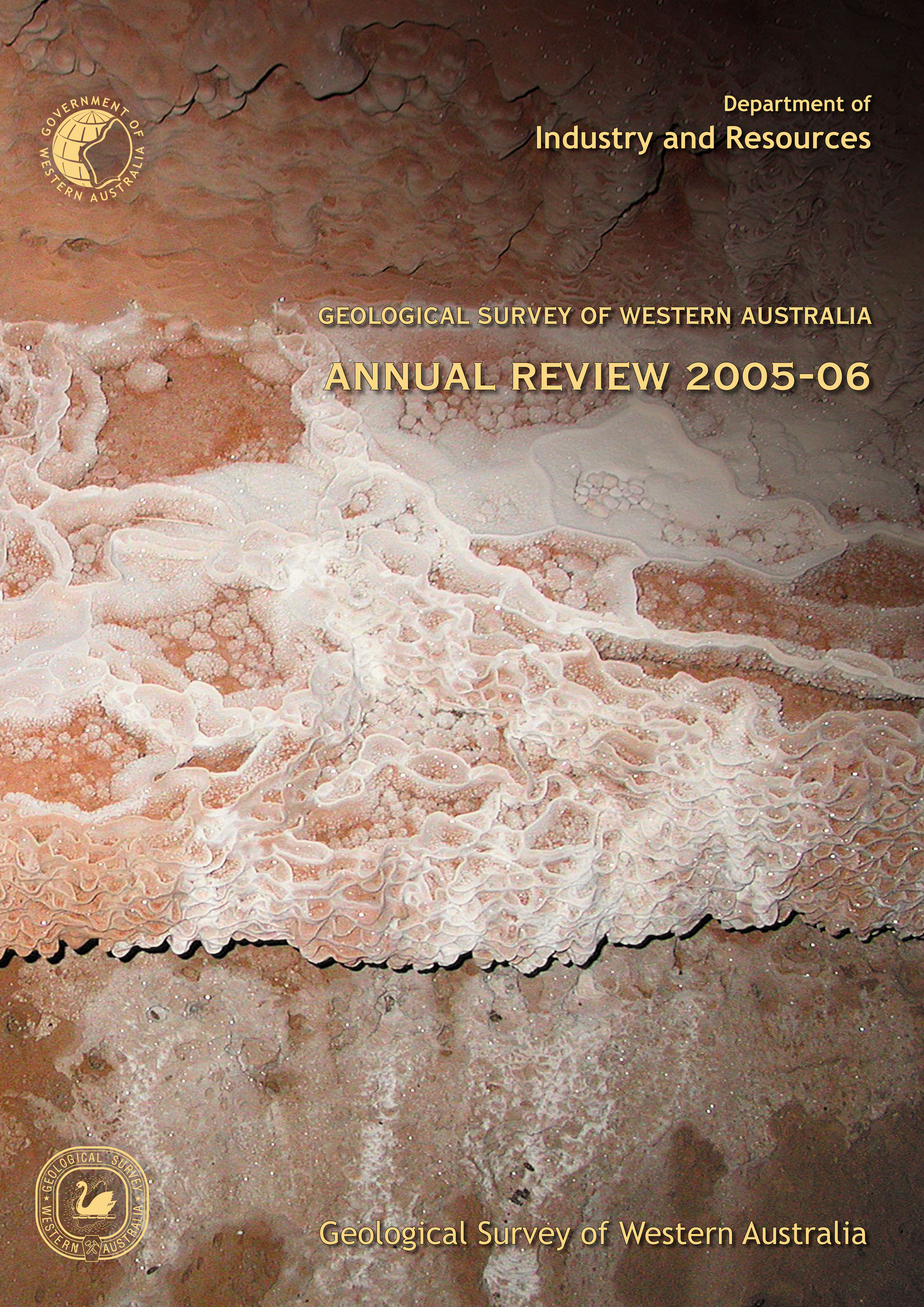

Department of
Industry and Resources

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 2005-06

Geological Survey of Western Australia

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Cover:
Rimmed terraces with cave pearls, Mimbi Caves, West Kimberley

Frontispiece:
These Bradshaw or 'Gwion Gwion' figures from the Lawley River area are among the oldest art traditions in the Kimberley and may be over 17 000 years old. They have been painted by Aboriginal people on King Leopold Sandstone with pigments that appear to be mainly iron oxides (hematite, goethite, and limonite). So far no datable material has been identified in the few art pigments investigated, and the age of rock art in the Kimberley remains poorly constrained.

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-enhancing, 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 landuse 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 landuse 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, palaeontology, 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.

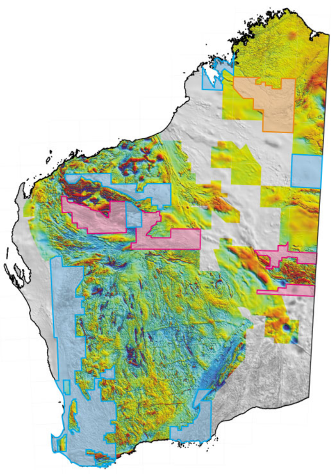
The year in review

by Tim Griffin, Executive Director

The strength of the resources industry during 2005–06 is shown by the dramatic increase in capital expenditure on mineral and petroleum extraction projects in Australia, up 76% on the previous year to $18.1 billion. Western Australia accounted for 56% of this expenditure, and the State's total of $10.2 billion in new capital expenditure on mining was up 84% on 2004–05. Commodity prices continued to rise on the back of strong demand, particularly for zinc (prices up over 70% on 2004–05), copper (up 55%), iron ore (up 45%), oil (up over 30%), and gold (up over 20%).

However, these higher prices did not translate into an increase in mineral exploration activity in Western Australia, where there was actually a 3% drop in expenditure, although there was a modest increase in mineral exploration expenditure for Australia as a whole. Petroleum exploration expenditure in Western Australia did show an increase of 3% to $594 million, compared with the country's increase of 15% to $1262 million. In 2005–06 Western Australia had about 47% of the national petroleum exploration budget, down slightly from the previous year. More needs to be done to attract increased exploration to the State if the future of the resources industry is to be sustained.

Pre-competitive geoscience funding



The $3 million per annum additional funding provided to GSWA by the State Government in 2004 for acquisition of new pre-competitive geoscience information has again provided a 'shot in the arm' for greenfields exploration in 2005–06. This funding allowed 528 000 line-km of airborne magnetic and radiometric surveys to be carried out, in collaboration with Geoscience Australia, covering some 145 000 km^2 in the Paterson, Gascoyne, and east Yilgarn regions. With company data purchased adjacent to the new surveys, some 250 000 km^2 of new magnetic/radiometric data was made available to explorers during the year, initially as preliminary enhanced compressed wavelet (ECW) images downloadable from the GSWA website and later as final point-located and gridded data from the Geophysical Archive Data Delivery System (GADDS) on Geoscience Australia's website. The interest generated by these surveys is evidenced by increased tenement applications over the areas covered immediately following the release of images and data.

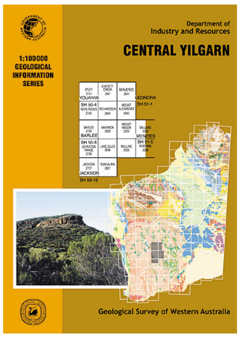
Also made possible with the additional funding and in collaboration with Geoscience Australia was a detailed regional gravity survey of the Paterson area surrounding the Telfer (gold), Nifty (copper), and Kintyre (uranium) deposits, and a seismic traverse across the Tanami Complex. The helicopter-assisted but ground-based Paterson gravity survey covered 20 000 km^2 with 4544 readings at a nominal 2.5 km spacing. The Martu Aboriginal people were consulted prior to the survey and at their request several culturally sensitive areas were excised from the area to be covered. Industry's enthusiasm for such detailed regional gravity surveys has encouraged planning for further surveys in coming years.

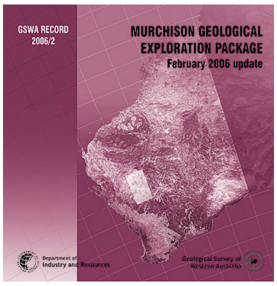
The 102 km-long Tanami seismic line passed close to the Coyote gold deposit and provides important information about the nature and attitude of major crustal structures that may be important in localizing gold mineralization in this exciting greenfields gold province.

GSWA publications

During 2005–06 GSWA published:

- 26 geoscience maps including 6 geological maps at 1:100 000 scale
- 24 Records, Reports, and other publications
- 18 digital information products.





The emphasis continues to be on digital products in response to requests from industry through the industry bodies APPEA, AMEC, and the Chamber of Minerals and Energy, and the Geological Survey Liaison Committee. GSWA's policy of releasing, prior to new mapping being undertaken, all available data on DVD as **Geological Exploration Packages** has proved very popular, and the year saw updated releases for the Northeastern Goldfields and the Murchison regions. New geological maps at 1:100 000 scale were released with large amounts of supporting information in GIS format as part of the **Geological Information Series** for the west Musgrave, central Yilgarn, and southern Pilbara areas. This series of seamless geoscience maps comprising geology, geophysics, satellite imagery, and associated sample and observational data has rapidly become the standard format for presentation of these multi-layer datasets, usable in common GIS software packages or with GSWA's GeoVIEWER.WA software that is provided with the information package. Conventional paper plotted maps for these areas are available on-line or from the Information Centre at Mineral House, Perth.

Geochronology

Geochronology continues to be an important activity for GSWA and an expanded capacity for SHRIMP and other dating techniques in 2005–06 enabled more rocks critical to the mapping program to be dated. Geochronology coverage of the State is summarized in the **Compilation of Geochronology June 2006 update**, which has data for 654 GSWA samples as well as 1162 samples from Geoscience Australia's Ozchron database. The GeoVIEWER.WA software developed by GSWA to view data in GIS format allows queries on many aspects including rock type, stratigraphic unit, or age range, with results plotted on screen with State 1:500 000- or 1:2 500 000-scale geology. Improved graphs help in visualizing results and interpretation of these complex data.

New mapping process

A new approach to GSWA's mapping processes was introduced during the year to take advantage of new technologies, speed up field mapping programs, and shorten the time it takes to deliver the final digital and paper maps. The new process involves desktop production of an interpreted bedrock geology map using all available information such as aeromagnetics, radiometrics, existing 1:250 000-scale geology, and company exploration data prior to any new fieldwork. At the same time, regolith-terrain maps are produced from satellite images, orthophotography, and digital elevation models. The field geologist can then target new mapping and concentrate on the regolith and bedrock geological features identified as most likely to provide new insight into the geology and mineralization potential. Field data is collected digitally and is readily transferred to corporate databases for incorporation into the final digital geological map. This can be released with all associated data such as structural measurements, field photos, petrographic descriptions, and any geochemical or geochronological information, in a multi-layered GIS format. The first products using the new process will be released in 2006–07.

Web delivery of products and reports

GSWA's implementation of DigitalPaper XE now includes the ability to view online, print, or download without charge almost all GSWA products released since 1895, including maps, Reports and Bulletins. The same facility enables viewing and downloading of open-file company mineral exploration (WAMEX) reports and at the end of 2006 almost 30 000 reports were available for viewing by this facility, including the first reports released under the sunset clause provisions of the Mining Act.

The data download centre on the GSWA website now has 1:100 000 and 1:250 000 geological maps as vector files for downloading as ArcMap or MapInfo formats. Free training sessions for users of our online systems were implemented in 2006

Access to Aboriginal lands

Geological mapping on Aboriginal reserve lands or Native Title determined areas is extending modern 1:100 000-scale mapping into greenfields areas of Western Australia in the west Musgrave region at Blackstone–Wingellina (Papulankutja–Irrunytju), Cosmo Newbery in the northeastern Goldfields, and Tjurabalan lands in the Tanami. GSWA has agreements with traditional owners and the Ngaanyatjarra Council regarding access to Ngaanyatjarra lands and employs local people to help in the mapping fieldwork. An agreement is also being discussed with the Kimberley Land Council and the Tjurabalan people regarding ongoing access to sensitive areas of the Tanami.

Petroleum systems studies

The Petroleum Systems group finalized studies of the Officer Basin during 2005–06 and turned its attention to the underexplored Canning Basin. Planned work includes reappraisal of existing seismic records and exploration drillholes to provide industry with pre-interpretive workstation-ready data packages as well as field-based studies focusing on the sedimentology through the Ordovician and Permian–Carboniferous sequences. Regional petroleum geochemical studies are also underway to refine the prospectivity of the basin. This comes at a time when there is renewed interest from both international and local petroleum explorers in the hydrocarbon potential of the Canning Basin.

The petroleum exploration information database (WAPIMS) continued to improve access to exploration data with a total of 342 Gb of data now available online. The transcription of valuable historic seismic data to modern media continued to ensure availability, with 60% of the archive now completed. Discrete data packages are now being produced for release starting in the second quarter of 2007, and these packages will be updated on an annual basis.

Geological field excursions

In 2005–06, GSWA staff participated in field excursions to the Proterozoic Albany–Fraser Orogen, the Archean Kurnalpi Terrane, and the Devonian reefs of the Kimberley. Field guides were published by GSWA for the Albany–Fraser Orogen and Kurnalpi Terrane excursions.

The Albany–Fraser excursion was organized by the Tectonics Special Research Centre and the Geological Society of Australia as part of the Supercontinents and Earth Evolution Symposium that marked the end of the Tectonics Special Research Centre.

The Kurnalpi Terrane excursion was held in conjunction with the Australian Institute of Geoscientists' 'Outcrop to Orebody' symposium held in Kalgoorlie in May 2006. The excursion visited key outcrops on the recently mapped MINERIE 1:100 000 sheet, including felsic volcanics of the Welcome Well Formation and ultramafic rocks of the Murrin Murrin Formation, as well as the Sunrise gold deposit.

The Devonian reefs field trip showed oil industry geoscientists the well-preserved aspects of the fossil reef system that has been the subject of detailed research by GSWA over many years. This research is summarized in GSWA Bulletin 145, which will be completed in 2007.

Promotional events

As part of its role in promoting the prospectivity of Western Australia and attracting exploration investment in the State, GSWA has targeted the major international mineral-exploration promotional events of the Prospectors and Developers Association of Canada (PDAC), China Mining, and a meeting with the Japan Oil Gas and Metals National Corporation (JOGMEC), as well as the NAPE petroleum exposition in Houston, USA. In addition, GSWA had promotional booths at major mineral and petroleum exploration conferences within Australia, including the RIU Explorers Conference in Fremantle, Mining 2005 in Brisbane, Diggers and Dealers in Kalgoorlie, the AIG Symposium in Kalgoorlie, the AMEC Conference in Perth, and the APPEA Conference on the Gold Coast.

The future

Strong demand and prices for many of the mineral and petroleum products important to Western Australia's resources industry look set to continue for at least the next few years. However, the resources that are currently being exploited or will be coming into production in the next year or so were largely discovered many years ago. It is critical to the sustainability of these industries that new deposits are discovered soon, as the lead time in bringing major new mines, oil- or gasfields, and associated downstream-processing facilities into production can be ten years or more. Although exploration expenditure in Western Australia increased slightly in the September 2006 quarter, it actually declined over the 2005–06 year despite the record value of production and royalties in the State during that time. Western Australia's share of Australian and world exploration expenditure continues to fall, and this trend must be reversed if the industry is to be sustained at or near current levels into the future.

The Geological Survey of Western Australia is charged with attracting mineral and petroleum exploration investment to the State. To make Western Australia the preferred destination for explorers, be they local, interstate or multi-national organizations, we need to improve the perception of prospectivity, land access, and government support for the industry within the State. We also need to compete favourably with other jurisdictions in these areas, and in this regard increased coverage of quality geological, geophysical, and geochemical data is seen as a major incentive for explorers. This can only be achieved with substantial additional funding for GSWA, and this is being sought within Government. A formal review of the Geological Survey will be undertaken by external consultants in 2007, with appropriate funding levels being included in the terms of reference.

With mineral and petroleum production at a record $43.2 billion and royalties totalling $2.09 billion in 2005–06, this would appear to be an opportune time to seriously address this issue.

Overview of mineral exploration in Western Australia for 2005–06

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

Overview

Notable highlights and trends for the industry during 2005–06, including some that are not encouraging for Western Australia, were as follows:

- Major greenfields gold exploration discovery at Tropicana, 220 km southeast of Laverton;
- A new gold mine was opened in the Pilbara region at Indee, and another gold mining operation is planned near Nullagine in early 2007;
- Spectacular gold intersections at Bright Star (30 km southeast of Laverton), Blue Spec near Nullagine, and at Wiluna;
- Renewed interest in the Spinifex Ridge molybdenum–copper project, with a bankable feasibility study progressing;
- Southdown, Karara, and Mount Gibson iron ore projects lead the way in the race to be the State's first iron-ore mine with a magnetite product;
- The Heron Resources Ltd and Inco Ltd joint venture has successfully completed Step 1 of the Kalgoorlie laterite nickel project and will continue to Step 2, and plans to produce about 50 000 tpa of contained nickel from the project by 2011;
- Australian mineral exploration expenditure in 2005–06 increased by 20.6%, but Western Australia experienced a 2.6% decrease over the same period;
- The worldwide non-ferrous mineral exploration expenditure increased by an estimated 35% (for calendar year 2005, Metals Exploration Group, Canada);
- During the last decade, Western Australia's share of global non-ferrous mineral exploration expenditure has fallen from 10 to 4% of the total. Australia (as a whole) is also losing market share, with its proportion falling from 17 to 13% over the same period;
- Western Australia's share of the national exploration expenditure for minerals (excluding petroleum) fell sharply from 59% in 2004–05 to 48% in 2005–06, the lowest level for at least 20 years;
- Western Australia continues to experience an unprecedented mineral-production boom, with value of production up by 33% in 2005–06;
- We surmise that the mining and exploration industries are so focused on ensuring that the numerous, large development projects are successful

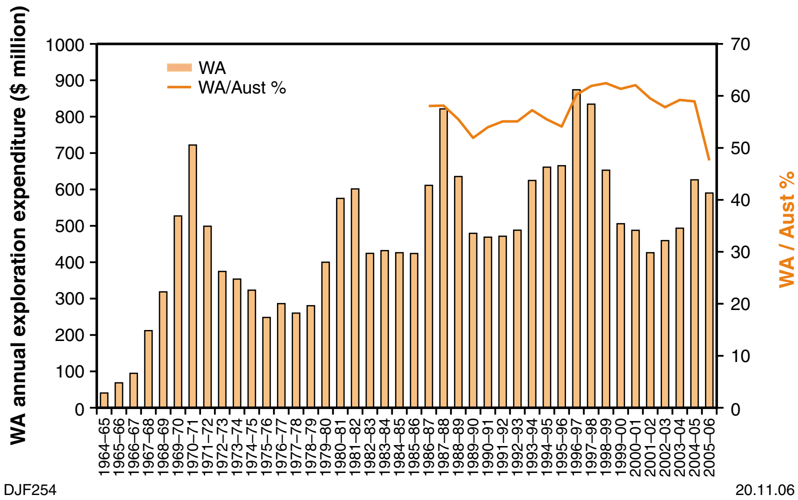


Figure 1. Mineral exploration expenditure in Western Australia, by financial year (2005–06 dollars)

that exploration activity is not being supported by mining companies as strongly as expected for the long-term benefit of the industry and Australia's economy.

