WA, a free GSWA software package for interactive visual access to the database.

Compilation and processing of YARDINA and ERAYINIA have been completed and these maps should be released in the near future. Mapping of BULDANIA – FRASER RANGE, COWALINYA – MOUNT ANDREW, and MINERIE has been completed and compilation is advanced. Field mapping on NEARANGING and DUNDAS is well advanced.

The Joe Lord Core Library continues to assist the mining and exploration industry through the acquisition, storage, and display of drillcore. Industry and university research projects have made use of the core, and detailed sampling for metallogenic studies has been undertaken. The use of hyperspectral scanning of drill core to provide detailed mineralogical logs was completed for more than 18 km of core. This was done in collaboration with CSIRO researchers who constructed automated equipment to perform the analysis.

Regional mapping geologists at the Kalgoorlie regional office of the Geological Survey routinely provide advice to the general public, mining companies, and others on the geology of the East Yilgarn.

In October 2004, the East Yilgarn mapping team conducted a three-day field excursion to the southeastern margin of the craton. The 50 geologists who attended the excursion were shown the effects on the Archean Eastern Goldfields Granite–Greenstone Terrane of the Mesoproterozoic Albany–Fraser collision orogeny that occurred along this cratonic margin. High-grade metamorphic rocks ascribed to the orogenic belt were also visited. A presentation delivered at the GSWA 2005 Seminar outlined advances in the understanding of the Woodline beds, Paleoproterozoic sedimentary rocks parallel to the cratonic margin; they are preserved in grabens formed parallel to the orogenic belt during a period of post-collisional extension. Deposition of these sediments occurred several hundred million years before the Albany–Fraser collision and the outcrops are remnants of a much more extensive depositional basin.

2004–05 publications and products

- East Yilgarn 1:100 000 Geological Information Series — update and inclusion of YARDILLA;
- Report 95: *East Yilgarn 1:100 000 Geological Information Series — an explanatory note*;
- Record 2004/6: *Mineralization of the Woolgangie–Yilmia region, Eastern Goldfields Granite–Greenstone Terrane, Western Australia*;
- Record 2004/18: *Archaean and Proterozoic geology of the southeastern margin of the Yilgarn Craton — a field guide*;
- YARDILLA 1:100 000 Explanatory Notes and map;
- Geological Exploration Package for the southeastern Yilgarn margin;
- Geological Exploration Package for the northeastern Yilgarn.

Future work

MINERIE, ERAYINIA, YARDINA, BULDANIA – FRASER RANGE, and COWALINYA – MOUNT ANDREW will be published in a new digital format that includes field notes, photographs, petrography, and Explanatory Notes. Mapping of MULGABIDDY CREEK, TOPPIN, NEARANGING, and DUNDAS will be completed.

Other products to be completed in 2005–06 will include:

- a detailed field guide to the 'Physical volcanology of the felsic–ultramafic rocks on MINERIE';
- an expansion of the East Yilgarn 1:100 000 Geological Information Series to include YARDINA and ERAYINIA;
- an expansion of the Geological Exploration Package for the northeastern Yilgarn to include interpreted bedrock geology and ASTER imagery.

New 400-m line spacing aeromagnetic and radiometric data will be released for the Southern Cross to Ravensthorpe region. New 400-m line spacing aeromagnetic and radiometric data will be flown for the eastern margin of the craton and the northern part of the Albany–Fraser Orogen.

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Central Yilgarn (Southern Cross) project

Objectives: *To increase geoscientific knowledge of the central part of the Yilgarn Craton by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps and supporting publications that integrate field and laboratory studies including petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*

The central Yilgarn 1:100 000-scale field mapping program began in the Marda–Diemals area, the geographic centre of the Yilgarn Craton, in late 1997 and thirteen 1:100 000 sheets have been published to date (Fig. 10).

Highlights and activities 2004–05

In 2004–05, fieldwork was completed on MONTAGU*, YOUNO DOWNS and YAGANOO, thus completing field mapping of the Gum Creek greenstone belt. These sheets also contain parts of several smaller greenstone belts including the Poison Hills, Barrambie, and Red Handed Bore greenstone belts. New U–Pb zircon SHRIMP geochronology was published for igneous and sedimentary rocks from ATLEY, SANDSTONE, LAKE MASON, EVERETT CREEK, RICHARDSON, and MARMION. A paper describing large-scale shear zones of the central Yilgarn Craton was published externally.

The Gum Creek greenstone belt contains abundant metamorphosed mafic rocks; common metamorphosed banded iron-formation, chert, and clastic sedimentary rocks; and subordinate metamorphosed ultramafic rocks. As in other greenstone belts in the region, banded iron-formation is most abundant low in the preserved stratigraphy. New mapping and examination of numerous mineral-exploration

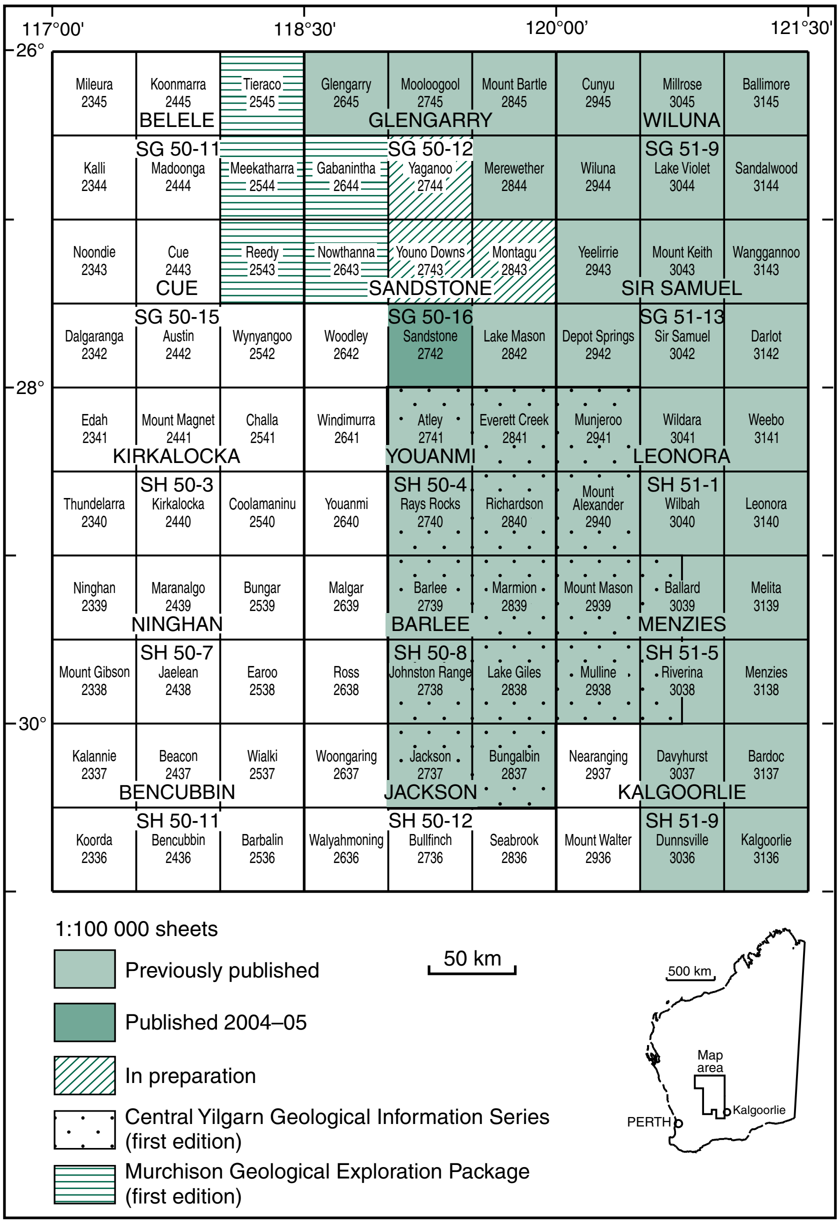

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Figure 10. Progress of recent geological mapping for the Central Yilgarn and Murchison projects

* Capitalized names refer to standard 1:100 000 map sheets.

drillholes has also delineated the distribution of substantial volumes of clastic metasedimentary rocks within the greenstone succession, possibly associated with metamorphosed felsic volcanic and associated intrusive rocks. The large extent of metasedimentary rock is unusual in greenstone belts in this region. Although relationships are difficult to determine due to the poor exposure and complex deformation, it is likely that the felsic rocks and at least some of the clastic metasedimentary rocks form a younger succession that rests unconformably on the mafic-dominated greenstones. Greenstones of the Gum Creek belt record a protracted deformation history that includes major east–west shortening like that described previously for the central Yilgarn.

The Red Handed Bore and Poison Hills greenstone belts contain slivers and large enclaves that include major east–west shortening of metamorphosed mafic, ultramafic, and sedimentary rocks, including banded iron-formation, that have been extensively intruded by granite. The poorly exposed Barrambie greenstone belt contains a similar range of rock types but also includes mafic rocks of the Barrambie Intrusion, a layered intrusion like the larger Windimurra Intrusion to the southwest.

2004–05 publications and products

- ATLEY, RAYS ROCKS, and southern SANDSTONE 1:100 000 Explanatory Notes;
- SANDSTONE 1:100 000 map.

Future work

Maps for MONTAGU, YOUNO DOWNS, and YAGANOO will be completed in 2005–06; and the first edition of the Central Yilgarn 1:100 000 Geological Information Series will be released as a GIS package on DVD.

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Murchison project

Objectives: *To increase geoscientific knowledge of the western part of the Yilgarn Craton by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps and supporting publications that integrate field and laboratory studies including petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*

A new field mapping program commenced in the Murchison region in 2004–05.

Highlights and activities 2004–05

In 2004–05, orthophotography that included a digital elevation model was acquired over TIERACO*, MEEKATHARRA, GABANINTHA, REEDY, and NOWTHANNA, and released as part of the Murchison Geological Exploration Package (Fig. 10).

Work began on a 1:500 000-scale geological interpretation of the Murchison region based on pre-existing data and newly acquired geophysical data and satellite imagery. Field mapping commenced on MEEKATHARRA and GABANINTHA.

2004–05 publications and products

- The first edition of the Murchison Geological Exploration Package was released.

Future work

Field mapping and GIS-based compilation will continue on TIERACO, MEEKATHARRA, GABANINTHA, REEDY, and NOWTHANNA. A second edition of the Murchison Geological Exploration Package incorporating a new solid geology interpretation and newly acquired Landsat TM imagery will be released in 2006.

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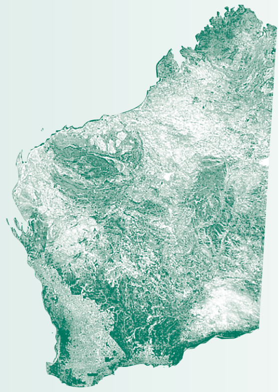
* Capitalized names refer to standard 1:100 000 map sheets.

SCIENTIFIC, TECHNICAL AND FIELD SUPPORT

Chief Geoscientist and Terrane Custodianships

Objectives:
- *To ensure an up-to-date and coherent geological framework for Western Australia is maintained*
- *To ensure that GSWA databases are consistent and integrated, and are capable of providing a seamless coverage of the State at a uniform standard, unconstrained by predefined geological or geographical boundaries. Multi-themed geoscience information products will be generated from the data stored in GSWA databases*
- *To lead the development of standards for geoscience information collection and presentation within GSWA*
- *To provide scientific leadership within GSWA, and promote new developments in Western Australian geoscience to local, national, and international explorers and researchers.*



Highlights and activities 2004–05

Activities continued to be focused on revising and upgrading database structures and standards. A major ongoing task is the review and approval of all manuscripts and map products to ensure the quality of their content and the consistency of their presentation.

The redevelopment of WAROX — GSWA's field observation database — neared completion with extensive testing of WAROX8. Central to the redevelopment was consistency with GSWA's revised rock classification scheme, and the structured nature of data entry. Field and petrographic observations will be more accessible with the introduction of a series of lithology data look-up tables that allow the construction of searchable descriptions of an outcrop, a rock specimen, or a thin section. A WAROX dataset is provided with each 1:100 000 Geological Information Series product, as well as a GIS viewing-tool on CD or DVD. Alongside the redevelopment of WAROX, a version was written and tested for use on an iPAQ Pocket PC (WAROX Mobile). Observations are now entered in the field for upload to the geologist's PC and then into the main corporate WAROX database.