Australian mineral exploration expenditure* rose by 20.6% ($212 million) from $1028.3 million in 2004–05 to $1240.4 million in 2005–06 (2005–06 dollar terms). During 2005–06, mineral exploration expenditure in Western Australia fell by 5.6% from $625.4 million to $590.2 million, well below the peak of $874 million in 1996–97 (in 2005–06 dollar terms; Fig. 1).

Despite the commodity boom, Western Australia's share of the national spend on mineral exploration fell sharply during 2005–06, from 59% (2004–05) to 48%, its worst level for at least twenty years (Fig. 1). Quarterly mineral exploration data also highlights this diverging trend in mineral exploration between Western Australia and the rest of Australia (Fig. 2). Despite this, Western Australia still accounts for the major proportion of exploration dollars expended in Australia for major commodities such as iron ore (97%), nickel–cobalt (79%), diamond (49%), gold (60%), heavy mineral sands (44%), silver–lead–zinc (20%), and copper (7%).

Recent mineral exploration expenditure in Australia and Western Australia has not kept pace with the boom in worldwide exploration expenditure, and Australia and Western Australia have again both lost market share in the expanded pool of exploration capital (Fig. 3; based 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 17 to 13% of the total, whereas that for Western Australia has dropped from 10 to 4% of the total. In stark contrast, the proportion of worldwide mineral exploration expenditure spent in Canada recovered strongly after 1997, whereas the proportion has continued to fall in Australia and Western Australia (Fig. 3). The buoyant situation in Canada reflects a combination of high-profile discoveries, ongoing exploration success, and favourable and innovative government regimes (including fiscal incentives to exploration).

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

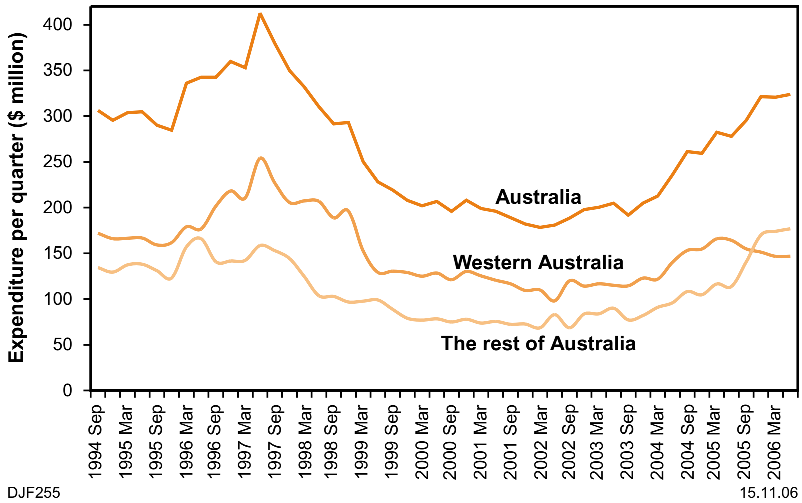


Figure 2. Mineral exploration expenditure, by quarter and on seasonally adjusted terms, for Western Australia versus the rest of Australia (2005–06 dollars)

Developments and mineral exploration highlights by commodity

Only iron ore and copper–lead– zinc–silver attracted increased exploration expenditure in Western Australia during 2005–06, with decreased exploration expenditure for gold, nickel–cobalt, and diamond. Iron ore expenditure has set a new record of $149.7 million in 2005–06. Expenditure on nickel exploration has declined in 2005–06 from an apparent peak in 2004–05.

Gold

Trends in the gold industry in Western Australia during 2005–06 included:

- A 3.6% fall in gold production to an output of 161 t;
- A 10% decline in gold exploration expenditure, continuing an eight-year-old trend;
- The international gold price rose to 20-year highs, reaching US$610 in April 2006;

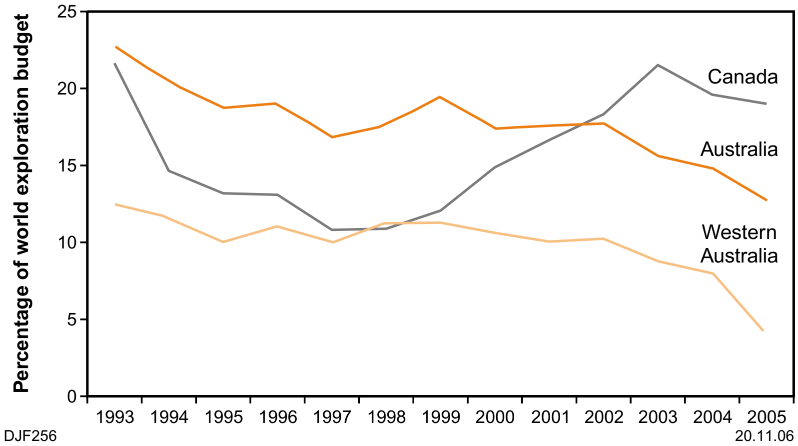


Figure 3. Non-ferrous mineral exploration expenditure — comparative market share of Canada, Australia, and Western Australia since 1993. Source: Metals Economics Group (Canada), ABS, and DoIR

- Investor interest in Western Australia for gold remained very subdued;
- The world-class Telfer Au–Cu mine ramped up to near-full production capacity, while the go-ahead for developing the Boddington Au–Cu mine was announced;
- The major greenfields gold exploration discovery at Tropicana*.

Although gold exploration has been the backbone of the mineral exploration industry in Western Australia for many years, during the last ten years it has undoubtedly lost its shine — gold exploration expenditure was around 75% of the total mineral exploration expenditure in the mid-1990s, but has declined to only 40% during 2005–06 (Fig. 4). During 2005–06,

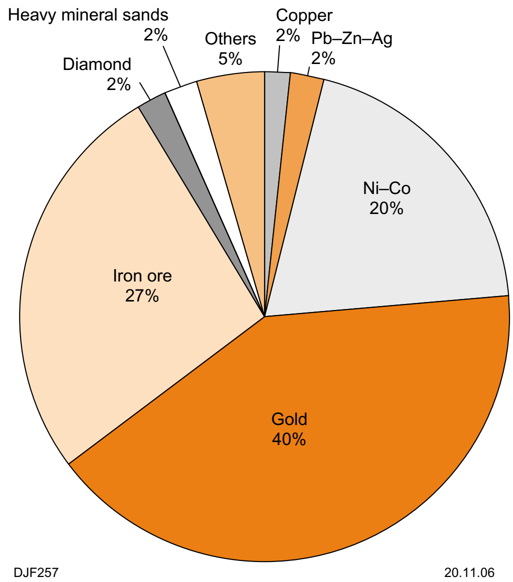


Figure 4. Mineral exploration expenditure in Western Australia, by commodity (2005–06 dollars)

$240.3 million was expended on gold exploration in Western Australia, which is a decrease of 10% ($27.6 million) from the $267.9 million spent in 2004–05 (Fig. 5). The exploration expenditure is now 35% below its peak levels experienced eight years ago during 1996–97, and is at a level last experienced more than twenty years ago. A considerable amount of exploration focused on converting near-mine mineral resources into ore reserves, thus diverting the focus from programs for discovering new deposits in greenfields areas. An inadequate level of greenfields mineral exploration is of ongoing concern for the future of gold mining in this State. The decline of gold exploration expenditure in Western Australia is also reflected in gold production, both of which have continuously declined over the last 8 years (Fig. 6).

Despite this, important gold discoveries are still being made in Western Australia, but few have been sufficiently spectacular to excite international

* 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 sees the relevant company websites, or DoIR's online databases (MINEDEX or GeoVIEWER.WA) at www.doir.wa.gov.au, or Cooper and Flint (2005).

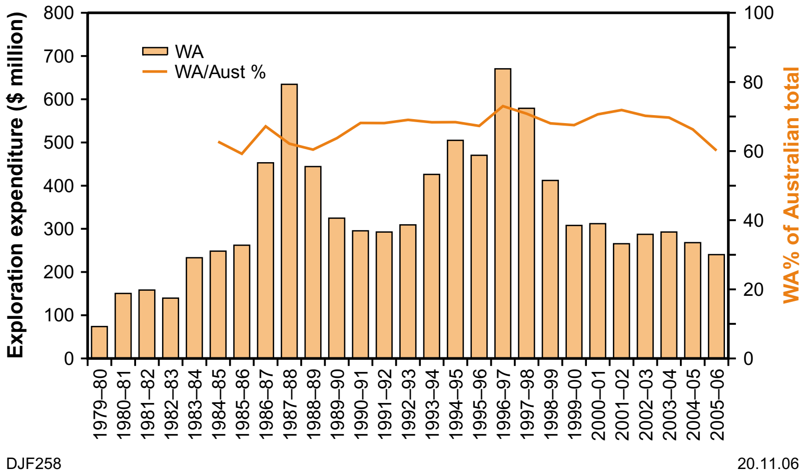


Figure 5. ***Gold exploration expenditure in Western Australia, by financial year (2005–06 dollars)***

attention. The most newsworthy was the greenfields discovery by the Independence Group NL and AngloGold Ltd joint venture at Tropicana (220 km east of Laverton and apparently in rocks of the Albany–Fraser Orogen), which has potential to host gold deposits containing more than 1 Moz of gold. This is the best gold discovery in Western Australia since the discovery of Thunderbox about seven years ago. The gold intersections at Tropicana include 42 m at 3.3 g/t Au and 32 m at 6.6 g/t Au. Within 15 km of Tropicana, other new prospects have been discovered at Rusty Nail, Kamikaze, Black Feather, and Havana.

Elsewhere in Western Australia spectacular gold intercepts were obtained at Brightstar (22 m at 28.6 g/t Au) southeast of Laverton by A1 Minerals Ltd, at Blue Spec near Nullagine (3 m at 37 g/t Au) by Northwest Resources Ltd, and at Wiluna (18 m at 10.42 g/t Au) by Agincourt Resources Ltd.

At Trident (south of Kambalda), Avoca Resources Ltd has an estimated resource of 4.3 Mt at 6.2 g/t gold for 855 000 ounces of contained gold,

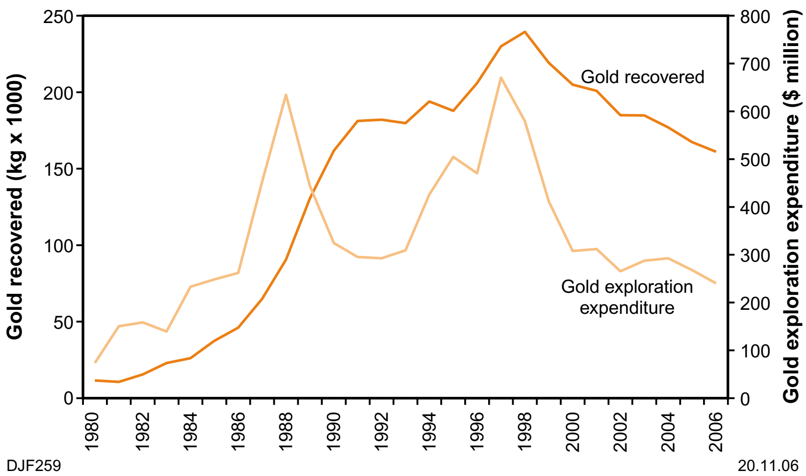


Figure 6. ***Gold exploration expenditure and production in Western Australia (years ending 30 June; 2005–06 dollars)***

with plans in place to commence gold production. At Golden Eagle prospect near Nullagine, further high-grade gold intersections were reported by Wedgetail Exploration NL from the Falcon and Condor prospects. Wedgetail plans to start a mining operation in early 2007 with an output of 70 000 ounces of gold per year. At Burbanks near Coolgardie, Barra Resources Ltd reported more exploration success (Wahloo Shoot: 6.8 m at 33.2 g/t Au, 11.9 m at 4.9 g/t Au, and 9.5 m at 3 g/t Au).

Development highlights for gold in Western Australia have been dominated by the decision by Newmont Mining Corporation and AngloGold Ashanti Ltd to reopen the Boddington gold–copper mine, 110 km southeast of Perth, in the Yilgarn Craton. Initial gold–copper production from Boddington is expected in late 2008. Total resources of contained gold at Boddington are estimated at 19.7 Moz and that of contained copper at 790 kt. The average annual production will be in excess of 800 000 oz of gold and 30 000 t of copper.

Gold mines opened in the State during 2005–06 include the following: Tanami–Coyote (572 000 oz of contained gold) 280 km southeast of Halls Creek by Tanami Gold NL; Indee (529 000 oz of contained gold) south of Port Hedland by Range River Gold Ltd; Comet Vale – Sand Queen (136 000 oz of contained gold) south of Menzies by Reed Resources Ltd and Kingsrose Pty Ltd; and Burbanks (74 000 oz of contained gold) near Coolgardie by Barra Resources Ltd.

Iron Highlights in Western Australia during 2005–06 included:

- Unprecedented price increases meant that although Western Australian iron ore production increased by only 5% in quantity, it jumped by a remarkable 63% in value;
- Western Australian iron-ore exploration expenditure was at the highest level ever recorded (A$156 million), representing 27% of the State's total (Figs 4 and 7);
- Numerous mines targeting zones of supergene enrichment were being developed or at an advanced feasibility stage, and the State moved significantly closer to its first iron ore mine with a magnetite product;
- Overseas companies greatly increased their direct ownership or involvement (e.g. through long-term off-take agreements) in the Western Australian iron ore industry.

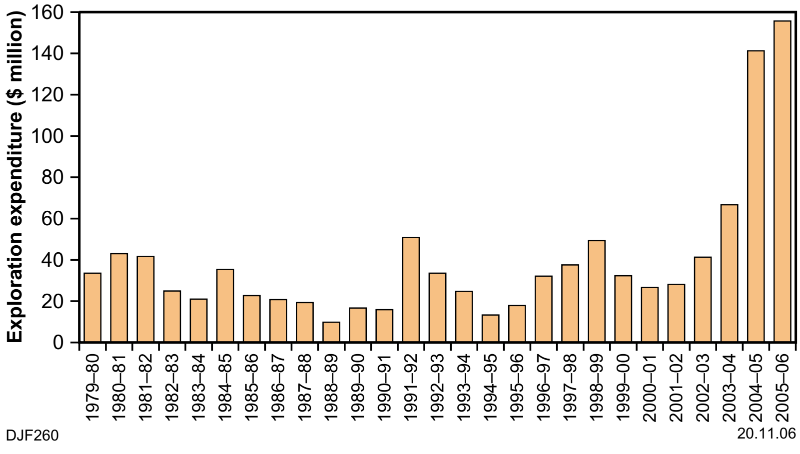


Figure 7. Iron ore exploration expenditure in Western Australia, by financial year (2005–06 dollars)

The unprecedented iron ore boom during the past two years was driven by extremely strong customer demand for iron ore, particularly from China, concomitant with a worldwide supply shortage. The production of iron ore in 2005–06 was 244 Mt (valued at A$13 billion), which is an increase of 5% (11 Mt) compared with 2004–05 production of 233 Mt (valued at A$8 billion), whereas the value of production increased by 63%. The major producers in the Pilbara region are responding rapidly by expanding their operations at existing projects and planning new projects. The high iron-ore prices have greatly assisted the capital raisings of junior companies, opened up the industry to juniors, and diminished the duopoly of Rio Tinto and BHP Billiton. New iron ore mines that were under development during 2005–06 were Koolanooka, Jack Hills, Koolan Island, and Christmas Creek — Cloud Break. Numerous iron ore projects were at the feasibility stage, with Southdown (Grange Resources Ltd), Karara (Gindalbie Metals Ltd), and Mount Gibson (Asia Iron Holdings Ltd and Shougang Group) leading the way in the race (at the moment) to be the State's first iron-ore mine with a magnetite product.

At present over 80 companies are exploring for iron ore in Western Australia, with significant and diverse direct-equity investment by Chinese, Korean, and Japanese companies, which seek to ensure supplies at lower than current prices.

Iron ore exploration targeted several mineralization styles including: channel iron deposits; supergene-enriched hematite over Archean (Marra Mamba) to Paleoproterozoic (Brockman) banded iron-formations (BIF); primary magnetite in BIF of the Pilbara and Yilgarn Cratons; magnetite in BIF within Mesoproterozoic gneiss terrane of the Albany–Fraser Orogen; clastic hematite in Paleoproterozoic–Mesoproterozoic sedimentary rocks of the Kimberley Basin (Cockatoo Island, Koolan Island) and the Carr Boyd Basin (Pompeys Pillar); and hematite in granular iron within the Frere Formation in the Paleoproterozoic Earaheedy Basin (Giralia Resources NL). There was ongoing 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).

Nickel

Highlights in Western Australia during 2005–06 included:

- The international price rose to 18-year highs, reaching US$20 754 per tonne in April 2006;
- Nickel production in Western Australia increased by 6% to 191 kt of contained nickel;
- Nickel exploration expenditure in Western Australia fell by 25%; primarily due to completion of the feasibility study of the Ravensthorpe laterite project, with the project now under development. The planned production rate is about 50 000 t of contained nickel.

The 6% rise in nickel production in Western Australia during 2005–06 is set to escalate, with two advanced lateritic nickel projects coming on-line. BHP Billiton is developing the Ravensthorpe project with plans to produce about 50 000 tpa of contained nickel, commencing production in late 2007. In a longer term, Heron Resources Ltd and Inco Ltd plan to produce about 50 000 tpa of contained nickel from the Kalgoorlie nickel laterite project, with the bankable feasibility study for the project expected to be completed by 2011.