As part of the ongoing revision of the State tectonic units, interpreted bedrock geology, and regolith datasets, a review was begun of all mapped geological units in Western Australia. The intention was to standardize the information provided for each unit in all GSWA map-product look-up tables, geological map references, and in Explanatory Notes. The results were compiled as a series of spreadsheets that represent the preferred stratigraphic name, map code, and description for each unit. Units were also being attributed for their tectonic unit and their age, both in terms of geological time, and geochronological age where known. The tables will be the basis for development of a geological units database for Western Australia (STRATWA).

The Chief Geoscientist took part in a Workshop on synthesizing of the Australian Proterozoic, which was held in Canberra and hosted by Geoscience Australia (GA) and the Tectonics Special Research Centre. Large areas of Proterozoic rocks in Western Australia are underexplored and can be regarded as mineral exploration 'greenfields'.

Elsewhere in Australia, and the rest of the world, Proterozoic rocks host significant mineral systems and major mines. This national synthesis project will encourage the use of compatible databases and database standards between GA and the state geological surveys, and highlights the need for data generated by academic researchers to be routinely captured. GA will manage the project in cooperation with the state geological surveys, together with interested university researchers. The main focus of this Workshop was on the use of time–space plots and their generation on-demand from databases.

The Phanerozoic basins Terrane Custodian attended a workshop at the University of Western Australia on GTS 2004, the new global geological time scale introduced by Gradstein et al. (2005)*. GSWA has adopted this time scale, including all divisions and spellings, for all GSWA publications and databases. The Archean Terrane Custodian is acting as Vice Chair of the newly reappointed Subcommission on Precambrian Stratigraphy of the International Commission on Stratigraphy (ICS). The aim of the subcommision is to review the existing division of the Precambrian time scale by absolute age, defined as Global Standard Stratigraphic Ages (GSSA), to determine if this system should be replaced by rock record-based Global Standard Section and Points (GSSP), as used to divide the Phanerozoic time scale. The subcommission will make recommendations for any revision for the annual meeting of the ICS in Beijing in 2008. Western Australia will have an important role to play in this review, as the State has one of the best-preserved and most complete Precambrian rock records on Earth.

The Chief Geoscientist continued to provide advice as required to the Executive Team, to members of the public, exploration companies, visiting research geoscientists, and to the media on aspects of the geology of Western Australia.

2004–05 publications

The Chief Geoscientist contributed an invited chapter on the Proterozoic of Australia to the Encyclopedia of Geology published by Academic Press. A revision of the regolith-coding scheme (GSWA Record 2005/10) was published.

Future work

The Chief Geoscientist and the Terrane Custodians will be involved in the ongoing assessment of computer hardware for field data-entry.

The various GSWA geological datasets will continue to be improved to ensure a genuine seamless coverage is achieved across the State. The Chief Geoscientist and the Terrane Custodians will be involved in the development, testing, and roll-out of the STRATWA database. STRATWA will be linked to GIS map polygons at all scales, and geological map references and Explanatory Notes to accompany geological map products will be derived from the database. The database framework will provide the basis for these to be constructed on-demand for customer-defined areas. Information in the database will be consistent with national standards such as the Stratigraphic Units Database maintained by GA.

Work will continue on revising the State 1:500 000 digital interpreted bedrock geology map. The revised map will be used to derive a new 1:2 500 000 digital tectonic units map and, together with the State 1:500 000 digital regolith map, a new 1:2 500 000 digital geological map of Western Australia.

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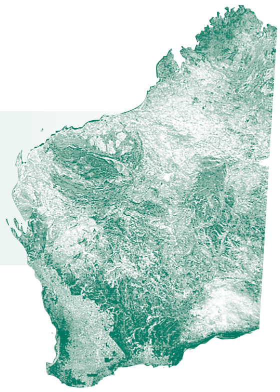
* GRADSTEIN, F. M., OGG, J. G., and SMITH, A. G., (editors), 2005, A Geologic Time Scale 2004: Cambridge University Press, 589p.

Geochronology



Objectives: *To increase the knowledge of the geology of Western Australia by acquiring and disseminating geochronological data, which complement other geological information in support of regional mapping initiatives.*

Geochronology is an essential component of geological interpretation, particularly in terms of understanding the geological history of Precambrian rocks that constitute a major part of Western Australia and contain most of its known mineral resources.

Highlights and activities 2004–05

A total of 67 samples were dated via U–Pb analysis of zircon by sensitive high-resolution ion microprobe (SHRIMP), with typical precision of ±6 Ma. These data have contributed to the solution of important geological problems in the Pilbara Craton, the Southern Cross and Eastern Goldfields Granite–Greenstone Terranes, the Gascoyne and Musgrave Complexes, and the Officer Basin.

The latest release of geochronology data is a digital compilation (on CD) of data acquired by GSWA between 1994 and 2003, which also incorporates the subset of Geoscience Australia's OZCHRON database specific to Western Australia. This self-contained digital data package uses GeoVIEWER.WA software to view, access, and query the geochronology data, within a framework provided by other data layers, such as geology at 1:500 000 scale and tectonic units. GeoVIEWER.WA provides an on-screen summary of the age data for the selected sample(s), together with links to associated locational, stratigraphic, petrographic, and analytical metadata, in PDF format. These digital data will be supplemented by new data as they become available. It is planned that future geochronology updates will be published directly via the GSWA website.

2004–05 publications and products

- CD: *Compilation of geochronology data: October 2004 update* (containing GSWA geochronology data obtained between 1994 and 2002);
- CD: *Compilation of geochronology data: June 2005 update* (containing GSWA geochronology data obtained between 1994 and 2003).

Future work

Geochronology in the Pilbara Craton, the Southern Cross, Eastern Goldfields, and Murchison Granite–Greenstone Terranes, the Granites–Tanami, Gascoyne, and Musgrave Complexes, and the Edmund, Collier, and Officer Basins will continue in 2005–06. An update of the *Compilation of geochronology data* CD (containing GSWA geochronology data obtained between 1994 and 2004) will be released.

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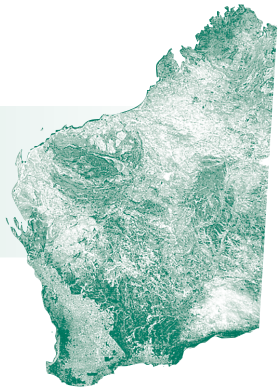
Biostratigraphy and paleontological services



Objectives: *To provide biostratigraphic, paleoenvironmental, paleobiological, and paleontological information that allows precise interpretation of correlation, age, environment, and processes in the evaluation of the State's hydrocarbon and mineral potential.*

Highlights and activities 2004–05

The monograph on the palynology of the newly defined Ediacaran System is now at the printers, and will be released early in the next financial year. This publication is the culmination of a major project begun in 1991 to correlate terminal Neoproterozoic rocks, and it will be a key reference tool for both petroleum and mineral explorers looking at the potential of older rocks across Australia. This study of Ediacaran biostratigraphy paved the way for a parallel study of Cryogenian biostratigraphy in the western Officer Basin, based largely on GSWA's Empress 1 and 1A and Lancer 1 drillholes and on earlier field studies. Both stromatolites and palynology show consistent results across the basin, match results from stable isotope chemostratigraphy, and allow correlation with units of similar age elsewhere in Australia. A revised lithostratigraphy of the Officer Basin, incorporating these results, and a preliminary biostratigraphy for Lancer 1 were completed and published.

Several external publications were prepared on various aspects of Precambrian paleobiology and correlation. Two have been accepted for publication, and others are either in review or about to be submitted. Work continues on the preparation of a handbook on microbialite and stromatolite methodology and terminology.

Visits to Europe, Melbourne, and Sydney allowed presentations of results to be made to various audiences, including the International Palynological Congress in Granada, Spain. In November, an invited presentation about the Acraman impact event was given to the Geological Society of America Annual Meeting in Denver. Several presentations were made to local societies, mainly in connection with either early life in the Pilbara or the Acraman impact event and its role in biotic changes in the Ediacaran.

Numerous requests, ranging from specific scientific enquiries to tourists seeking advice about visiting fossil sites and collecting constraints, were answered. Protection of significant stromatolite sites in the Pilbara continues to be an issue. Several geoscientists (mainly from overseas) visited the section this year seeking advice or to examine material. Work continues on updating the collection, with the focus on capturing digital locational data for the general fossil collection.

Work released during 2004–05

- Report 93: *Lithostratigraphic nomenclature of the Officer Basin and correlative parts of the Paterson Orogen*;
- Record 2005/4: *Preliminary report on the Proterozoic biostratigraphy, Lancer 1, Officer Basin, Western Australia* in *Lancer 1 well completion report*;
- Several external papers were published.

Future work

Work will continue on data capture of biostratigraphic and paleontological information. The stromatolite handbook should be close to completion, and work will begin on detailed accounts of stromatolite and palynological distributions in the Officer Basin. Several external publications on aspects of Precambrian paleontology should be submitted this coming year.

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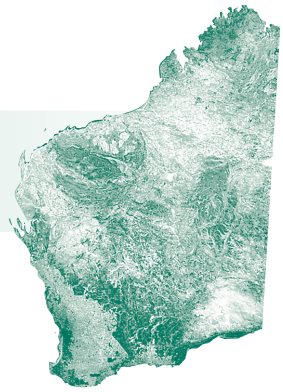
Geophysics and remote sensing



Objective: *To provide geophysical and remote sensing maps and interpretation products to support the regional mapping projects and for publication. To provide advice and liaise with industry.*

Regional airborne geophysics

In the first year of the Government's four-year, $12 million program to increase airborne magnetic and radiometric coverage of Western Australia, GSWA and GA initiated two new National Geoscience Agreement airborne geophysical survey projects in the south Yilgarn and Paterson–Rudall regions.

In both areas, survey companies UTS Geophysics and Fugro Airborne Surveys were contracted to fly new surveys at a line spacing of 400 m at a mean altitude of 60 m above ground level. Where appropriate, the Department acquired intellectual property rights to existing data from private companies to complement the new surveys.

In the south Yilgarn, UTS Geophysics and Fugro Airborne Surveys were contracted to fly approximately 270 000 line-km between September 2004 and June 2005 in three survey blocks. Data from the new surveys were merged with existing data to provide almost 400 000 line-km of magnetic and radiometric coverage of approximately 112 000 km^2 in a region extending from Kellerberrin to Ravensthorpe. Data releases occurred in stages between May and July 2005.

In the Paterson–Rudall region, the same companies were engaged to acquire 200 000 line-km of data in three blocks over an area of approximately 70 000 km^2. Flying of about 70 000 km of data in the northern block was completed at the end of May; flying of the remaining blocks commenced in June. There will be staged data releases during 2005–06. In addition, some 60 000 km of previously confidential private company data were acquired and released to the public.

GA contracts made in 2003–04 with Fugro Airborne Surveys and UTS Geophysics to extend 400-m coverage over CUE*, KIRKALOCKA, and NINGHAN were completed and the data released.

Regional gravity surveys

Regional gravity traverses were conducted in the following regional-mapping project areas and the data submitted to GA for inclusion in the National Gravity Database:

- Gascoyne–Bangemall
  2 traverses 320 km 740 stations
- Musgrave
  3 traverses 310 km 486 stations

Some 374 samples were collected for density measurements to assist with the interpretations of these data for the project teams.

Airborne geophysical survey register and data repository

During 2004–05, 109 new airborne survey datasets, containing approximately 613 000 line-km of magnetic, radiometric, digital elevation, and electromagnetic data, were received for inclusion in the MAGIX data repository. At the end of the year, about 3.7 million line-km of private data from 738 surveys were held in the repository.

Most companies submitting data have agreed to make public the location and basic specifications of their surveys; this information is available through the GeoVIEW.WA database on the Department's website (www.doir.wa.gov.au).

* Capitalized names refer to standard 1:250 000 map sheets.

Remote sensing

During 2004–05 an in-house study identified a series of geologically meaningful images that could be processed from ASTER data. This series of images was produced in support of the Pilbara, Musgrave, and North Murchison regional mapping teams. GSWA's archive of ASTER data continues to grow as granules are acquired to support the regional mapping projects. Processing of Landsat TM data was also undertaken in support of the Pilbara and Lennard Shelf regional mapping teams.

2004–05 publications and products

Regional airborne geophysical survey digital datasets:

- South Yilgarn Block A: KELLERBERRIN (part), SOUTHERN CROSS, HYDEN
- South Yilgarn Block B: BOORABBIN, LAKE JOHNSTON

1:250 000 hardcopy magnetic and radiometric images:
Cue, Kirkalocka, Ninghan, Southern Cross, Hyden, Boorabbin, Lake Johnston.