Exploration expenditure for nickel (and cobalt) reached a peak of $153.9 million in 2004–05, but fell by 25% in 2005–06 to $114.9 million (Fig. 8); this accounted for 20% of the total Western Australian exploration

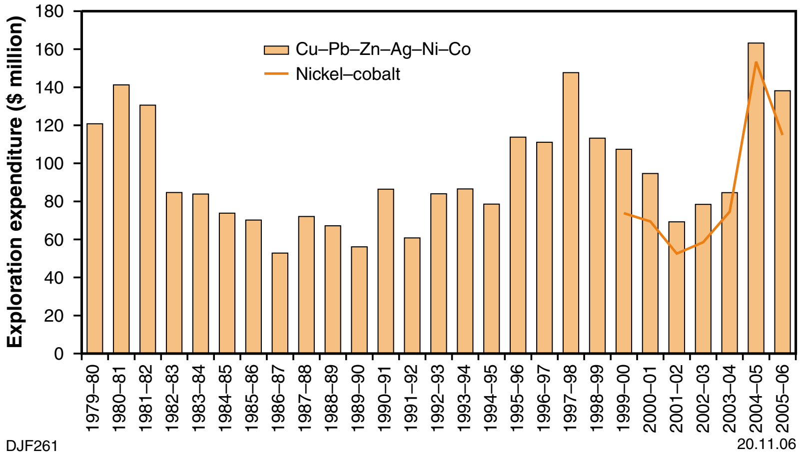


Figure 8. Nickel, cobalt, and base metal exploration expenditure in Western Australia, by financial year (2005–06 dollars)

expenditure in 2005–06 (Fig. 4). Most of the exploration activity centred on the Leinster, Forrestania, Kambalda, and Gerry Well regions of the Yilgarn Craton, and the Halls Creek region in the Lamboo Complex.

Significant brownfields exploration successes in the nickel sector included:

- High-grade nickel sulfide mineralization at Prospero, Tapinos, Anomaly 1, and Alec Mairs (all near Cosmos) and Sinclair (about 90 km south of Cosmos) by Jubilee Mines NL;
- T5, T5 South, $2, and T Zero North at Flying Fox – Forrestania by Western Areas NL;
- North Miitel and South Miitel (40 km south of Kambalda) by Mincor Resources NL;
- Copernicus North (70 km northeast of Halls Creek) by Sally Malay Ltd and Thundelarra Exploration Ltd.

There was also significant exploration success in the Yilgarn Craton at Pioneer JH (85 km south of Kambalda; Pioneer Nickel Ltd), the Marshall prospect of the Golden Ridge project (40 km north of Kambalda; Australian Mines Ltd and Pioneer Nickel Ltd), the Talc Lake prospect of the Roe Hills project (about 95 km east of Kambalda; Oroya Mining Ltd), Cassini (55 km south of Kambalda; Jupiter Mines Ltd), Emu Lake nickel project (70 km northeast of Kalgoorlie; Image Resources NL), Martins Zone of the Riverina project (45 km west of Menzies; Barra Resources Ltd), Jocks Dream prospect (55 km north-northeast of Southern Cross; Western Areas NL), Bodkin and Longbow prospects (both within 10 km of Wiluna; Agincourt Resources Ltd). Exploration successes in the Pilbara Craton included Ruth Well (15 km south of Karratha; Fox Resources Ltd) and Daltons (70 km southwest of Marble Bar; Giralia Resources NL).

Base metals (copper–lead–zinc–silver)

Highlights in Western Australia during 2005–06 included:

- A 15% increase in copper production, attributed mostly to the Telfer gold–copper mine;
- Production of lead up from 2324 to 58 739 t following the opening of the Magellan lead mine;

- A 123% rise in zinc production, mostly due to improved performance at Golden Grove.

There was a significant increase in production of copper, lead, and zinc in the State in 2005–06, with copper increasing by 15% (from 61 933 t in 2004–05 to 71 060 t in 2005–06), largely due to the revamping of the Telfer gold–copper operation. The opening of the Magellan lead mine in 2005 resulted in a considerable increase in lead production in the State from 2324 t (which was a byproduct at the Golden Grove operation) in 2004–05 to 58 739 t in 2005–06. The production of zinc increased by 123% (from 48 400 t in 2004–05 to 107 863 t in 2005–06) due to improved production from the Golden Grove operation.

Exploration expenditure directed at copper–lead–zinc–silver in Western Australia considerably improved from $9.5 million in 2004–05 (dollars of the day) to a total of $23.4 million in 2005–06, attributed mainly to exploration and development of the Jaguar deposit (Archean volcanogenic massive sulfide (VMS)-style) in the Yilgarn Craton; exploration for Archean VMS-style mineralization in the Pilbara Craton at Whundo, Panorama, Sulphur Springs, and Orchard Well; exploration for VMS-style mineralization in the Halls Creek Orogen at the Eastman prospect; exploration for stratabound sediment-hosted mineralization in the Edmund Basin at Abra; and exploration for the Mississippi Valley-type Pb–Zn mineralization (sedimentary carbonate-hosted deposits) in the Lennard Shelf, where Teck Cominco Ltd announced plans to restart the mining operations in March 2007, at a cost of A$20 million.

Diamond

Highlights in Western Australia during 2005–06 included:

- Diamond sales up 29% to 29.3 Mcts, from production at Argyle and Ellendale;
- Diamond exploration expenditure down a further 32%, the fourth year of decline;
- Greenfields exploration success in the west Pilbara (Blacktop, Clurrie, and Railway prospects).

Diamond production (strictly sales production rather than mine production) in Western Australia in 2005–06 was 29.3 Mcts, which is an increase of 29% (6.5 Mcts) compared with 2004–05 production of 22.8 Mcts. Rio Tinto announced plans to develop a US$760 million underground mine at Argyle in the east Kimberley, and an additional US$150 million allocated to openpit cutback and production until underground mining commences in 2008.

At Ellendale, in the west Kimberley, mining expanded at Ellendale 9 and there was commencement of mining at Ellendale 4. The Ellendale 9 plant was upgraded to 3.3 Mtpa in mid-2006, and this will be followed by another upgrade to 4.4 Mtpa in mid-2007. Gravels extracted at Terrace 5 yielded 2114 diamonds weighing 826 cts; the diamonds have an average size of 0.39 cts, with the largest stone weighing 5.92 cts. Numerous other sites in the Ellendale area were being drill tested and bulk sampled (Kimberley Diamond Company NL, Blina Diamonds NL).

Greenfields exploration success was focused at three prospects in the west Pilbara, 90 km south-southwest of Karratha — Blacktop, Clurrie, and Railway (De Beers Australia Exploration Ltd, Helix Resources Ltd).

Expenditure decreased on diamond exploration by a further 32% during 2005–06, falling by $5.3 million to $11.1 million for the year (2005–06 dollar terms; Fig. 9), which is only 2% of the total Western Australian

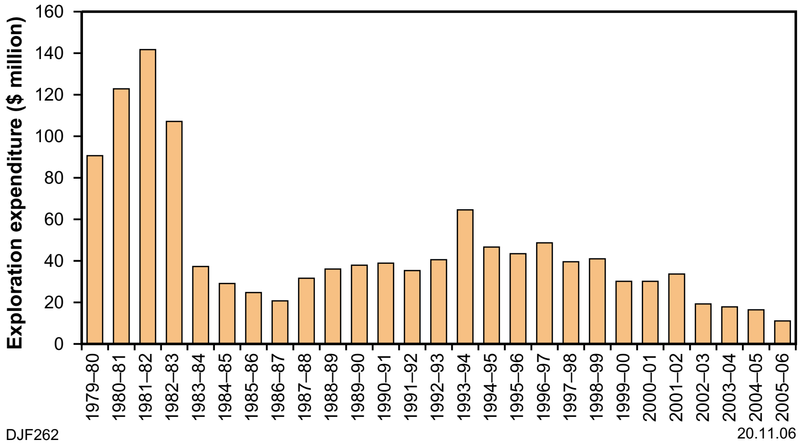


Figure 9. Diamond exploration expenditure in Western Australia, by financial year (2005–06 dollars)

mineral exploration expenditure (Fig. 4). This is the fourth year in a row that diamond expenditure in Western Australia has declined, reflecting the general lack of exploration success and hence investor interest. The decline was primarily due to reduced resource–reserve drilling activities at Argyle, with the openpit approaching the end of its estimated mine life and the underground feasibility study being completed. Although there were encouraging mining and exploration results in the Ellendale region, they were not sufficient to outweigh the decreased exploration expenditure at Argyle.

Heavy minerals (Ti–Zr–garnet)

The production of heavy mineral sands (ilmenite, leucoxene, zircon, and garnet) in Western Australia in 2005–06 was 1.3 Mt valued at A$799.5 million, which is slightly less than the 2004–05 production of 1.4 Mt valued at A$800.9 million. Sector highlights were the commencement of mining at Gingin and Wagerup near Perth in mid-2005 (Iluka Resources Ltd); proposals to mine at Waroona and Cataby (both deposits near Perth; Iluka Resources Ltd) and also at Coburn (near Shark Bay; Gunson Resources Ltd); and completion of a bankable feasibility study of the Keysbrook deposit (south of Perth; Olympia Resources Ltd).

In greenfields exploration during 2005–06, there was renewed interest in strandlines of the Eucla Basin in Western Australia. This followed on from the discovery in late 2004 of world-class zircon-rich heavy mineral sands in the Eucla Basin of South Australia at the Jacinth and Ambrosia prospects (Iluka Resources, Adelaide Resources Ltd). Elsewhere, the main greenfields exploration projects are at Coburn (250 km north of Geraldton), which progressed during 2005–06 to the development phase, and Keysbrook (55 km south of Perth), which is progressing steadily through the environmental approval process.

Exploration expenditure in this sector during 2005–06 in Western Australia fell by 16% ($2.5 million) to $12.8 million. However, expenditure is still better than the $8–11 million per year that has been the trend during the last ten years (Fig. 10). 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 nearly 70% of the total in the mid-1990s to only 29% in 2002–03. However, during 2005–06 Western Australia's share recovered to 44% of the total.

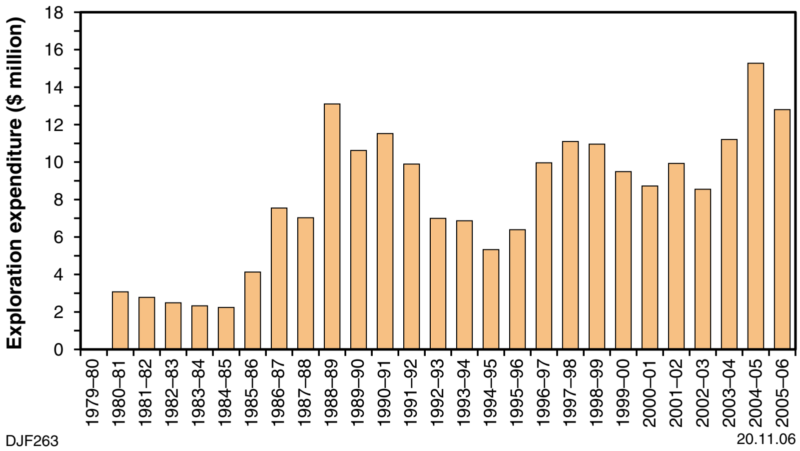


***Figure 10.** Heavy mineral sands (Ti–Zr) exploration expenditure in Western Australia, by financial year (2005–06 dollars)*

Other commodities

The exploration expenditure for other mineral commodities in Western Australia in 2005–06 was 5% of the total (Fig. 4) and decreased by 7% ($1.9 million) to $26.8 million in 2005–06 (in 2005–06 terms). 'Other commodities' include all industrial minerals, construction materials, platinum group elements, molybdenum, tantalum, manganese, chromium, vanadium, rare earth elements, and coal–lignite. A new measured, indicated, and inferred resource totalling 500 Mt at 0.06% Mo, 0.09% Cu, and 1.7 g/t Ag has been estimated for the Spinifex Ridge molybdenum–copper deposit in the Pilbara region and a bankable feasibility study is in progress. Exploration expenditure for all these commodities is still at a relatively high level compared with about 5 years ago, which can be attributed to the keen interest in steel alloying metals (manganese, chromium, and vanadium) and an awakening of interest in coal. Although there has been renewed interest in uranium during 2005–06 and much stock-market activity, there has been negligible exploration expenditure in Western Australia.

Drilling activity

Exploration drilling activity throughout Australia has been rising modestly over the last four years (as has general exploration expenditure), but with this only partially offsetting the huge decline from peaks in 1996–97 to 2001–02 (Fig. 11). However, the rise in metres drilled during 2005–06 in Australia was only 1% (0.053 million metres) to a total of 6.837 million metres. The estimated mineral exploration drilling in Western Australia follows the same trend (based on Western Australia's proportion of total Australian exploration expenditure for each year).

However, mineral exploration drilling in Australia and in Western Australia is now only 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 the lack of significant RAB drilling in greenfields areas, which characterized the previous exploration boom that peaked in 1996–97. The data support the suggestion that government financial incentives should be directed at stimulating more greenfields exploration, particularly drilling.

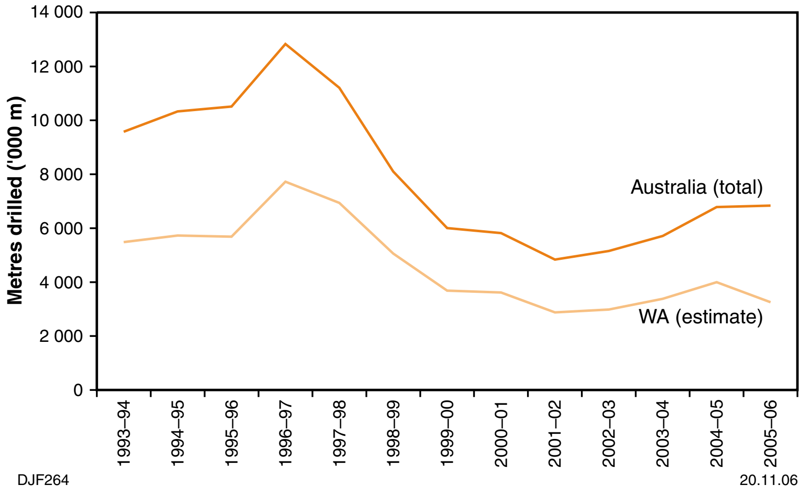


Figure 11. Mineral exploration drilling in Australia and Western Australia, by financial year (metres drilled)

Mining tenement activity

There was an increase in the number of granted tenements (in force) during 2005–06; this is in contrast to the decreasing trend in exploration expenditure. The number of granted tenements (all tenement types combined) increased by 8.6% (1411) from a total of 16 347 in force at 30 June 2005 to 17 758 at 30 June 2006. A similar trend is shown by the number of tenement applications (Fig. 12). The area under granted tenure increased by 38% from a total of 26.3 Mha at 30 June 2005 to 36.3 Mha at 30 June 2006.

Trends in longer term data since 1983–84 (Fig. 12) show some correspondence between exploration expenditure and tenement activity (granted tenements and tenement applications). The trend in increased tenement activity appears to have been a leading indicator of increased exploration expenditure. It would be encouraging if this trend is repeated in the next year or two following the recent increasing trends in the number of tenements granted and tenement applications.

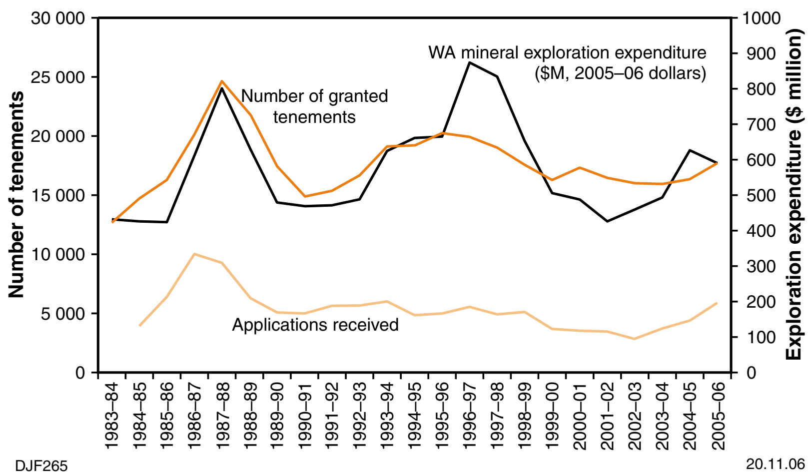


Figure 12. Trends in exploration expenditure and tenement activity (1904 and 1978 Mining Acts) since 1983–84. Source: DoIR

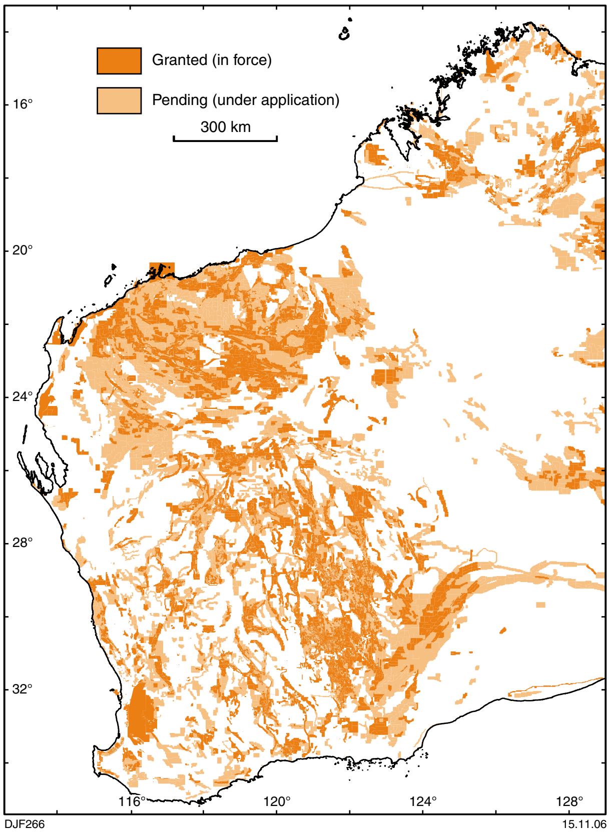


Figure 13. The distribution of mining and exploration tenements, granted and pending, in Western Australia as at 30 June 2006

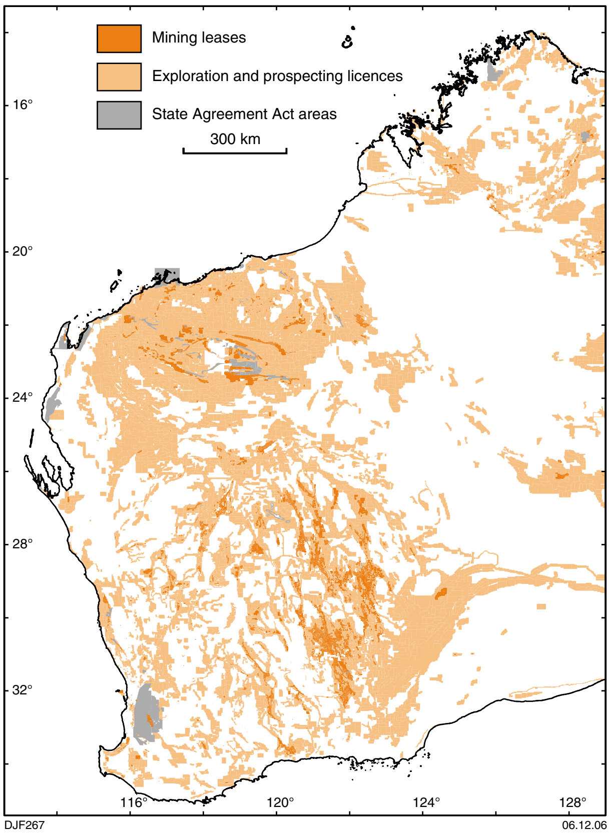


Figure 14. The distribution of mining leases, exploration and prospecting licences (granted and pending) and State Agreement Act areas in Western Australia as at 30 June 2006

The distribution of tenements, both granted and under application at 30 June 2006, is shown in Figure 13. The distribution of mining leases, exploration and prospecting licences (granted and under applications) and State Agreement Act areas is shown in Figure 14.