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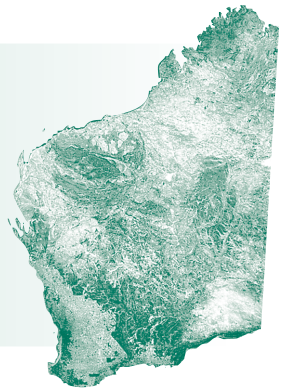
Logistics support and core libraries

Objective:
- *To manage core library facilities in both Perth and Kalgoorlie to service the needs of industry, academia, and GSWA*
- *To manage field support services, including transport and other equipment, and provide field assistants and communication links for all GSWA field parties*
- *To manage inventory services for all GSWA publications, including maps, Bulletins, and Reports*
- *To promote and monitor safety both in the field and throughout the logistical support areas in Perth and Kalgoorlie.*



Perth and Kalgoorlie core libraries

A high level of activity in the petroleum exploration industry has ensured an intense year of both sample receivals and provision of viewing and sampling activities for clients at the Perth Core Library. There was a 100% increase from last year in the number of petroleum cuttings and a 300% increase in the number of sidewall cores accessioned into the collection. A large number of geochemistry samples from industry and Geological Survey projects were also archived.

A program to collect valuable historical mineral core is ongoing. Much of this core has been archived at the J. H. (Joe) Lord Core Library in Kalgoorlie. The Kalgoorlie facility maintains a mineral core archiving and viewing service for the mineral exploration industry in the Eastern Goldfields.

The first phase of scanning core using a new continuous core-logging system (HyLogger) developed by CSIRO was carried out in the first quarter. A total of 24 000 m of core was scanned, 6000 m more than originally scheduled for the project, which is funded by Placer Dome, Goldfields Australia, and GSWA. MERIWA has also contributed funds to assist in the development of the CSIRO HyLogger. Phase 2 of this project will be carried out in October 2005 at the core library in Kalgoorlie and will provide additional information including silicate analysis and magnetic susceptibility measurements of selected cores.

During the year 718 clients viewed and/or sampled core or cuttings at the Perth and Kalgoorlie facilities. Clients spent 3107 hours viewing core and cuttings and took samples for further analysis. Some 14 839 m of core was acquired, and 2847 boxes of cuttings and 4025 sidewall cores were accessioned into the collection.

Field support

The specialized 4WD fleet satisfied all divisional requirements with a high emphasis on swift 'turn-around time' for vehicle preparation between scheduled field trips. Fly-in, fly-out arrangements incorporated with carefully programmed field schedules in regional mapping areas ensured efficient use of the fleet.

Some eight vehicles were disposed of, and replaced (5 Toyota utilities, 2 Toyota 100 Series station wagons, and one Hilux utility). Refurbishment costs and customization of new vehicles continues to have a significant impact on the vehicle budget. These costs will diminish after the next financial year when the entire fleet will have been upgraded to meet the new standard for vehicle modification. One caravan was refurbished to meet requirements for the Musgrave mapping team and another caravan was purchased.

Additional field assistants continue to be provided by an employment agency to allow flexibility in meeting short-term needs. Sourcing suitable assistants has been a problem with the recent high level of activity in the mining industry; however, outsourcing for peak periods has proved to be the best means of meeting our requirements.

The Survey places a high priority on safety in the field with continuous improvement in work practices and training. The one-day training and 4WD-vehicle familiarization course carried out at the Carlisle depot has been reviewed, upgraded, and documented. Twenty-three persons were trained at the in-house Safety Training course. The high-frequency radio communications base at the Carlisle depot and a Safety Officer on weekend roster remain the focal points for monitoring safe operations in the field. An automated vehicle-tracking system is currently being investigated.

The number of satellite telephones for use in the field has also been increased.

The Geological Survey's publication store was maintained from the new purpose-built facility. New systems have been developed to increase efficiency in the annual stocktake, and also the daily issue and receipt of publication material.

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Geoscience information products

Objectives:

- *Provide a quality and timely editing and publishing service for geoscientific manuscripts, maps, and database products produced by Geological Survey geoscientists*
- *Provide the infrastructure for the management of geoscientific data*
- *Develop and coordinate geoscientific database policies and standards*
- *Promote Geological Survey products and services through displays, advertising, and other promotional events*
- *Monitor product sales and develop marketing strategies to ensure products are reaching the appropriate market*
- *Provide information and advice for the general public on all aspects of Western Australian geology*

2004–05 publications and products

The geoscience information products group continued to produce high-quality geological and geophysical maps, printed and digital reports, and digital data packages.

Geological and geophysical maps

Forty-seven maps and images at various scale were published (see Appendix: Planned achievements and publications released, p. 129), including:

- seven 1:100 000 geological series maps
- eleven project maps at various scales
- fifteen geophysical images at various scales
- fourteen miscellaneous plates.

Geoscientific digital data packages

Twenty-one geoscientific digital data packages were released in 2004–05 (Appendix, p. 129), including:

- two 1:100 000 Geological Information Packages
- four Geological Exploration Packages
- one mineral occurrences and exploration potential data package

- update of one mineral occurrences and exploration potential data package
- one well completion report data package
- two acreage release data packages
- three geoscience of WA promotional CDs
- two geochronology packages, including spatial data in GeoVIEWER.WA
- five miscellaneous data packages.

Geoscientific reports

Thirty-two manuscripts were edited, illustrated, and published (Appendix, p. 129), including:

- Explanatory Notes for eleven series maps
- eighteen Records and Reports
- eight miscellaneous publications including the GSWA Annual Review 2003–04.

Other activities

Promotional activities

Publication of Fieldnotes (the GSWA quarterly newsletter) continued during 2004–05 and provided a medium for informing our customers about our activities, and promoting newly released maps, publications, and datasets. During the year, advertisements and short articles publicizing the release of GSWA published products were placed in a number of newspapers, industry magazines, and journals. Media releases describing GSWA products, services, and new publications were prepared and issued during the year, in cooperation with the Corporate Communications Branch of DoIR.

The promotion of Western Australia's prospectivity by GSWA continued at industry events both in Australia and overseas including at:

- Diggers & Dealers (Kalgoorlie, July 2004)
- ASEG–PESA (Sydney, August 2004)
- Good Oil (Perth, September 2004)
- SEG (Perth, September 2004)
- Mining 2004 (Brisbane, October 2004)
- NAPE (Houston, Texas, January 2005)
- Australian Oil & Gas (Perth, February 2005)
- Explorers Conference (Perth, February 2005)
- PDAC (Toronto, Canada, March 2005)
- Paydirt Gold (Perth, April 2005)
- APPEA (Perth, April 2005)
- AAPG (Calgary, USA, June 2005).