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Understanding the landscape

by J. R. Gozzard

From the stability of the Darling Plateau to the dynamic coastal environments, the landscapes of the Perth Region have influenced the development of Perth from earliest colonial times. In 1829, Captain James Stirling established the Swan River Colony, later to become Perth, on the north bank of the Swan River, describing it as ideal for establishing a permanent settlement. In particular, he recognized the defensive prospects of Mount Eliza, situated as it is where the Swan River narrows, which would make defending the fledgling colony from gunships easy, with just a few cannons.

The landscape is intimately related to the nature of the underlying geology and many striking landforms and geological sections in the Perth Region provide insights into the geological history of the region, and to the development of the landscape as we see it today. The landforms of the coastal areas record the fluctuating sea level and are the result of the glaciations of the Pleistocene; exposed river-banks and subtle landforms of the Swan Valley reveal the history of the migrating river systems of the past; sedimentary rocks of marine origin at the foot of the Darling Scarp are evidence for an ancient shoreline, when the ocean covered all of what is now the Swan Coastal Plain; and quarries on the Darling Plateau reveal the complex history of the Yilgarn Craton, where metamorphic belts were intruded by large volumes of granitic rocks, and then eroded and deeply and intensely weathered over millions of years.

However, the landscape is many things to many people — to mining companies it is a source of mineral wealth; to farmers a source of agricultural wealth; to construction companies a setting for major infrastructure projects; to waste disposal providers a receptacle for rubbish; to government, industry and environmental lobby groups a challenge of sustainable development whereby competing land uses can be combined with a respect for the natural environment.

There is also a growing public appreciation of the need to understand landscapes and the importance of geology as the underpinning framework. In this regard, GSWA recognizes that it has a vital role to play in community education and assisting with increasing the awareness of schools and the general public about the importance of geoscience by making geoscience as accessible as possible. One of the ways GSWA is achieving this is by presenting geoscience information in a form suited to a range of non-specialist users.

GSWA is currently producing a book that provides a concise and informative guide to the geology and landscapes of the Perth Region (Gozzard, in prep.). For the purposes of the guide, the Perth Region includes most of the Perth Metropolitan area between the Indian Ocean to the west and the Darling Plateau to the east, and extends about 150 km from Moore River and Gingin Brook in the north to Mandurah in the south.

The guide is aimed at those in secondary and tertiary education who require resource materials for teaching, and those with a basic understanding of geological principles, but it is also readily accessible to the layperson. The guide provides an insight into the range of natural features that characterize the Perth Region. It describes the geological setting of the Perth Region from its beginnings in warm, shallow, ancient seas about 3170 million years ago to the youngest sedimentary rocks of the Perth Basin that formed during erosional and depositional events related to periods of higher and lower sea levels caused by glaciation during the Pleistocene and Holocene. It then goes on to explain the origin and evolution of the various landscapes found in the Perth Region and describes those landscapes in relation to the underlying geology.

It has not been possible in the guide to describe all localities within the Perth Region that merit consideration. Instead, only a selective, but nonetheless representative, number of localities are discussed in detail. Many of the sites described in the guide have been nominated for protection as sites of special geological significance (Lemmon et al., 1979).

The guide describes in detail the geology and landforms of nine areas across the Perth Region. It puts each area into the geological and geomorphological framework of the Perth Region described in the introductory chapters of the guide. In each area, locations of particular interest are identified on easy-to-read maps and access directions and any constraints to access are provided. The geological and geomorphological details for each location are described in detail. In this way, readers are readily able to gain an understanding of both the characteristics of each area and how these details can be fitted together like a jigsaw to provide a picture of the landscape history of the Perth Region.

For example, the Cottesloe – Mosman Park area is an ideal place to observe the results of sea-level changes that have occurred over the last 300 000 years or so, at a time when the Earth experienced dramatic climate changes and underwent its last period of glaciation. Evidence of these fluctuating sea levels is recorded by the presence of interfingering shallow-marine limestones within the overall dune limestones of the Tamala Limestone. These and similar deposits along the coast of Western Australia have been used to determine the sea-level history of the coast during this period (Price et al., 2001).

At Peppermint Grove, there is a section that records the continuing retreat of the sea (regression) from a shallow-marine environment to a beach environment (Fig. 1). At the base of the section is a medium-scale, cross-bedded limestone that indicates deposition offshore in shallow-marine water. In this environment, water currents cause ripples in the sediment to migrate and the orientation of the cross-beds indicates the direction of the currents. This shallow-marine limestone is overlain by a ripple-bedded limestone that formed as a result of the oscillating motion of waves in a near-shore surf zone. The ripple-bedded limestone is overlain by a planar-bedded limestone, which indicates high-energy movement of sediment in a beach environment.

Much higher up the section is another shelly marine limestone that is up to 7.3 m above present sea level. This indicates that there was a later episode of marine deposition during which the sea level was about 7.5 m higher than it is today (Playford et al., 1976)

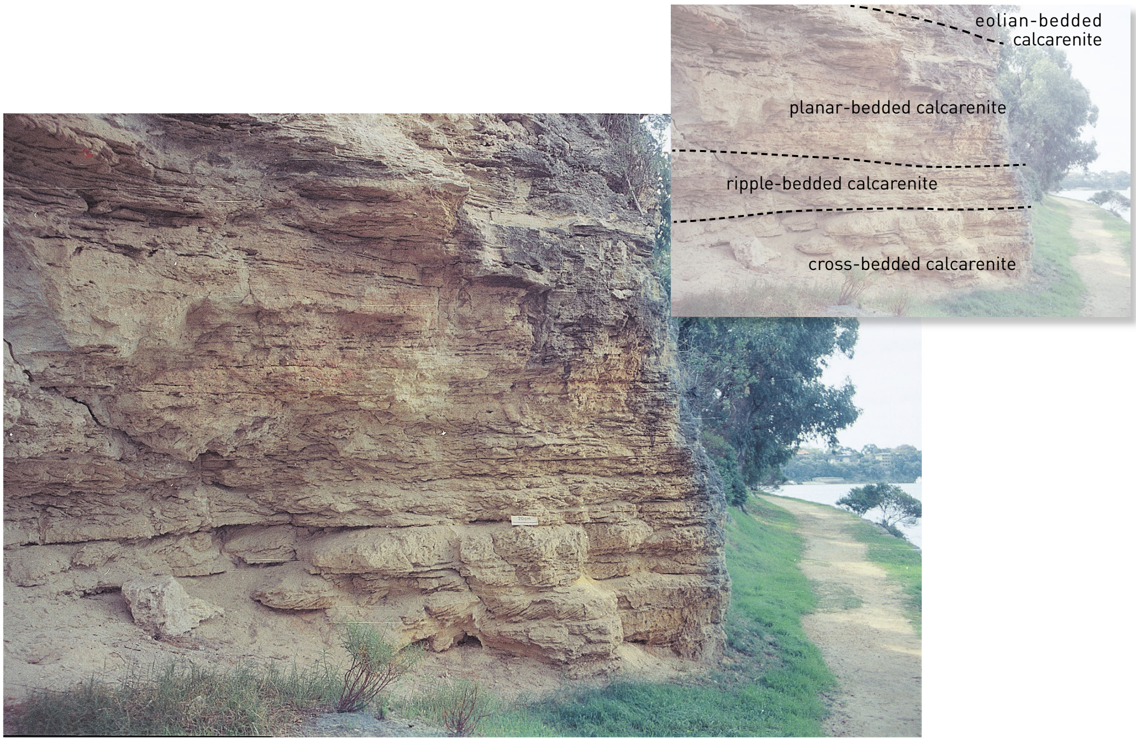

***Figure 1.** Shallow-water, cross-bedded and ripple-bedded marine limestone grading up into planar-bedded beach limestone at Peppermint Grove (MGA 384020E 6459370N)*

A thick sequence of large-scale, cross-bedded dune limestone overlies the complete marine sequence and indicates that a major dune-building episode followed the period of marine and shoreline deposition.

Absolute ages of the marine units (Hewgill et al., 1983; Murray-Wallace and Kimber, 1989) indicate that the upper marine limestone was deposited in the second-last interglacial period, between 240 000 and 190 000 years ago. The age of the lower marine sequence is more problematic. It could have been deposited during the same interglacial period as the upper shell unit or earlier, in the third-last interglacial period between 340 000 and 300 000 years ago (Kendrick et al., 1991).

In contrast, a disused railway cutting at Jarrahdale on the Darling Plateau is the ideal site to observe the development of a thick lateritic profile over granitic and doleritic rocks. Lateritic profiles result from a combination of deep and intense weathering of near-surface material in seasonally tropical climates with relatively high temperatures and rainfall.

A typical lateritic profile on the Darling Plateau is distinctly zoned. In a complete profile there is a general upward sequence of: parent bedrock; saprock, which is the zone of slightly weathered rock; saprolite, which is composed mainly of white, sandy kaolinitic clays that retain some of the parent rock fabric; an earthy, mottled zone; cemented ferruginous duricrust, rich in gibbsite and hematite; and loose, superficial iron-rich nodules, fragments, and pisoliths. Margins between zones are commonly diffuse. The influence of bedrock on the materials of the overlying lateritic profile can be most pronounced and it is possible to distinguish the lithology of the bedrock from examination of the weathered material.

The railway cutting at Jarrahdale is 650 m long and up to 15 m deep. Bedrock in the railway cutting consists of Archean gneissic metagranitic rocks that are monzogranitic in composition, and intruded by northeasterly to northwesterly trending metamorphosed quartz dolerite dykes. However, fresh bedrock is only exposed over a distance of about 125 m, about half way along the cutting. The remaining sections of the cutting expose white and mottled kaolinitic saprolite clays — the weathering products of granitic rocks.

In the central part of the cutting, developed over the fresh bedrock, is a complete lateritic profile. Despite the intensely weathered nature of the materials in the exposed profiles, simple visual examination reveals the significant differences between the profile developed over granitic rocks and that developed over doleritic rocks. It is clear that, even in the uppermost parts, the profile retains characteristics that can be related to parent material. Figure 2 shows the contact between the gneissic metagranite and the main intruding dolerite dyke. The sharp contact between these rock types is clearly seen at the base of the cutting, and the contrasts in colour and texture of the weathered material above the fresh bedrock allow the intrusive contact to be identified and followed up the weathered profile. Close examination shows that, even in the ferruginous duricrust at the top of the profile, the contact is preserved.

Quartz is dominant throughout the profile developed over granitic rock, even up to and including the ferruginous duricrust, whereas quartz is almost totally absent throughout the profile developed over the dolerite. Other mineralogical and geochemical patterns are also apparent (Sadleir and Gilkes, 1976) and have been used to confirm that the intensely weathered lateritic profiles exposed in the Jarrahdale railway cutting have developed in situ over contrasting rock types.

In these times of greater environmental awareness, many people have become interested in all aspects of the landscape, because understanding the landscape is the first step in appreciating its value and the need to use and

***Figure 2.** Contact between metagranitic rocks (g) and the main dolerite dyke (d) in the Jarrahdale railway cutting (MGA 414735E 6426400N) traceable through the lateritic profile*

manage it sustainably. The Perth Region guide is designed to help interested laypersons understand and appreciate their local landscape. Visiting the localities described in the guide offers insights into geological processes in the past that have shaped the landscape and provides an awareness of how similar processes may shape our future. For example, understanding the effects of past sea-level changes will help us understand the possible effects of sea-level changes predicted for the coming century as a result of climate change.

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Tamala Limestone — a significant resource for the Australian building block industry

by J. M. Fetherston

Abstract

Western Australia was settled in the Swan River Colony in 1829, later to become the City of Perth. The extensive resource of high-grade Pleistocene Tamala Limestone was soon discovered along the coastline and at Rottnest Island and became the first stone to be used extensively in early buildings of the colony. Tamala Limestone and equivalent units extend in places along the coastline from Shark Bay south to Cape Leeuwin and eastwards to Esperance, and consist mainly of a fine- to coarse-grained, cream to pale-brown eolian calcarenite. The State's building-block extraction industry extends from Geraldton in the north to the Perth Metropolitan area and south towards Bunbury.

Natural limestone blocks are quarried only in the Carabooda–Nowergup and Moore River areas to the north of Perth, since these areas contain a higher strength limestone with calcium carbonate contents often in excess of 85%. Lower grade limestone (48–78% calcium carbonate) is crushed for the manufacture of reconstituted limestone blocks and other products. Some natural limestone block manufacturers also produce reconstituted block products as a byproduct from low-grade and waste materials, while in all other areas, reconstituted blocks and pavers are produced as a substitute product for natural limestone blocks. Soft calcarenite requires special quarrying techniques for extraction in block form. Block processing is divided into two parts. The first of these is the quarry-cut block extraction process over a level site where rough-sawn building blocks are cut to final size and packed for sale on site in the quarry. In the second added-value stage, quarry-cut blocks are removed to a processing plant for fine sawing and machining into a variety of diamond-cut bricks, cladding, pavers, pier blocks, and special profile products.

In recent years, the Western Australian industry has become the largest producer of cut limestone blocks in Australia. Estimates for 2003–04 show the State produced almost 234 000 tonnes valued at approximately $4.5 million. Estimated production figures for reconstituted limestone products were in the order of 237 000 tonnes valued at about $3.08 million. In 2004, Austrade identified niche market opportunities for Australian dimension stone mainly in the Indo-Pacific region, particularly New Zealand. In 2006, the Tamala Limestone natural stone-block industry maintains its position as Australia's largest producer of high-quality, cut limestone blocks, backed up by the production of a substantial quantity of reconstituted limestone blocks, bricks and other products. Over recent years, the industry has expanded in line with increased sales both in Western Australia and the eastern states. In addition, exports to New Zealand, Malaysia and other countries in the Indo-Pacific region have continued to increase.

KEYWORDS: Western Australia, Perth Basin, dimension stone, building stones, limestone, history, mineral exploration, quarrying, natural resources, mineral economics.

Introduction

In 1829, Western Australia was settled in the Swan River Colony that was later to become the City of Perth. The early settlers soon discovered the extensive resource of high-grade Pleistocene Tamala Limestone located in places along the coastline, mainly from Scarborough southwards to Coogee. Another large limestone resource was also located on Rottnest Island, about 20 km offshore from Fremantle. This coarse- to medium-grained, sandy limestone, more correctly referred to as 'calcarenite', was found to be relatively soft and easily workable. Accordingly, Tamala Limestone became the first stone to be used extensively in early buildings of the colony. Over time, quarries were established at Fremantle, Rottnest Island, Cottesloe, Mosman Park, Coogee, and Reabold Hill in the City Beach area.

In 1831, Western Australia's oldest public building, the Round House, was built at Arthur Head in Fremantle to be used as a gaol and detention centre. Building continued in Perth, Fremantle and Rottnest Island using Tamala Limestone in the construction of splendid colonial and early 20th century buildings for the next 100 years. These included the Fremantle Boys' School (1854), the Main Lighthouse on Rottnest Island (1896), and the Perth Mint (1899). In 1932, Winthrop Hall at the University of Western Australia, the last of Perth's grand dimension-stone buildings of the era, was completed. Built in the style of an Italian medieval guildhall, the walls and belltower of this magnificent building are of high-grade, cream-coloured Tamala Limestone blocks quarried from the university's own quarry at Coogee (Fig. 1).

The onset of World War II heralded a period of comparative inactivity in the building stone industry that persisted for almost 50 years. In the 1980s, dimension stone was rediscovered by architects as a building material of choice and they began cladding large buildings both inside and out with pre-cut stone slabs. Since that time, limestone blocks have once again found numerous applications in home and office construction, as well as in streetscape and landscape design.

A full description of the limestone block industry in Western Australia is discussed in Fetherston (in prep.). This includes the location of deposits, chemical analyses and petrological sample descriptions, quarrying and processing, as well as product applications for natural-cut limestone blocks and reconstituted limestone products. In addition, an overview of the dimension stone industry in Western Australia, including reference to the Tamala Limestone block industry, is given in Fetherston (2004).

Location of Tamala Limestone resources

In Western Australia, the Pleistocene Tamala Limestone and equivalent units extend, in places, in parallel and close proximity to the modern coastline from Shark Bay on the central-west coast southwards to Cape Leeuwin, and eastwards to Esperance along the south coast. This limestone unit consists mainly of a fine- to coarse-grained, cream to pale-brown eolian calcarenite.

The State's limestone building-block extraction industry is located at sites extending from Geraldton in the north, to the Perth Metropolitan area, and southwards towards Bunbury. Currently, the only areas where natural limestone blocks are quarried from high-grade limestone are in the Carabooda–Nowergup area on the northern fringes of the Perth Metropolitan area and at Moore River in the Guilderton area about 80 km north-northwest of Perth (Fig. 2).