In addition to the above, DoIR and GSWA held four events to promote communication with our customers. These were:

- Petroleum Open Day — showcasing recent work by the Department and issues of interest to petroleum explorers (Perth, October)
- Earth Science Careers display by GSWA and the Mining Hall of Fame for the Careers Expo at the Kalgoorlie Boulder Science Awareness Festival (Kalgoorlie, October)
- GSWA 2005 (Perth, February)
- Company visits — A number of companies in Perth and Kalgoorlie where visited to promote our latest products and services and to provide an opportunity for feedback.

GSWA 2005 was again held in February to hook up with the RIU Explorers Conference conducted at the same venue in Fremantle.

Online services

In 2004–05, GSWA implemented a new online system that provides a vastly improved means to store, index, and deliver company exploration reports, map and manuscript publications, and digital data items using the Internet. DigitalPaper XE, supplied through Fuji Xerox Australia and designed by ePlus, is an integrated web-enabled browser-based viewing and document-searching application that allows you to view, print, and download documents online without the need for installing additional software on your computer. This system allows users to view and print the documents without having to download them first. Users can choose to download a document, knowing what is in it and how large it is, and are able to assess how long download will take given personal web-connection circumstances. This is a significant improvement on our previous service in this area.

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Appendices

Planned achievements and publications released

Major planned achievements for 2004–05

GSWA again proposed an ambitious project-based program of work for 2004–05 that was designed with a major component of promoting Western Australia's exploration potential. The planned achievements for 2004–05 included the release of 49 geoscientific maps at various scales; publication of 45 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers; publication of 26 digital geoscience datasets; and continued and enhanced provision of geoscientific data and exploration information to industry and the public through our library services and the mineral (WAMEX) and petroleum (WAPIMS) exploration databases. Work under a A$12 million commitment over four years (now ongoing at A$3 million per annum) to double the area of the State covered by high-tech aerial geophysical surveys was commenced. The surveys aim to increase mineral exploration expenditure in Western Australia. In 2004–05, data were collected over the south Yilgarn, and released for the south Yilgarn and Murchison regions. During 2004–05, changing priorities resulted in the completion of a slightly different mix of published output for the year than was originally planned.

In 2004–05 GSWA published:

- 47 geological maps, including seven 1:100 000 Geological Series Maps
- 32 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers
- 21 digital datasets

This product mix is similar to that in recent years, reflecting the Survey's continued emphasis on providing a large volume of geoscience data in digital form. In overall terms, GSWA publication milestones for 2004–05 were met. The total combined number of published products released was 100, which was down relative to our stated predictions, partly due to the fact that some products that would in the past be released as separate products were released as one combined product (e.g. 1:100 000 Explanatory Notes).

Provision of open-file company exploration reports to industry via the WAMEX and WAPIMS database systems continued through the year. A three-year program has commenced to accelerate the public release of archival information contained in 21 000 non-confidential exploration reports from exploration companies, in order to encourage greenfields exploration activity. Some 7168 reports were scanned in 2004–05. A new system was installed to deliver digital documents and data over the web for the WAMEX system, which now allows the viewing, downloading, and printing of online mineral exploration reports.

Maps, books, and datasets released in 2004–05

Geological maps

1:100 000 Geological Series

COONGAN by M. J. Van Kranendonk
KENNETH RANGE by A. M. Thorne and D. McB. Martin
NOREENA DOWNS by T. R. Farrell and R. H. Smithies
SANDSTONE by S. F. Chen and M. G. M. Painter
WARRIE by M. J. Van Kranendonk
YARDILLA by S. A. Jones and A. A. Ross
YILGALONG by I. R. Williams

1:500 000 maps

Mineralization and geology of the Earaheedy area
by P. B. Abeysinghe and R. M. Hocking (Report 96)

Resource potential for land use planning maps

Eastern Goldfields — Resource potential for land use planning
scale 1:600 000; compiled by F. I. Roberts
Hope Downs Railway — Resource potential for land use planning
scale 1:500 000; compiled by C. J. Kojan
Mid West region — Resource potential for land use planning
scale 1:1 000 000; compiled by C. J. Kojan
Mount Manning Range region — Resource potential for land use planning
scale 1:500 000; compiled by M. J. Freeman and C. J. Kojan

Geological maps at other scales

Western Australia atlas of mineral deposits and petroleum fields 2005, compiled by R. W. Cooper and D. J. Flint
Western Australia mineral deposits and petroleum fields 2005 (scale 1:2 500 000), compiled by R. W. Cooper and D. J. Flint
Major resource projects map, 2005, scale 1:2 500 000
Western Australia mines — operating and under development, March 2005, scale 1:2 500 000
Industrial minerals in Western Australia, scale 1:5 000 000 by J. M. Fetherston (Record 2004/21, Plate 1)
Industrial minerals in southwest Western Australia, scale 1:2 000 000 by J. M. Fetherston (Record 2004/21, Plate 2)
Location map of seismic lines, petroleum exploration and stratigraphic wells, and selected mineral exploration drillholes, western Officer Basin (Report 98, Plate 1)
Two-way time structure map of the near base Neoproterozoic seismic horizon (Report 98, Plate 2)
Two-way time structure map of the top Browne Formation (near top salt) horizon (Report 98, Plate 3)
Two-way time thickness map of the Browne Formation (Report 98, Plate 4)
Two-way time structure map of the top Hussar Formation horizon (Report 98, Plate 5)
Two-way time thickness map of the Hussar Formation (Report 98, Plate 6)
Two-way time structure map of the top Kanpa Formation horizon (Report 98, Plate 7)
Two-way time thickness map of the Kanpa Formation (Report 98, Plate 8)
Two-way time structure map of the base Table Hill Volcanics horizon (Report 98, Plate 9)

Kwinana – East Rockingham strategic industrial area, scale 1:25 000
Regional development areas in Western Australia
Geology of areas within the Whim Creek greenstone belt, Pilbara Craton, Western Australia, by R. H. Smithies and G. Pike (Report 101, Plate 1, on two sheets)
Kalgoorlie–Kanowna kaolin disorder, scale 1:100 000, by T. Cudahy, M. Cacceta, A. Cornelius, R. Hewson, M. Wells, M. Skwarnecki, and P. Hausknecht

Geophysical images

1:250 000 images

KIRKALOCKA Total Magnetic Intensity image
KIRKALOCKA Ternary Radiometric image
CUE Total Magnetic Intensity image
CUE Ternary Radiometric image
NINGHAN Total Magnetic Intensity image
NINGHAN Ternary Radiometric image
SOUTHERN CROSS Total Magnetic Intensity image
SOUTHERN CROSS Ternary Radiometric image
HYDEN Total Magnetic Intensity image
HYDEN Ternary Radiometric image
LAKE JOHNSTON Total Magnetic Intensity image
LAKE JOHNSTON Ternary Radiometric image
BOORABBIN Total Magnetic Intensity image
BOORABBIN Ternary Radiometric image

1:500 000 image

East Murchison Total Magnetic Intensity image

Reports

93 **Lithostratigraphic nomenclature of the Officer Basin and correlative parts of the Paterson Orogen, Western Australia**
by K. Grey, R. M. Hocking, M. K. Stevens, L. Bagas, G. M. Carlsen, F. Irimies, F. Pirajno, P. W. Haines, and S. N. Apak

95 **East Yilgarn 1:100 000 Geological Information Series — an explanatory note**
by P. B. Groenewald and A. Riganti

96 **Mineral occurrences and exploration potential of the Earaheedy area, Western Australia**
by P. B. Abeysinghe

98 **Seismic mapping, salt deformation, and hydrocarbon potential of the central western Officer Basin, Western Australia**
by A. P. Simeonova and R. P. Iasky

99 **Mesoproterozoic sill complexes in the Bangemall Supergroup, Western Australia: geology, geochemistry, and mineralization potential**
by P. A. Morris and F. Pirajno

100 **Geology, geophysics, and hydrocarbon potential of the Waigen area, Officer Basin, Western Australia**
by C. D'Ercole, F. Irimies, A. M. Lockwood, and R. M. Hocking

Records

2004/1 **Geological Survey work program for 2004–05 and beyond**

2004/6 **Mineralization of the Woolgangie–Yilmia region, Eastern Goldfields Granite–Greenstone Terrane, Western Australia**
by F. I. Roberts

2004/16 **Gold and nickel deposits in the Archaean Norseman–Wiluna greenstone belt, Yilgarn Craton, Western Australia — a field guide**
by P. Neumayr, M. Harris, and S. W. Beresford

2004/17 **Major mineral deposits of southwestern Western Australia — a field guide**
by M. J. Freeman and M. J. Donaldson

2004/18 **Archaean and Proterozoic geology of the southeastern margin of the Yilgarn Craton — a field guide**
by S. A. Jones and C. E. Hall

2004/21 **Industrial minerals in Western Australia: the situation in 2004**
by J. M. Fetherston and S. M. Searston

2005/3 **Nickel–cobalt in Western Australia: commodity review for 2003**
by D. J. Flint, S. Searston, R. W. Cooper, and P. B. Abeysinghe

2005/4 **GSWA Lancer 1 well completion report (interpretive papers), Officer and Gunbarrel Basins, Western Australia**
edited by A. J. Mory and P. W. Haines

2005/5 **GSWA 2005 extended abstracts: promoting the prospectivity of Western Australia**

2005/7 **Regolith–landform mapping and hyperspectral data for the Kalgoorlie–Kanowna area**
by M. S. Skwarnecki

2005/9 **Geology of the northern Perth Basin, Western Australia — a field guide**
by A. J. Mory, D. W. Haig, S. McLoughlin, and R. M. Hocking

2005/10 **A classification system for regolith in Western Australia — an update**
by R. M. Hocking, R. L. Langford, A. M. Thorne, A. J. Sanders, P. A. Morris, C. A. Strong, J. R. Gozzard, and A. Riganti

Explanatory Notes

1:100 000 Geological Series

Geology of the Lamil 1:100 000 sheet, by L. Bagas
Geology of the Yardilla 1:100 000 sheet, by S. A. Jones
Geology of the Atley, Rays Rocks, and southern Sandstone 1:100 000 sheets, by S. F. Chen
Geology of the Nullagine 1:100 000 sheet, by L. Bagas
Geology of the Maroonah, Ullawarra, Capricorn, Mangaroon, Edmund, and Elliott Creek 1:100 000 sheets, by D. McB. Martin, S. Sheppard, and A. M. Thorne

Miscellaneous books

GSWA Annual Review 2003–04
Overview of mineral exploration in Western Australia for 2003–04
by D. J. Flint
Fieldnotes v. 32, 33, 34, 35
Summary of petroleum prospectivity, Western Australia 2005: Bonaparte, Bight, Canning, Officer, Perth, Northern Carnarvon, and Southern Carnarvon Basins
Catalogue of geoscience products 1980–2004 (July 2004)
Catalogue of geoscience products 1980–2005 (May 2005)

Digital products

Atlas of 1:250 000 geological map sheet images, Western Australia (January 2005 update)

Compilation of geochronology data (October 2004 update)

Compilation of geochronology data (June 2005 update)

East Yilgarn (1:100 000 Geological Information Series, June 2005 update)

Gold mineralization in the Edjudina–Kanowna region, Eastern Goldfields, Western Australia (Report 90)

GSWA 2005 CD

GSWA Lancer 1 well completion report (interpretive papers), Officer and Gunbarrel Basins, Western Australia (Record 2005/4)

Inventory of abandoned mine sites: progress 1999–2004 (update)

Mineral and petroleum explorers' guide — CD

Mineral occurrences and exploration potential of the Earaheedy area (Report 96)

Mineral occurrences and exploration potential of the east Pilbara — 2005 update

Mineralization of the Woolgangie–Yilmia area, Eastern Goldfields Granite–Greenstone Terrane, Western Australia (Record 2004/6)

Murchison Geological Exploration Package (Record 2004/19)

Northeastern Yilgarn Geological Exploration Package (Record 2005/8)

Petroleum explorers' guide (June 2005) — CD

Regolith–landform mapping and hyperspectral data for the Kalgoorlie–Kanowna region (Record 2005/7)

Southeastern Yilgarn Geological Exploration Package (Record 2005/2)

Western Australian Petroleum Acreage Release, April 2005

Western Australian Petroleum Acreage Release, September 2004

Western Capricorn Orogen (1:100 000 Geological Information Series, December 2004 update)

Western Tanami Geological Exploration Package (Record 2005/6)

Major planned achievements for 2005–06

GSWA will continue to pursue a project-based program of work and maintain a vigorous level of output to match funding received. In 2005–06, GSWA's budget will include the first component of A$12 million funding over four years from the State Government to double the area of the State covered by high-tech aerial geophysical surveys. The survey aims to address the decline in Western Australia's market share of world exploration expenditure through collection of this data. The priority areas for the surveys are the Murchison–Gascoyne region and the eastern Wheatbelt (highly prospective for nickel and gold); the Esperance to Warburton area (potential base metal and nickel deposits); the Musgrave–Arunta region (base metals, nickel and gold); and the Kimberley (nickel, base metals, and diamond). Expenditure planned for 2005–06 is A$3 million.