Nowergup, where six quarrying operations are currently in progress (Meteor Stone, Italia Limestone, Limestone Building Blocks, Limestone Natural, Limestone Resources Australia, and Crown Limestone Supply), is currently the principal area of activity for natural limestone building blocks. At

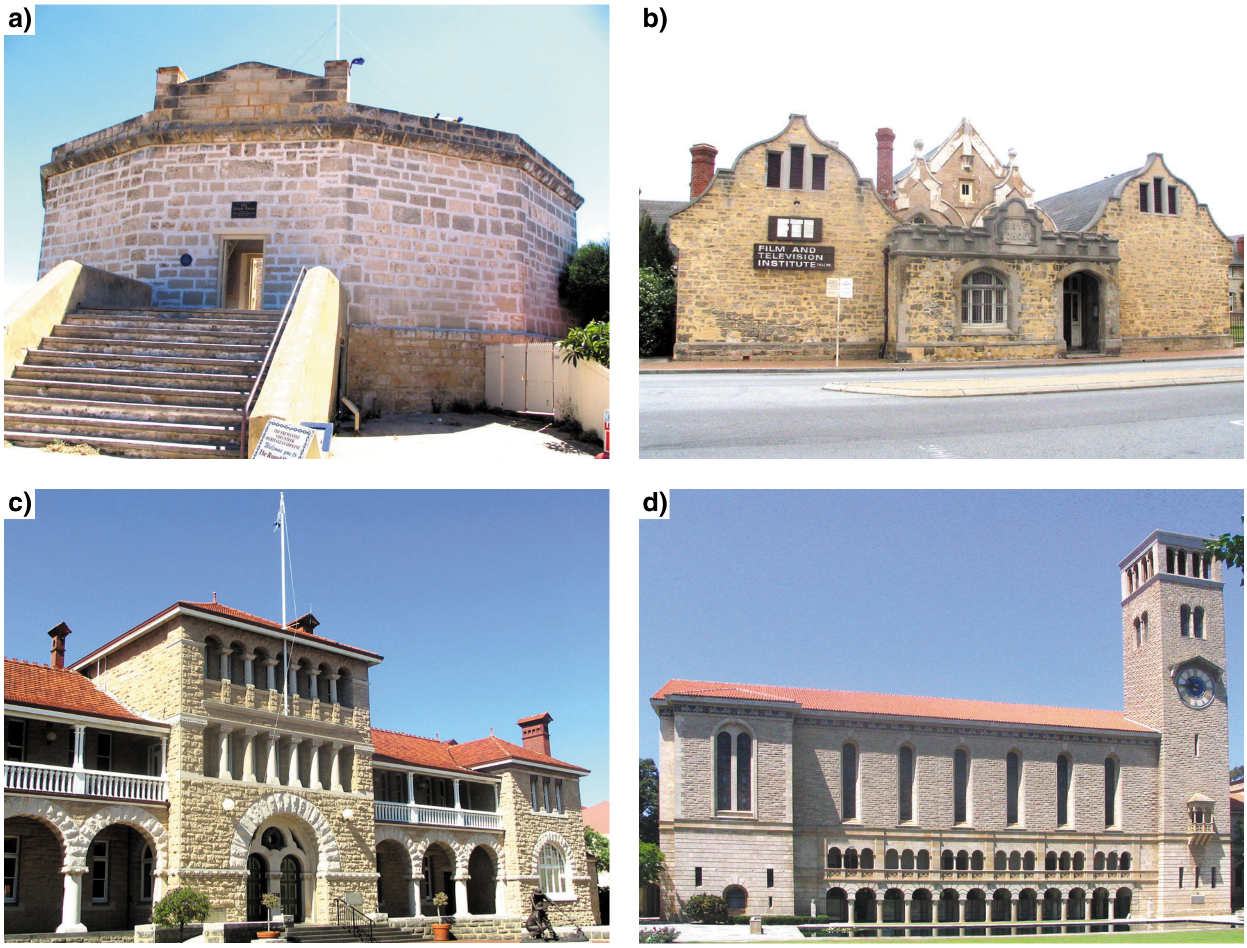

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Figure 1. Historic Tamala Limestone buildings in Fremantle and Perth: a) the Round House in Fremantle is Western Australia's oldest public building (1831); b) Fremantle Boy's School (1854); c) the Perth Mint (1899) constructed from limestone blocks quarried on Rottnest Island; d) Winthrop Hall at the University of Western Australia (1932). Limestone blocks for the walls and belltower were sourced from the university's own quarry at Coogee

Carabooda, there is one block quarry in operation (Limestone Resources Australia), and at Moore River, Limestone Resources Australia is quarrying blocks from two adjacent mining leases. In general, it appears that the overall strength of the calcarenite limestone is governed by the stone's physical properties of compressive and flexural strength that are often be related to a high calcium carbonate ($CaCO_3$) content in excess of 85% for high-grade building block material (Abeysinghe, 1998).

In other extractive areas, the limestone is mostly too soft for cutting natural stone blocks. In general, this is attributed to the lower strength limestone present in these areas, where the calcium carbonate ($CaCO_3$) content ranges between a high of 78% and a minimum of 48%. In these areas, lower grade limestone is crushed and used for the manufacture of reconstituted limestone blocks, pavers, and other products. This situation is present at Carabooda, where Limestone Building Blocks manufacture reconstituted limestone blocks as a substitute industry. Other similar areas include the Yanchep area north of Perth (Archistone), Hope Valley north of Kwinana (Stoneridge Quarries W. A.), Narngulu southeast of Geraldton (Amazzini and Son), and a number of private operations at Myalup and Kooallup north of Bunbury (Fig. 2).

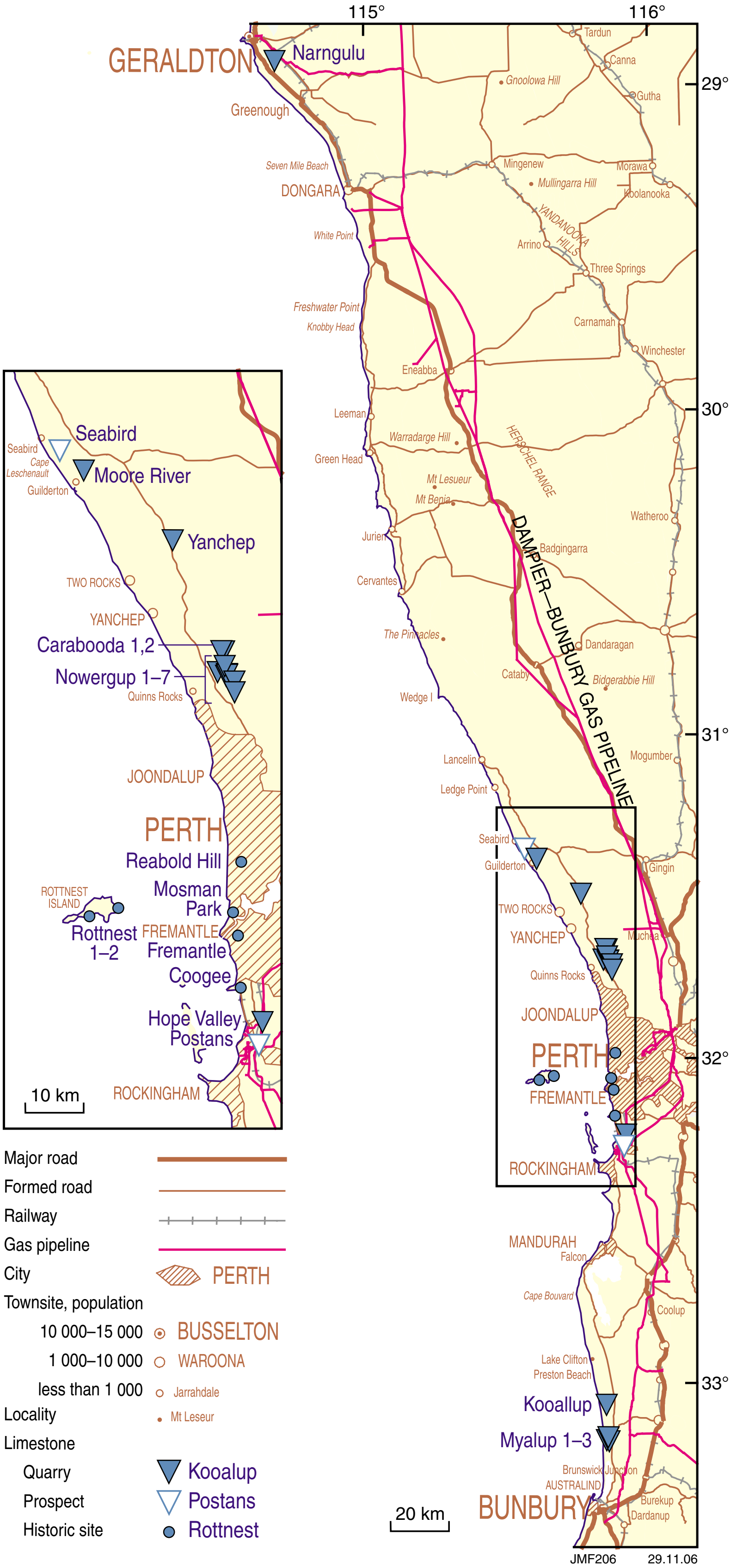

Figure 2. Location of Tamala Limestone dimension stone quarries, prospects, and historic sites

Calcarenite block quarrying and processing techniques

Soft calcarenite limestones require special quarrying techniques for their extraction in block form. Before operations commence, a smooth and level site must be prepared over extractable stone. Calcarenite block processing is divided into two parts. The first of these is the quarry-cut block extraction process, where rough-sawn building blocks are cut to final size and packed for sale on site in the quarry. The second added-value stage requires the removal of a proportion of the newly produced quarry-cut blocks to a processing plant for fine sawing and machining into a variety of diamond-cut bricks, cladding, pavers, pier blocks, and special profile products.

Quarry-cut block extraction

In the first stage of the block extraction process, large areas of the quarry floor are sawn with a series of parallel, vertical cuts up to 350 mm deep, using a rail-mounted, electric-powered sawing machine fitted with a tungsten-tipped saw blade. The parallel cuts are spaced to produce blocks in a variety of sizes. In the second stage, the cutting machine travels at right angles to the original quarry-floor cut lines. Block cutting is achieved by using the rail-mounted machine fitted with several tungsten-tipped saws designed for making simultaneous vertical and horizontal cuts. During these passes, the machine is adjusted to cutting different widths and heights to produce quarry-cut blocks in a variety of standard sizes (Fig. 3).

Quarry-cut blocks, ranging in size from 1000 × 350 × 350 mm to 500 × 117 × 105 mm, are removed from the cutting operation in an excavator bucket and stacked onto pallets on the quarry floor. Once packing is complete, the blocks are ready for dispatch to clients requiring a more natural-textured surface. The finished blocks have a slightly roughened, quarry-cut texture reminiscent of early colonial cut stone. They are produced specifically for use as housing bricks, and blocks for landscaping and retaining walls (Fig. 4).

Added-value processing

The second part of the operation is the diamond-cut block process where quarry blocks are removed to a sawing plant for added-value processing using diamond saws and other machinery to produce a vast array of bricks, blocks, wall cladding, pavers, and special profile products.

Bricks

According to customer requirements, quarry-cut blocks delivered to the cutting plant are progressively reduced in size by cutting with diamond-tipped saws to produce more highly finished blocks and bricks with much smoother surfaces and increased dimensional accuracy. In the plant, quarry blocks are diamond sawn in the first instance to produce quarry-face housing bricks in which the visible face and perps (vertical ends) are left in their natural state. The bricks may then have their quarry-cut faces smooth sawn with perps remaining, and finally, may be diamond-cut on all surfaces. Finished products range from 330 to 500 mm in length, 100 to 165 mm in thickness, and are produced in a variety of heights from 76 to 332 mm.

Cladding, pavers, and pier blocks

Other mass-produced limestone products that only requiring diamond sawing include cladding, pavers, and pier blocks. While most styles are diamond cut on all sides for improved visual appearance and dimensional accuracy, a few designs retain quarry-cut edges and perps. Cladding slabs are 30 to 35 mm in thickness and are produced mainly as rectangular panels with their longest sides between 300 and 500 mm (Fig. 4).

Paver blocks have a standard thickness of 60 mm and are square or rectangular in outline with their longest sides between 300 and 500 mm. Pier blocks are cut as rectangular prisms in about six sizes up to a maximum size with a face measuring 400 × 332 mm and a thickness of 195 mm.

Figure 3. Extractive process for Tamala Limestone building blocks: a) the level limestone floor is cut with a series of parallel saw cuts to produce blocks in a variety of standard sizes; b) rail-mounted, multi-blade quarry saw cutting standard size blocks; c) quarry saw blade fitted with tungsten carbide cutting teeth; d) quarry-cut blocks packed on site for dispatch to clients (photo (d) courtesy Meteor Stone)

Special profile products

A number of special profile products are produced for the building and landscaping industries. All these products require special diamond cutting and many require special curved profiles to be added to complete the design. Curved profiles are accomplished using a milling machine fitted with a variety of diamond-faced grinding or specially shaped profiling wheels designed to cut the required curvature in stone edges.

Special products include pier caps for fixing to the top of limestone piers, ornamental copings for fitting to the top of walls, corbels for wall ornamentation, and bullnoses and sills for fitting around doors, windows, and other ornamental features. Many designs require a combination of diamond cuts and curved profiles to complete while others only require

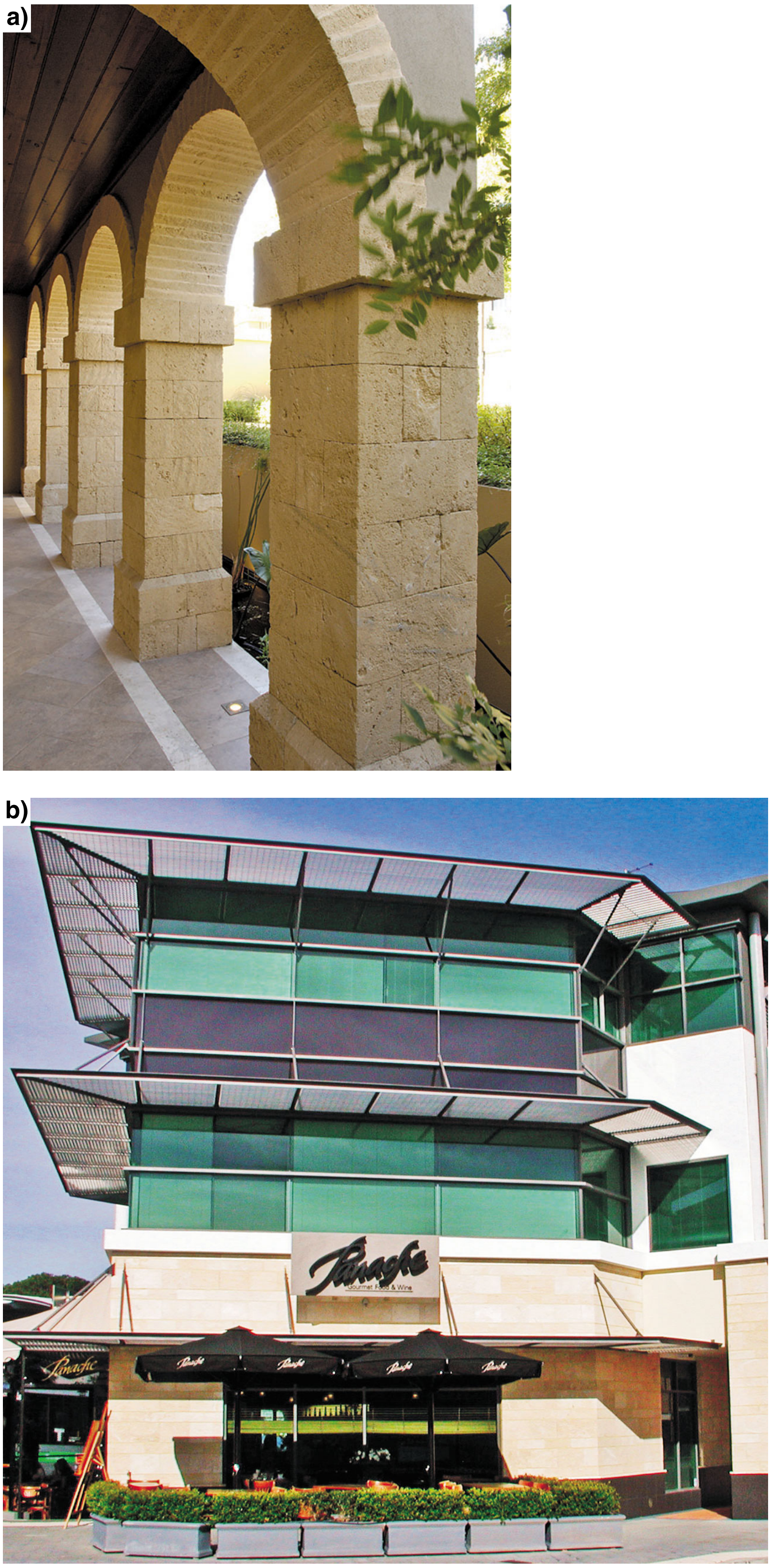

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Figure 4. Applications for Tamala Limestone natural stone blocks: a) biscuit-coloured quarry blocks from Moore River used in archways and as column cladding in a contemporary Italian-style villa in Melbourne; b) diamond-cut, cream-coloured slabs from Nowergup used to clad a modern office building in Perth; (photo (a) courtesy Limestone Resources Australia, © Discovering Stone, 2006; photo (b) courtesy Meteor Stone)

additional cutting. Most products are produced in lengths or square sides ranging from 300 to 500 mm. Some sills have lengths up to 1000 mm.

Corner returns are right-angled blocks designed to wrap around wall ends for a more complete finish. These special blocks only require multiple diamond cuts to complete and range from 150 to 490 mm on the longest side.

A number of other limestone products also require added-value processing for completion, including diamond sawing, profiling, and other processes. These include ornamental pedestals and plinths between 420 to 1030 mm in height, table legs, and garden edging, as well as ornate fireplace surrounds including mantelpieces and hearths.

Byproducts and substitutes

Byproducts

In a number of Tamala Limestone block quarries, minor zones of weathering have developed in areas of groundwater movement where some or all of the calcium carbonate binder within the limestone has been dissolved and removed from the rock. This weathering process generally renders the limestone too soft for block cutting, resulting in its removal as waste material. Rather than dumping the limestone waste into landfill areas, it is retained and combined with other limestone waste products such as large quantities of limestone grit, offcuts from sawing operations, and other reject material.

These waste materials form the basis of the reconstituted limestone byproduct industry that is carried out as a secondary process by many of the limestone block producers in the Carabooda–Nowergup area north of Perth. Producers in this area estimate that generally about 40% of total limestone production goes into the manufacture of reconstituted limestone blocks. In areas where weathering is more extensive, this estimate may be higher, possibly reaching 60% in a few places. The reconstituted block-making process is described below.

Substitutes

In a number of areas on the Swan Coastal Plain, at Carabooda, Yanchep, Hope Valley, Narngulu near Geraldton, and Myalup and Kooallup north of Bunbury, the Tamala Limestone is quarried as a weathered, friable calcarenite. This material is crushed and processed for the manufacture of reconstituted limestone building blocks and pavers as substitutes for natural limestone blocks.

There are two methods employed in the manufacture of reconstituted limestone products. Firstly, in both the substitute and limestone byproduct industries, the weathered limestone is crushed to a coarse powder. It is then mixed with water and cement in a predetermined ratio. Coloured oxides for tinting may also be added. The mixture is added to a batching machine that applies considerable pressure to compress the material into block-sized moulds. The newly formed blocks are produced in various sizes and profiles, with the largest size being 1000 × 350 × 350 mm. These are deposited in batches as the machine progresses across a concrete pad on the quarry floor, forming lines of finished product (Fig. 5a).

In addition to the batching process, the second method adopted by Archistone at its Yanchep processing plant is the manufacture of pavers by wet casting in rubber moulds. In this process, a wet mixture of crushed limestone and cement is poured into rubber moulds. Other additives to the mixture may include aggregate for added strength, coloured oxides for standardized tinting, and a moisture dispersant to reduce the effects of efflorescence. The moulds are designed to produce pavers in various standard sizes and surface textures. On drying, the pavers are turned out of the moulds and stockpiled for curing. In a third stage, special orders may be hand finished with profiling treatments such as bullnosing (Fig. 5b).

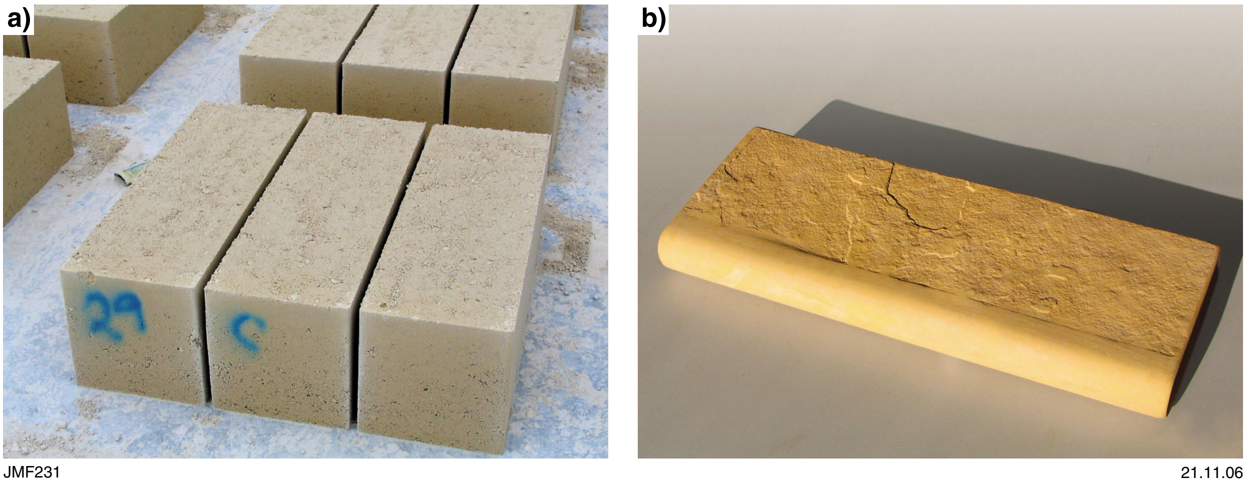

Figure 5. Reconstituted limestone blocks: a) batch-produced blocks 1 m in length; b) an example of a colour-tinted bullnosed paver, 40 cm in length, produced by wet casting (photo (b) courtesy Archistone)

In this industry, reconstituted limestone products are produced to simulate most blocks, pavers, and special application items such pier caps, copings, and bullnoses produced by the natural limestone block industry. Reconstituted limestone products have several advantages over natural limestone. In the first instance, they are inherently stronger due to their vastly increased density (up to 60%) caused by a substantial reduction of pore space. As well, body strength is increased by the addition of aggregate to the mixture. This material may also be tinted by natural oxides to produce products in about ten different standardized colours. It appears the main disadvantage of reconstituted limestone is that it is extremely difficult to reproduce the appearance and feel of surface textures present in natural limestone.

Current trends in the limestone block industry

In recent years, the limestone block industry has increased production to the point where the State has become the largest producer of cut limestone blocks in Australia. Estimates for 2003–04 show that Western Australia produced almost 234 000 tonnes valued at approximately $4.5 million. In addition, estimated production figures for reconstituted limestone blocks, bricks, and pavers were in the order of 237 000 tonnes valued at approximately $3.08 million. This figure, when combined with the figures for natural limestone block production, yields a total production for the limestone building block industry in excess of 471 000 tonnes, with an estimated total value of production in the order of $7.65 million for that year.

In 2004, Austrade identified niche market opportunities for Australian dimension stone mainly in the Indo-Pacific region, particularly in New Zealand where Australia may have a competitive advantage in their steadily growing building industry due to our close proximity and lower transportation costs. This is borne out by the export figures for 2004 for limestone quarry blocks and diamond-cut blocks and slabs where Australia's main overseas markets were New Zealand (95%) and Fiji/French Polynesia (5%; Keating, 2005).

Summary

In 2006, the Tamala Limestone natural stone block industry continues to maintain its position as the largest producer of high-quality cut limestone blocks in Australia. It also continues to produce a substantial quantity of reconstituted limestone blocks, bricks, and other products. In recent years, the industry has expanded in line with increased sales both within Western Australia and also to the eastern states due to rapid growth in the building industry. In addition, exports to New Zealand, Malaysia, and other countries in the Indo-Pacific region have continued to increase in recent years.

It is important that this significant industry be allowed to maintain or increase production in future years, particularly when current sites become worked out. Past investigations indicate that there are probably adequate resources of high-grade limestone situated in places along the coastal corridor between Perth and Dongara. To prevent disruption to production and current markets it is vital that companies to be permitted to access land in these areas, which contain adequate resources of high-grade limestone, for use as future quarry sites.

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Impact of regional airborne geophysical surveys on exploration sentiment: GSWA south Yilgarn magnetic and radiometric surveys, 2004–05

by S. H. D. Howard

Summary

The coincidence of spikes in exploration activity with the release of new survey data in the south Yilgarn area confirms the dramatic impact that regional geophysical surveys can have on exploration sentiment in Western Australia.

Background

On 12 February 2004, the Premier of Western Australia announced a $12 million, four-year additional funding package for GSWA to provide regional aeromagnetic and radiometric coverage for some of the State's most prospective areas. The decision came in response to recommendations of the State Government's Bowler Inquiry into greenfield exploration, the Federal Government's Prosser Inquiry into impediments to increasing investment in mineral exploration, and the industry-led Mineral Exploration Action Agenda process.

Planning for the new program commenced immediately and the southern Yilgarn Craton was selected as the initial area for coverage. In June 2004, advance notice was given of plans to cover an area of approximately 112 000 km^2 in a region extending from Kellerberrin to Ravensthorpe in three major and two minor survey blocks (Fig. 1).

The program included the acquisition of new magnetic and radiometric data along lines 400 m apart from aircraft flying at a nominal 60 m above ground level. The new data, integrated with existing data acquired from private companies, added approximately 400 000 line-km of magnetic and radiometric data to the Western Australia public data inventory.

Gauging exploration sentiment

Exploration sentiment can be gauged by the level of exploration activity that is occurring at a given time — the greater the level of activity the more positive the sentiment and vice versa. Exploration activity can be measured relatively simply by the number of tenements held, the area of ground under tenement, and the level of exploration expenditure.

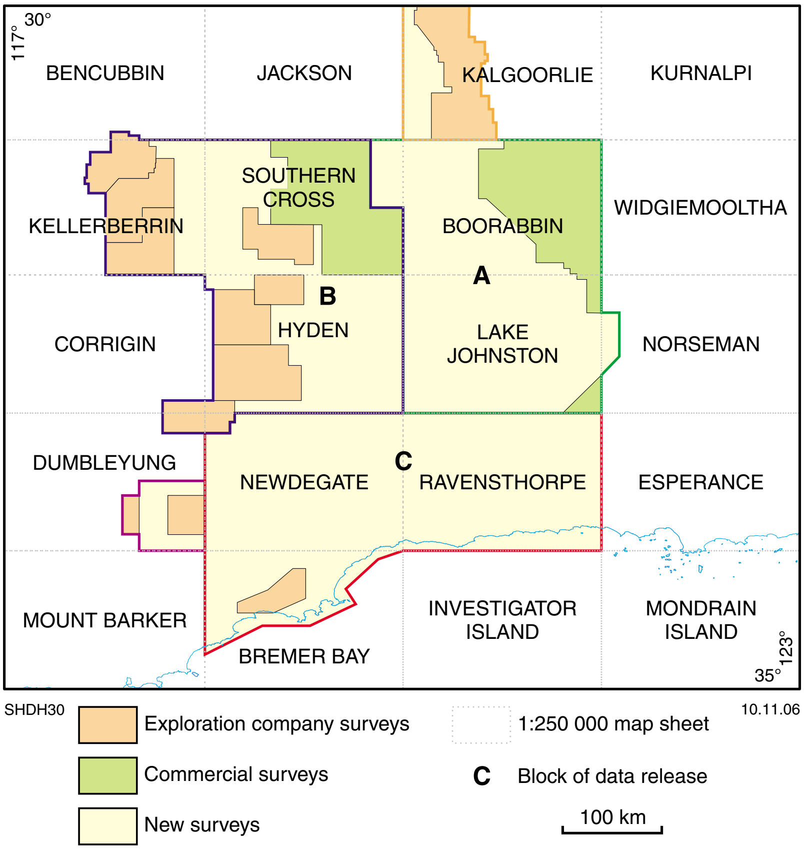

Figure 1. South Yilgarn airborne geophysical survey project area

Private-company exploration sentiment and resultant exploration activity are influenced by a number of factors that relate to the risk involved in exploration investment. These factors include land access, the fiscal and legal framework, the mining law, environmental legacies and security of tenure and, of course, the geological prospectivity or the likelihood that an economic deposit will be found in an area.

The number and complexity of these factors means that it is very difficult, as a general rule, to measure the effect of any one of them on exploration sentiment and activity. However, in cases where only one aspect of the exploration environment has changed, it may be possible to gauge the impact of that factor.

In a politically stable exploration environment such as Western Australia, one factor that can be changed relatively easily is the geological prospectivity, which is almost entirely a function of what is known or surmised about the geology of an area. It is this relationship that underpins the work of the Geological Survey of Western Australia in providing geological maps and other geoscience datasets that can be used to improve the level of understanding about the geology of Western Australia.

Because of the extensive regolith cover of soil and highly weathered rocks in Western Australia, magnetic and radiometric geophysical surveys are widely used as a means to interpret the underlying geology. Hence, the availability of new geophysical data can have a dramatic impact on the perception of the geological prospectivity of an area.

The effect of that change in perception on exploration sentiment might then be gauged by any changes that occur in the level of exploration activity if there have been no changes in other factors.

Key program dates in the south Yilgarn survey program

Advance public notice of surveys: 31 May 2004
New survey contracts let: 13 July 2004

Survey periods:	Start	End
Block A :	30 October 2004	17 February 2005
Block B:	18 September 2004	21 January 2005
Block C:	6 November 2004	5 May 2005

Release schedule announced: April 2005

Data releases	
Block A:	9 May 2005
Block B:	9 May 2005
Block C:	18 July 2005

Exploration activity indicators

Figure 2 shows graphs of exploration activity indicators — in the form of monthly new exploration tenement applications and potential minimum expenditure commitments — in the area of the south Yilgarn survey blocks from July 2004 to April 2006. Superimposed on the exploration activity graphs are the key survey dates.

On all three graphs, there is an undoubted coincidence between significant spikes in new exploration tenement applications and the data release dates.

During this period, the only significant change that we are aware of in the exploration environment in this area was the airborne magnetic and radiometric survey; all other factors either remained constant or changes were the same for the whole of Western Australia.

It is an inescapable conclusion that the availability of the new survey data had a direct impact on the decision to apply for tenement, in these areas.

Quite apart from the inferential conclusion of a causal link between the availability of the data and increased tenement activity, in at least one case, an Australian Stock Exchange (ASX) release notice issued by an exploration company three days after the data release date makes the linkage unequivocal: ‘Image Resources is pleased to announce the acquisition of 14 new tenements totalling 1045 sq km in the southern Yilgarn, centred on the Ravensthorpe belt of WA following the release of new government aeromagnetic and radiometric data’ (Image Resources, ASX release, 21 July 2005).

The new application spikes in the three areas are equivalent to first-year expenditure commitments of some $2 million in aggregate, if all applications were granted.

Effect on GSWA data release policy

Up to this time, GSWA policy has been that new survey data were released only after completion of all stages of processing and final data evaluation. For large surveys, this meant a delay of many months between commencement of the survey and final data release.

The impact of this demonstrated link between new geoscience data and tenement activity has resulted in a change to GSWA policy for data release. On subsequent surveys, preliminary images and datasets have been released in stages (with appropriate warnings to end-users) as blocks of data from the survey were acquired. A release of preliminary data over the whole survey area is made at the completion of the data-acquisition stage. This allows exploration companies and other users of these datasets to make initial plans and decisions in a much more timely manner.

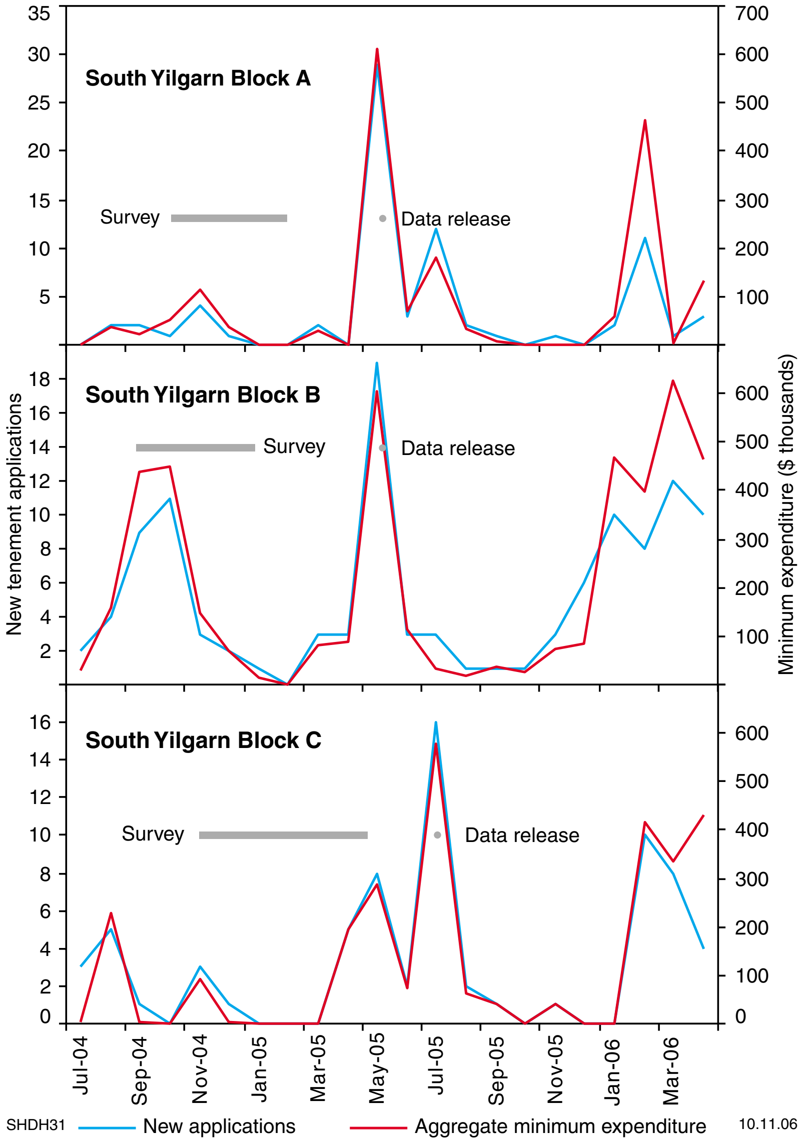

Figure 2. Exploration activity indicators in areas of regional geophysical surveys

As usual, the final data release is not made until all data processing has been completed and the data fully evaluated.

Inside GSWA

Trevor Holland

Trevor Holland has had a somewhat chequered career with the Geological Survey. He first joined as a field assistant for a trip to the Devonian reefs of the West Kimberley in 1994. This followed a career in applied engineering (asbestos removal and noise reduction) and a stint selling Atari computers, at the time a popular choice for people in GSWA making an early leap into personal computers other than expensive IBM compatibles. The 1994 trip saw the invention of our 'Holland blind', engineered from shade-cloth and designed to keep spinifex seeds from clogging both radiator and air conditioning condenser in Landcruisers; portable gas-powered soldering irons making an appearance in vehicle repair; eight punctures after 3.30 pm one day due to a particularly nasty but unavoidable section of scrub; and creation of the honorary title of 'Trev' as something a Jaffa (just another flamin' field assistant) could aspire to in another life. The trip also saw several new place names for memorable localities in the West Kimberley: Galah Wipeout (the galahs were colourful to the point of distraction and a near miss whilst driving), Icicle (a very scenic but very cold spring), Club Mud (it was, very much so, around the tank), Rialto on Barramundi (a riverside campsite at Barramundi Pool), and Lawford Country Club (the base of operations for work in the Sparke Range, at Lawford Spring), among others. And some sayings have carried on through the years: 'That's not too bad. It's three bad', 'My grandmother was slow but she was old', and 'Hungry enough to eat a low-flying duck.' Trev came out of the trip half the man he was, due to a dedicated exercise program that included carrying mid-morning apples and oranges considerable distances up hills for the geologist's mid-morning snack.

Following the 1994 winter sojourn in the Kimberley, Trev continued on in the Survey, taking a position as Man Friday to the recently started Petroleum Initiatives teams. This position included assessing computing and data requirements in the teams, setting up and maintaining technical packages in the section, maintaining work flow (he has not-so-fond memories of using MS Project regularly, and even wading through the manual to understand the 'cumbersome obscure monster'), and assisting or supervising field operations related to the drilling of GSWA stratigraphic wells in the Southern Carnarvon Basin. He was so impressed with the country seen while involved with the latter that he later took his family on a vacation trip around some of the back blocks of the basin. After a couple of years, Trev's usual restless pattern kicked in again unfortunately, leading to him returning to the engineering field in the private sector.

Ultimately, the return to engineering led to an unacceptable work–family balance, despite financial benefits. Three weeks out every four were spent over east away from the family, and even back in Perth there were long hours in the Perth office. So, when a position arose in the newly opened GSWA Core Library at Carlisle, Trev rejoined the Survey in 2002. The sweetener to the deal may have been the opportunity of a trip through central Western Australia visiting parts of the Earaheedy and northwest Officer Basins, and climaxing with work in the river and coastal gorges around Kalbarri. That trip saw on-the-spot rewiring of part of the Landcruiser's wiring loom after some pinched wires, 60 km east of the Canning Stock Route in the middle of the Little Sandy Desert. Since then, Trev's primary duties have been with the core library, where he presently shares management duties with Chris Brooks. The cheery greeting of 'Good morning! Perth Core Library, Trevor Holland speaking, how can I help you?' has become familiar to many core library users.