Planned achievements for 2005–06 include:

- release of 44 geological maps at various scales;
- publication of 37 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of 22 digital data packages;
- release of 560 000 line-km of airborne geophysical data.

The balance of product types within the planned achievements listed above may change during the course of the year as internal priorities change and the allocation of resources to reflect those priorities takes effect.

GSWA has also secured a three-year A$1.2 million commitment from the State Government to release more than 20 000 confidential geological reports submitted by mineral exploration companies over many years. Expenditure planned for 2005–06 is A$400 000, sufficient to release up to 7000 reports.

External publications by GSWA staff 2004–05

The following lists papers published by GSWA staff in external journals during the year.

Note: GSWA authors in italics

ALLWOOD, A., WALTER, M., *VAN KRANENDONK, M.*, and KAMBER, B., 2005, Life on a trangressive rocky shoreline and carbonate platform: 3.43 Ga Strelley Pool Chert, Pilbara Craton, Western Australia: European Geosciences Union, General Assembly 2005, Vienna, Austria, April 2005; Geophysical Research Abstracts, v. 7, 3p (paper EGU05-A-00548).

BILKI, F. P., and *FREEMAN, M. J.*, 2005, Shoemaker Impact Structure and three other impact features of Western Australia. A Field Guide: Perth, W.A., Perth Observatory Volunteer Group and Perth Observatory, 43p.

BLEWETT, R. S., *SHEVCHENKO, S.*, and BELL, B., 2004, The North Pole Dome: a non-diapiric dome in the Archaean Pilbara Craton, Western Australia: Precambrian Research. v. 133, p. 105–120.

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CARLSEN, G. M., and *GHORI, K. A. R.*, 2005, Canning Basin and global Palaeozoic petroleum systems — A review: APPEA Journal, v. 45, p. 349–364

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CHEN, S. F., LIBBY, J. W., *WYCHE, S.*, and *RIGANTI, A.*, 2004, Kinematic nature and origin of region-scale ductile shear zones in the central Yilgarn Craton, Western Australia: Tectonophysics, v. 394, p. 139–153.

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List of acronyms and abbreviations

AAPG	American Association of Petroleum Geologists
ABS	Australian Bureau of Statistics
AGSO	Australian Geological Survey Organisation, now Geoscience Australia
AIG	Australian Institute of Geoscientists
AMEC	Association of Mining and Exploration Companies (Inc.)
AMIRA	Australian Mineral Industries Research Association Limited
ANU	Australian National University
APPEA	Australian Petroleum Production and Exploration Association Limited
ASEG	Australian Society of Exploration Geophysicists
ASX	Australian Stock Exchange
AusIMM	Australasian Institute of Mining and Metallurgy
AVIMS	ArcView Internet Map Server
BHPB	BHP Billiton Limited
BMR	Bureau of Mineral Resources, now Geoscience Australia
BRGM	Bureau de recherches géologiques et minières
CALM	Department of Conservation and Land Management
CIAT	Centro Internacional de Agricultura Tropical
CME	Chamber of Minerals & Energy of Western Australia Inc.
CRC LEME	Cooperative Research Centre for Landscape Evolution and Mineral Exploration
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSIRO-AGE	CSIRO-Australian Geochemical Exploration joint venture
DLI	Department of Land Information
DoIR	Department of Industry and Resources, formerly MPR
ESA	European Space Agency
EXACT	Western Australian mineral exploration activities database
GA	Geoscience Australia, formerly Australian Geological Survey Organisation
GeoVIEW.WA[†]	GSWA's integrated geoscience information system
GeoVIEWER.WA[†]	GSWA's CD- and DVD-based visualization, query, and integration tool
GIS	Geographic Information System
GPS	Global Positioning System
GSA	Geological Society of Australia
GSLC	Geological Survey Liaison Committee
GSWA	Geological Survey of Western Australia
JORC	Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists, and Minerals Council of Australia
Landsat TM	Landsat Thematic Mapper
MAGIX	Mineral Airborne Geophysics Information eXchange
MERIWA	Minerals and Energy Research Institute of Western Australia
MINEDEX	DoIR's mines and mineral deposits information database
MCMPR	Ministerial Council for Mineral and Petroleum Resources
MPR	Department of Mineral and Petroleum Resources, now DoIR
NASA	National Aeronautics and Space Administration
NGA	National Geoscience Agreement

PDAC	Prospectors and Developers Association of Canada
PESA	Petroleum Exploration Society of Australia
pmd*CRC	Predictive Mineral Discovery Cooperative Research Centre
REGOCHEM	GSWA's regolith and geochemistry database
SGTSG	Specialist Group on Tectonics and Structural Geology of Geological Society of Australia
SHRIMP	Sensitive high-resolution ion microprobe
SLIP	Shared Land Information Platform in Western Australia
SRTM	Shuttle Radar Topography Mission
STRATWA	GSWA's geological units database for Western Australia
TENGRAPH†	DoIR's electronic tenement-graphics system
UWA	University of Western Australia
WABMINES	Western Australia's abandoned mine sites database
WACHEM	Western Australian inorganic geochemistry database
WACHRON	Western Australian geochronology database
WAMEX†	Western Australian mineral exploration database
WAMIN	Western Australian mineral occurrence database
WAPEX†	Western Australian petroleum exploration database
WAPIMS	Western Australian petroleum information management system database
WAREG	Western Australian regolith observation database
WAROX	Western Australian field observation database
WASM	Western Australian School of Mines

NOTE: † GeoVIEW.WA, GeoVIEWER.WA, WAMEX,1 WAPEX, and TENGRAPH are registered Trademarks of DoIR

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