From time to time he manages to convince his heirarchy that a quick trip bush would be a Good Thing, be it for helping out on a blasting trip or managing geologists' needs in the Musgraves. He has yet to convince them that another trip to the Kimberley is essential to his career development, despite a few tries.

Trev also spent three months in a fly in/fly out basis acting as core librarian for the Joe Lord Core Library in Kalgoorlie. He now fights off possible increases in waistline by commuting via hypertrike, a recumbent tricycle, and notes the irony in working for a Department that is encouraging and promoting oil exploration while he personally refuses to use 'the stuff', even at the cost of his nether portions getting soaked between three splashing wheels when riding in the rain. There may even be a certain pride in the fact that recumbent riders are referred to as 'bent', versus the 'wedgies' who ride upright bicycles.

This time Trev is determined to stay within the Public Service and break the pattern of firing himself each few years, as he sees positive aspects that may be overlooked by many who are tempted by the bright lights and better pay of industry. The corporate pay may have been much higher, but he considers a far greater price was extracted in terms of family and satisfaction. In the Department, Trev finds a good balance between his work and home life, which he devotes to wife Cheryl, who puts up with his eccentricities and has even taken up weekend hypertrike riding with Trev, and two adult kippers (kids in parental property, eroding retirement savings), Dean and Keryl.

Shannon Carter

Shannon Carter (formerly Coghlan) is friendly, extremely motivated and a team player. She joined the Geoscience Information Products Group (GIPG) within the Geological Survey in January 2005 and has been a valuable asset to the GIS section.

Shannon was born in Perth a mere 23 years ago. Being the only child of teacher parents, she had the opportunity to travel the world with them visiting places that some of us can only dream of. Her travelling started at the tender age of six months when she attended an aunt's wedding in Adelaide. Then it was Singapore and Hong Kong and this was only a taste of what was to come. Her family moved to the town of Newman when she was four years old and at the age of seven her parents took long service leave for one year to travel the world. Places they visited included Greece, Russia, England, France, Italy, the Netherlands, Israel, Egypt, Hawaii, New Zealand, Fiji and America, to name a few. A couple of years later she went to the USA again for six weeks and visited an uncle stationed there. She also went skiing in New Mexico and stayed in a cabin in the snow for a couple of weeks. At the age of 15 it was on to Scotland for Christmas and

Hogmanay near the castle where Mary, Queen of Scots was born. Shannon's travelling highlights were cruising the Nile visiting the pyramids of Egypt, visiting Disneyworld, and skiing in New Zealand.

In between travelling, Shannon managed to squeeze in her studies at numerous primary schools. Shannon completed her Bachelor of Science degree majoring in geography in 2003 at the University of Western Australia (UWA) where she also met her husband Ben through mutual friends. After years of courtship he finally whisked her away one weekend to Sydney and proposed. They recently married in February in the grounds at UWA, which obviously holds a special place in their hearts. For the honeymoon, they flew business class to Thailand and spent three fantastic weeks in Phuket, staying in a great resort, going diving, and enjoying the swim-up bar at the resort and the cheap massages on the beach.

Shannon's first real introduction to industry was work experience at ER Mapper, and then she began work with the Department of Indigenous Affairs, using the GIS skills that she had learnt at university to determine spatial accuracy of Heritage Sites.

Shannon currently works as a Spatial Information Officer in the GIS section, operating ESRI software in acquiring, integrating and editing spatial data and producing digital data products with the information. Recently, at the end of the financial year, Shannon sustained a broken leg whilst attempting to score a try in touch rugby. Her presence was sadly missed during the challenge of meeting the Survey's end-of-year production targets. But inevitably the question on everyone's mind is did she score the try? You may have to ask her that yourself.

Mike Freeman

Mike Freeman is passionate about many things, and whether it is geology, photography, the stars or old slightly off-beat 4WD vehicles, particularly Landrovers and Russian Ladas, he is a wealth of knowledge.

Mike is originally from South Australia, where in 1964 he completed high school with the honour of topping the State in geology. In 1969 he gained his science degree from Adelaide University majoring in geology/geochemistry and mathematical statistics/computing. After graduation Mike joined the Geological Survey of South Australia, where he worked in the engineering geology and hydrogeology section.

In 1970, Mike left the Geological Survey of South Australia to work in industry and for the next eight years was employed by Mines Exploration in Broken Hill, Adelaide, and Mount Isa, and during this period was actively involved in the exploration for a variety of commodities, particularly phosphate. This led to his involvement in the development of Phosphate Hill in Queensland.

In 1978, Mike joined the Northern Territory Geological Survey (NTGS) working on regional mapping projects based out of Alice Springs. In 1986 he was runner-up Achiever of the Year out of 700 staff in the Northern Territory Department of Mines and Energy.

Returning to industry in 1987, he accepted a position as project geologist for the Kundana gold deposit, 25 km west of Kalgoorlie. At the completion of the project, a resource of 1.5 Mt of 3.5 g/t gold was defined and this formed the basis to re-establish mining operations at this historical gold mine. The Kundana mine has since produced over 1 million ounces of gold. In 1988, Mike moved out of gold and into coal working for the Griffin Coal Mining Company.

Mike started work at the Geological Survey of Western Australia in February 1989 in the Engineering and Environmental Section and was involved in regional geology, mineral exploration and mining issues related to nature conservation and environmental and regional planning issues. Of great interest at this time was his involvement as an 'expert witness' to support the Western Australian Police in the Karpa Spring fraud case. Mike's scientific investigations in relation to this fraud received high acclaim and were even praised in Parliament. Mike still talks about being probably the only field geologist who explored a 'prospect' for two weeks with six detectives providing him with a 24-hour armed guard!

With the formation of a separate Land Access Branch within the Department Mike left GSWA. His role in the branch covered a very broad range of geoscientific applications, community consultations, and policy development related to mineral, construction material, and petroleum access for exploration and extraction access in areas of environmental, social or cultural sensitivity. In 2002, with the disbanding of the Land Access Branch, he moved back to the GSWA where he took on the role of Community and Industry Liaison.

Mike is an extremely hard working individual, passionate about his geology, who is often consumed with his work. On occasions it appears that he both lives and breathes the issues surrounding the protection of mineral and petroleum resources. Mike's contributions to the protection of resources has been significant, particularly titanium–zircon mineralization on the Swan Coastal Plain, the Darling Range bauxite, and construction materials. His large network of contacts, particularly with other Government departments, has often facilitated successful outcomes.

Mike has very broad interests and has been actively involved in the Geological Society of Australia. He was a member of Northern Territory Stratigraphic Nomenclature Subcommittee for five years and contributed to Geological Monuments (Geoheritage) Subcommittee, compiling a list of registered and proposed sites for central Australia, as well as secretary of the Western Australian Division for six years and a member of the Federal Executive Council for two years. For his contributions to the Society he was awarded the honorary category of Fellow of the Society.

If, on occasions, Mike appears 'starry eyed' it probably means he has been up all night looking at the stars, as he is a member of the Meteoritical Society and an active volunteer guide for star viewing at the Perth Observatory.

Mike is an avid photographer and never goes into the field without a camera. Those who have accompanied him on field trips can give testament that he is very good at taking the most unflattering photos of his work colleagues. He is a member of the Australian Photographic Society and has won several photo awards.

Mike has now left the Geological Survey, accepting a promotion to the Mineral and Title Services Division where he heads up a small team assisting and facilitating the development of small- to medium-sized mining projects.

Staff list
(30 June 2006)

GRIFFIN, Tim (Executive Director)

Regional Geoscience Mapping Branch

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

Terrane Custodians
FARRELL, Terry (Geoscience Database)
HOCKING, Roger (Basins)
MIKUCKI, Jenny (WA Geology Online)
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
GROENEWALD, Bruce
SHEPPARD, Steve

Earaheedy Basin
JONES, Amanda

West Musgrave
HOWARD, Heather
PIRAJNO, Franco
SMITHIES, Hugh

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DOYLE, Chris
HALL, Charlotte
PAWLEY, Mark

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FORBES, Caroline
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FERGUSON, Andrew[1]
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BODEKER, Donald
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D'ANTOINE, Neville
DOWSETT, Suzanne
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HAMILL, Sam[1]
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JEFFERYS, Stewart
KIRK, John
KUKULS, Liesma (Les)[2]
KUMAR, Manjeet
LADBROOK, David
LESIAK, Irena
McDONALD, Tuyen
MARON, Marcel
MULLIGAN, Sue
PRAUSE, Michael
SIMONETTI, Joseph
SUTTON, Dellys
TAYLOR, Peter
TRUICA, Oana
WEITER, Hana
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MIDDLETON, Michael
MORY, Arthur
SALUNDI, Michael
XU, Min

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ORMSBY, Warren
PEIRIS, Elias
RUDDOCK, Ian
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FETHERSTON, Mike

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FITTON, Ann
GRZESIOWSKA, Eva
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HEWSON, Paul
IRIMIES, Felicia
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KARNIEWICZ, George
MacCORQUODALE, Fiona
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NOACK, Scott
O'BRIEN, Richard
ORTON, Vergil
PIGOTT, Michele
PIZZI, Robert
SUCHODOLSKI, Christine
SZWEDZICKI, Mary

[1] On secondment to other parts of DoIR
[2] On secondment to other Departments or industry

Staff movements (1 July 2005 to 30 June 2006)

Internal reclassifications
DODD, Fiona — to Level 3
BODORKOS, Simon — to Level 5
CHEN, She Fa — to Level 7

Commencements
BLAKE, Alan
FALLETTI, Benjamin
LEIGHTON, Andrew
LIANG, Trent
MIDDLETON, Michael
PAWLEY, Mark
REDDIN, Renae
TRUICA, Oana
WALLACE, Darren
WILLIAMS, Samantha
WINGATE, Michael
XU, Min

Resignations
BAIRD, Angus
CUNNEEN, Jane
FREEMAN, Heather
IASKY, Robert
JONES, Sarah
PIZZI, Trevor
QUINN, Matthew
WEBSTER, Jeffery
ZENGERER, Matthew

Secondments
BANDY, Stephen — to Spatial Infrastructure project
FRANCOIS, Annick — to Mineral and Title Services Division
HAMILL, Sam — to Mineral and Title Services Division
KUKULS, Liesma — to Department of Environment
NAGY, Pearl — to Mineral and Title Services Division
SHEVCHENKO, Sergey — to industry

Transfers out
FREEMAN, Michael — to Mineral and Title Services Division
GOSS, Andrew — to Facility Services Branch
MASON, Jan-Sandra — to Mineral and Title Services Division
STEVENS, Mark — to Petroleum and Royalties Division

Casual and short-term contracts
EDMONDS, Tracey
THORNTON, Katrina
GOSS, Sarah
GRAY, Erin

Retirements
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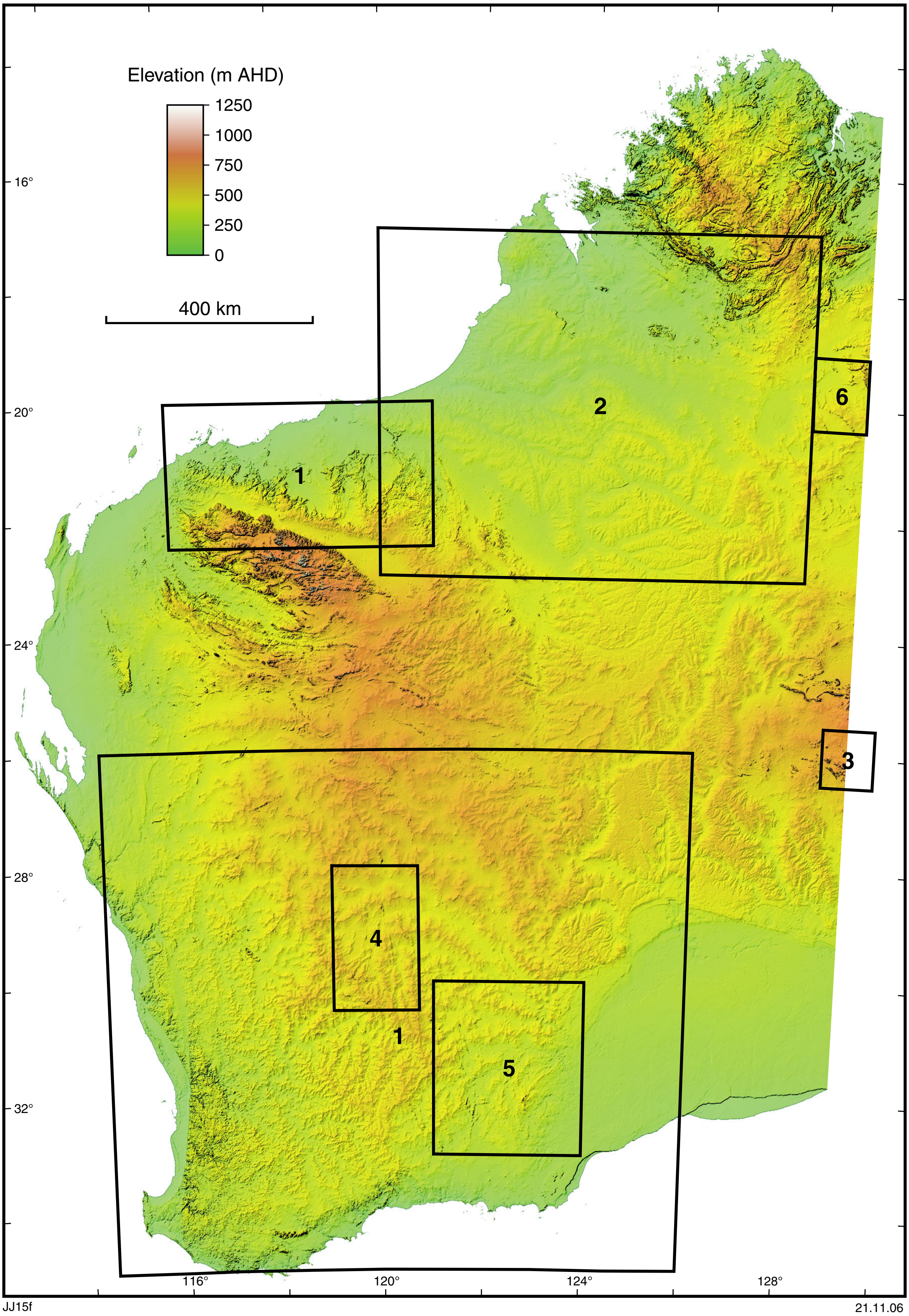
staff contacts for 30 June 2006



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

Archean tectonics in the Pilbara and Yilgarn Cratons

by S. F. Chen, A. H. Hickman, and P. B. Groenewald

Abstract

Western Australia has two Archean cratons — the well-exposed 3.72 – 2.83 Ga Pilbara Craton and the poorly exposed 3.01 – 2.62 Ga Yilgarn Craton (with minor older components, up to 3.73 Ga, in the western parts) that evolved independently until they collided during the Paleoproterozoic to produce the intervening Capricorn Orogen. Together, both cratons have recorded more than 1000 Ma of Archean geological history, and although they evolved independently, they do exhibit certain common evolutionary trends that are evident in many of the world's Archean cratons.

In the Paleoarchean East Pilbara Terrane, greenstone stratigraphy shows several cycles of mafic(–ultramafic)–felsic volcanic rocks, overlain by a thick Mesoarchean clastic sedimentary assemblage. The granites were generally coeval with greenstones, and the earlier tonalite–trondhjemite–granodiorite-type granites had given way to K-rich granites, and regional dome-and-basin structural patterns were developed mainly by vertical tectonic processes.

In the areas dominated by Mesoarchean to Neoarchean granite–greenstone belts, particularly in the Yilgarn Craton, localized greenstone stratigraphy defines a temporal change from mafic(–ultramafic) volcanic rocks to felsic volcanic rocks to clastic sedimentary rocks, although there are some significant exceptions. The majority of granites are younger than greenstones, and the dominant monzogranites were recycled from early crust. Structures with preferred orientations were formed mainly by horizontal tectonic processes.

In both the Pilbara and Yilgarn Cratons, pre-existing early crust, as indicated by Nd isotopic ages, and xenocrystic and detrital zircon ages, was largely recycled into granites.

KEYWORDS: Pilbara Craton, Yilgarn Craton, Archean, tectonics, crust, recycling.

Introduction

The Pilbara Craton (Fig. 1) comprises five granite–greenstone terranes — the East Pilbara Terrane, the dominantly granitic Kurrana Terrane, and the Karratha, Sholl, and Regal Terranes that together form the West Pilbara Superterrane — and a partly stacked series of basins — the Gorge Creek, Whim Creek, Mallina, Lalla Rookh, and Mosquito Creek Basins that form the De Grey Superbasin (Van Kranendonk et al., 2006). The terranes are separated from the basins by unconformities ranging in age from 3.05 Ga to older than 2.93 Ga. Greenstones in the terranes are dominantly volcanic, whereas, with the exception of the Whim Creek Basin, the basins are dominantly sedimentary.

In the Yilgarn Craton (Fig. 2; Cassidy et al., 2006) the 3.73 – 2.62 Ga Narryer Terrane and the 3.2 – 2.62 Ga South West Terrane are dominated by granite and granitic gneiss; and the 3.01 – 2.62 Ga Youanmi Terrane and the 2.72 – 2.63 Ga (locally >2.73 Ga) Eastern Goldfields Superterrane contain greenstone belts surrounded by granitic expanses. As in the Pilbara Craton, thick clastic sedimentary rocks overlie volcanic greenstones in parts of the Yilgarn Craton.

In this paper we highlight recent scientific work and advances in understanding the similarity and differences in granitic magmatism, greenstone volcanism, clastic sedimentation, structural styles, and tectonic processes of the two cratons, and then discuss the evidence for the presence and recycling of early crust, and the crustal evolution trends from the Paleoarchean to Neoarchean.

Granitic magmatism

In the Pilbara Craton the oldest (3.49 – 3.41 Ga), dominantly tonalite–trondhjemite–granodiorite (TTG)-type granites are only in the East Pilbara Terrane. The 3.32 – 3.29 Ga granites ranging from tonalite

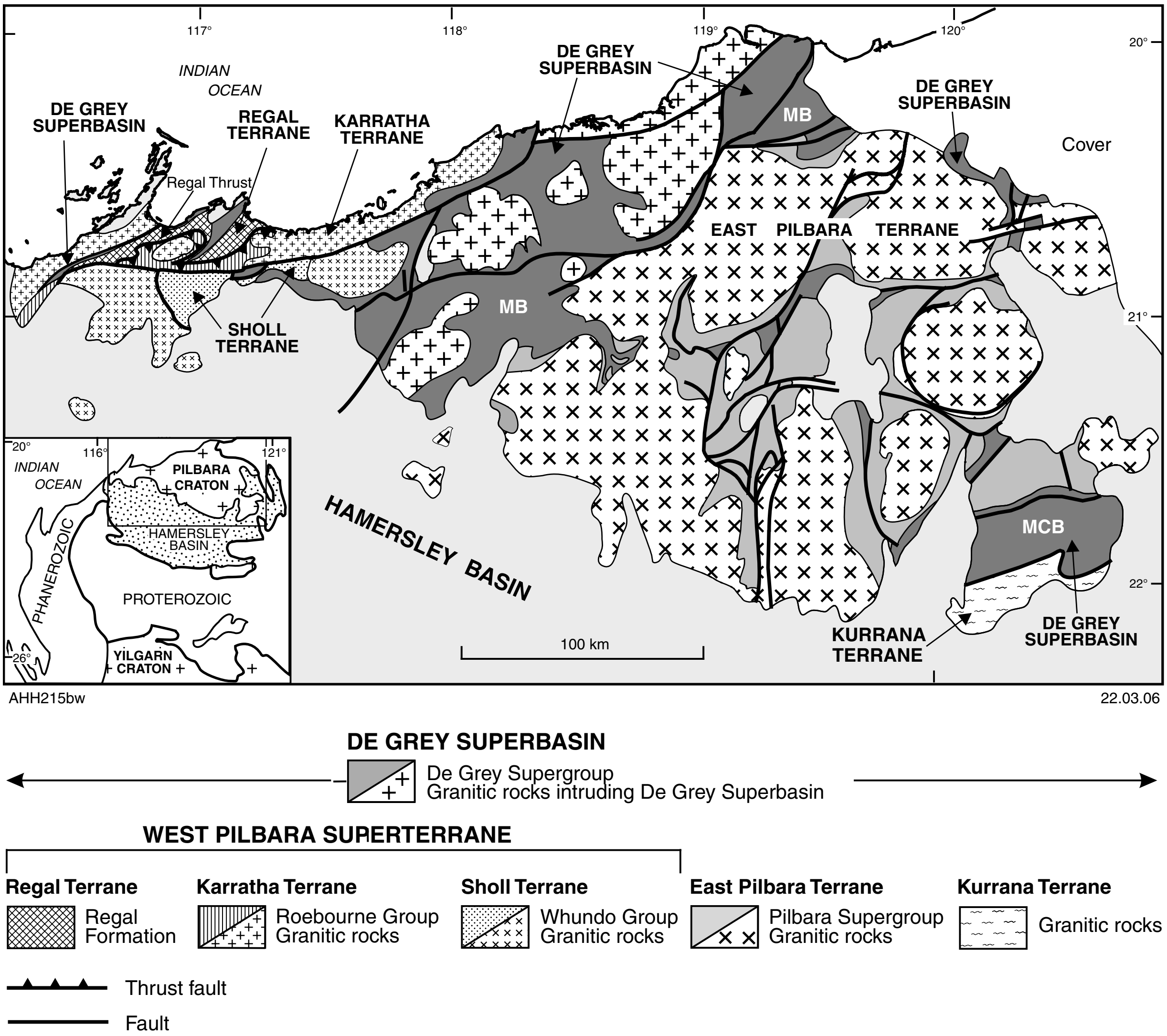


Figure 1. Simplified geology of the Pilbara Craton, with terrane subdivision after Van Kranendonk et al. (2006). MB = Mallina Basin; MCB = Mosquito Creek Basin

through monzogranite to syenogranite are restricted to the eastern half of the East Pilbara Terrane. The 3.27 – 3.23 Ga granites (mostly monzogranite) are mainly in the East Pilbara Terrane, but locally also in the West Pilbara Superterrane, where they are interpreted to be in a rifted fragment of the East Pilbara Terrane. The 3.02 – 2.97 Ga granites are only in the West Pilbara Superterrane, with no age equivalents in the East Pilbara Terrane, and the majority is relatively potassic. The 2.97 – 2.92 Ga granites (dominantly mozogranite to syenogranite) are in the Mallina Basin, West Pilbara Superterrane, and western part of the East Pilbara Terrane. The 2.88 – 2.83 Ga granites of mainly monzogranite are in the Mallina Basin and East Pilbara Terrane. Paleoarchean granites are mainly in the East Pilbara Terrane, where the majority of granites are coeval with felsic volcanism. Granites in the West Pilbara Superterrane and Mallina Basin were intruded mainly in the Mesoarchean. True TTG-type granites are rare and represent the oldest (>3.4 Ga) granite magmatism in the East Pilbara Terrane. In general, granite magmatism becomes more potassium-rich as it gets younger as a result of continual recycling of felsic crust (Champion and Smithies, 2001).

In the Yilgarn Craton granites and granitic gneisses were emplaced at 3.73 – 2.62 Ga in the Narryer Terrane, at 3.01 – 2.62 Ga in the Youanmi Terrane, and mostly at 2.72 – 2.63 Ga in the Eastern Goldfields Superterrane (Cassidy et al., 2006; Geological Survey of Western Australia, 2005). The granitic rocks in the Yilgarn Craton are dominated by monzogranite, with minor TTG, granodiorite, sanukitoid, and syenite. The majority of granites are younger than greenstones, although some older granites are coeval with felsic volcanism in greenstone belts. On the basis of geochemistry, Champion and Sheraton (1997) and Cassidy

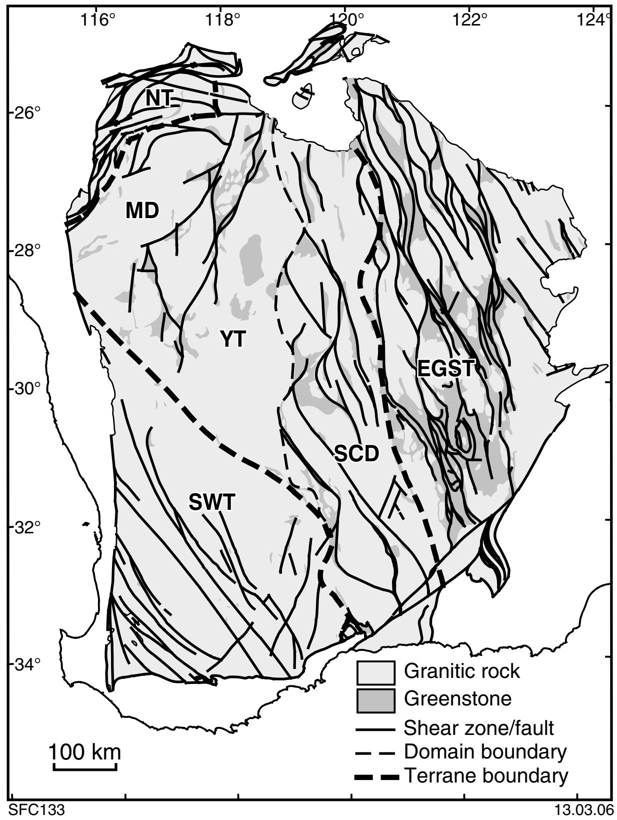


***Figure 2.** Simplified geology of the Yilgarn Craton, with terrane subdivision after Cassidy et al. (2006). EGST = Eastern Goldfields Superterrane; NT = Narryer Terrane; SWT = South West Terrane; YT = Youanmi Terrane that includes the Murchison Domain (MD) and Southern Cross Domain (SCD)*

et al. (2002) subdivided the granites in the Yilgarn Craton into five groups (the High-Ca, Mafic, Low-Ca, and High-HFSE Groups; and the Syenitic Group that is restricted to the Eastern Goldfields Superterrane). A major change at 2.65 Ga from High-Ca granites to Low-Ca granites indicates a distinct change in the tectono-thermal regime of the crust. The Low-Ca granites have similar ages across the craton, implying that a similar process occurred craton-wide at this stage (Champion and Smithies, 2001; Cassidy et al., 2002).

Greenstone stratigraphy

In the East Pilbara Terrane of the Pilbara Craton, greenstones (up to 20 km thick) are composed of four dominantly volcanic groups (the 3.52 – 3.20 Ga Warrawoona, Kelly, Sulphur Springs, and Soanesville Groups) that are overlain, across a regional unconformity, by the sedimentary basin successions of the 3.05 – 2.93 Ga De Grey Supergroup (Van Kranendonk et al., 2006). Greenstone stratigraphy of the East Pilbara Terrane shows several cycles from mafic–ultramafic volcanism to felsic volcanism. The greenstone succession of the 3.28 – 3.25 Ga Karratha Terrane of the West Pilbara Superterrane commences with ultramafic and mafic rocks that pass upwards into felsic volcanic and sedimentary rocks. The lower part of greenstone succession in the Sholl Terrane comprises ultramafic and mafic rocks and the top is felsic volcanic, but the central section contains both mafic and felsic volcanic rocks. The geochemical features of the Whundo Group within the Sholl Terrane provide unambiguous evidence of modern-style subduction processes at 3.12 Ga in the Mesoarchean (Smithies et al., 2005). The basal stratigraphy of the Regal Terrane is ultramafic, but most of the preserved greenstone succession consists of basalts. Within the De Grey Superbasin the basal 3.05 – 3.02 Ga Gorge Creek Basin extends 500 km east–west and up to 200 km north–south, and contains banded iron-formation and predominantly fine-grained clastic sedimentary rocks. The 3.1 – 3.0 Ga Whim Creek Basin is volcanic and restricted to the northwestern margin of the Mallina Basin, whereas the 2.97 – 2.93 Ga Mallina Basin and Mosquito Creek Basin are composed of siliciclastic turbidites (Van Kranendonk et al., 2006).

In most parts of the Yilgarn Craton correlation of greenstone stratigraphy between greenstone belts has so far been precluded by structural complexity, poor exposure, and limited geochronology. Greenstone stratigraphy in the central Southern Cross Domain of the Youanmi Terrane typically defines a temporal change from 3.0 Ga mafic(–ultramafic) volcanism with local basal quartzite sedimentation to 2.73 Ga felsic–intermediate volcanism to clastic sedimentation (Chen et al., 2003). Watkins and Hickman (1990) extended a lithostratigraphic interpretation of well-exposed greenstone successions in the southern Murchison Domain of the Youanmi Terrane into the northern Murchison Domain, and thereby proposed a regional stratigraphy for the Murchison Domain. In this interpretation a 3.0 Ga succession of komatiite, basalt, banded iron-formation, and felsic volcanic rocks is unconformably overlain by various local 2.8 – 2.7 Ga basin successions of volcanic and clastic sedimentary rocks. However, Pidgeon and Hallberg (2000) rejected this stratigraphy in the northern Murchison Domain on the basis of new geochronological data, where they recognized a similar lithological sequence to that of the Southern Cross Domain. In the Kalgoorlie area of the Eastern Goldfields Superterrane, volcano-sedimentary rocks also define a similar stratigraphic sequence to that of the Southern Cross Domain, but have younger ages (2.7 – 2.65 Ga; Swager, 1997; Krapez et al., 2000).

Structural styles and tectonic processes

In the Pilbara Craton the East Pilbara Terrane exhibits a regional dome-and-basin structural pattern, with no preferred structural orientations (Van Kranendonk et al., 2002). The 'domes' typically expose cores of granitic rocks and orthogneiss, whereas the 'basins' are developed in low-grade metamorphosed, synformal greenstones. Older granite components are commonly preserved along the margins of the domes, whereas successively younger phases occupy the cores. The contacts of granite domes with greenstones vary from being locally intrusive, or the locus of shearing, to an unconformity with younger supracrustal rocks. Where the contacts are sheared they commonly dip steeply towards greenstones and have a normal movement sense. In greenstones, bedding and foliation typically dip away from the granite domes, and mineral elongation lineations show a radial distribution pattern around the domes. Although some authors (e.g. Blewett, 2002) argued that horizontal extension and shortening was the dominant tectonic mechanism in the East Pilbara Terrane, Hickman (2004) and Van Kranendonk et al. (2002) provided evidence that the structural pattern of the East Pilbara Terrane is not the result of Alpine-style orogeny or cross-folding, but is mainly the product of vertical tectonism (diapirism). In contrast to the East Pilbara Terrane, the West Pilbara Superterrane exhibits a strong northeast-oriented structural grain defined by the elongation of granite complexes, the trend of greenstone belts, fold axes, closely spaced shear zones (e.g. Sholl Shear Zone), and faults. No diapiric domes are present in the West Pilbara Superterrane where all deformation is interpreted to be the result of successive episodes of horizontal shortening (Hickman, 2004). Similarly, structures in the Mallina Basin, Mosquito Creek Basin, and Kurrana Terrane are also derived from horizontal tectonic processes.

In the Yilgarn Craton the Narryer Terrane contains rocks with ages of up to 3.73 Ga, but most of the preserved structures within the terrane were formed by horizontal shortening events during the Neoarchean. In the Youanmi Terrane an early phase of north–south compression produced originally east-trending foliations, thrusts, and folds that are overprinted by northerly trending folds developed during east–west shortening (Myers and Watkins, 1985; Chen et al., 2003). Continued east–west shortening produced northeast-trending dextral shear zones in the Murchison Domain, and both northeast-trending dextral and northwest-trending sinistral shear zones in the Southern Cross Domain that are linked by north-trending contractional zones, forming large arcuate structures (Chen et al., 2001). Similar horizontal shortening events, but with younger ages are recognized in the Eastern Goldfields Superterrane, where early north–south thrusting was succeeded by east–west thrusting and regional folding that was followed by strike-slip shearing. Moreover, pre-, syn-to post-orogenic extensional events have also been documented in the Eastern Goldfields Superterrane by some authors (e.g. Swager, 1997; Blewett et al., 2004). Local dome-and-basin structures in the Yilgarn Craton are interpreted as a result of either diapirism (e.g. Gee et al., 1981) or overprinted folding (Myers and Watkins, 1985). However, most authors agree that the dominant structural patterns in the Yilgarn Craton reflect horizontal tectonic processes.

Presence and recycling of early crust

Increasing evidence, particularly from recent studies on Nd model ages, and from xenocrystic and detrital zircon ages, support the presence of early crust that was recycled during subsequent granite intrusion and greenstone deposition in the Pilbara and Yilgarn Cratons. In the East Pilbara Terrane, 3.72 – 3.53 Ga represents a period of early crust formation as determined from xenocrystic and detrital zircon ages as well as from xenoliths of gabbroic anorthosite and migmatitic tonalite orthogneiss (Van Kranendonk et al., 2002). Nd isotopic data indicate that the eastern two-thirds of the East Pilbara Terrane is underlain by older (>3.3 Ga) crust than the western third of the East Pilbara Terrane where there is far less common isotopic evidence of crust older than 3.2 Ga. Early crust is locally present in the West Pilbara Superterrane, as indicated by Nd and zircon ages of 3.5 – 3.3 Ga. For example, much older Nd model ages of 3.48 – 3.43 Ga from the 3.27 – 3.26 Ga Karratha Granodiorite indicate that granitic magma generation involved older crust or enriched lithospheric mantle (Sun and Hickman, 1998).

In the Yilgarn Craton, Nd model ages of granites are significantly older than their crystallization ages, generally 200–300 Ma and sometimes over 500 Ma older (Champion and Sheraton, 1997; Cassidy et al., 2002), which strongly supports the existence of early crust before the intrusion of granites. The Narryer Terrane has the oldest Nd model ages (generally 3.8 – 3.3 Ga), and the Youanmi Terrane comprises a relatively consistent block of 3.3 – 3.1 Ga crust, except for a belt of younger, 3.1 – 2.95 Ga model ages in the northern part of the Murchison Domain. A distinct 'break' that approximates the Ida Fault marks the boundary between the Youanmi Terrane and Eastern Goldfields Superterrane. All granites in the Eastern Goldfields Superterrane have Nd model ages younger than 3.1 Ga, and generally younger than 2.95 Ga (Champion and Sheraton, 1997; Cassidy et al., 2002). The presence and recycling of extensive early crust in the Yilgarn Craton is also indicated by older inherited zircons in younger granites, contamination of mafic and ultramafic rocks by the early crust, and the occurrence of basal quartzites and metasedimentary rocks with detrital zircon ages as old as 4.4 Ga (e.g. Barley, 1986; Wilde et al., 2001). The early crust in the Yilgarn Craton has been largely recycled, probably through crustal reworking, into voluminous Neoarchean granites, and crustal recycling has largely destroyed the basement to the greenstones. This may explain why it is difficult to identify the basement within the craton.

Conclusions

In the Paleoarchean East Pilbara Terrane, early TTG-type granites (>3.4 Ga) were subsequently recycled into more K-rich granites. In the Mesoarchean to Neoarchean Yilgarn Craton, monzogranite is abundant as a result of crustal recycling.

Greenstone stratigraphy in the Paleoarchean East Pilbara Terrane is common to many greenstone belts, defines several cycles of mafic(–ultramafic)–felsic volcanic rocks, and correlates with episodes of granitic intrusion. In the Mesoarchean West Pilbara Superterrane and the Mesoarchean to Neoarchean Yilgarn Craton, greenstone stratigraphy appears to be localized to individual greenstone belts, some of which show a temporal change from mafic(–ultramafic) volcanism to felsic volcanism to clastic sedimentation. Thick clastic sedimentary rocks were typically deposited in late basins in both the Pilbara and Yilgarn Cratons.

Structures in the Paleoarchean East Pilbara Terrane are characterized by a dome-and-basin pattern, with no preferred structural trends, and tectonic processes are dominated by vertical diapirism. In the Mesoarchean West Pilbara Superterrane and the Mesoarchean to Neoarchean Yilgarn Craton, structures show preferred trends, and tectonic processes are dominated by horizontal extension and shortening.

Crustal recycling played an important role in the formation of Archean granite–greenstone terranes of both the Pilbara and Yilgarn Cratons. The pre-existing early crust was largely recycled into voluminous granites.

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Fingerprinting reservoir sandstone provenance in the Canning Basin using detrital zircons

by P. W. Haines and M. T. D. Wingate

Abstract

Detrital zircons have been dated from potential sandstone hydrocarbon reservoirs in the Willara (Acacia Sandstone Member), Gap Creek, and Carranya Formations of the Canning Basin. Two discrete detrital-zircon source areas are recognized, which are most probably the North Australia Craton and adjacent Neoproterozoic sedimentary basins or their source terrain. Significant differences between zircon age spectra in the Acacia Sandstone Member in petroleum exploration wells Looma 1 and Acacia 2 suggest that either this unit is not a single entity, but several discrete sandstone bodies of similar age fed from different sediment input points during relative low stand(s) of sea level, or that provenance switching during deposition led to provenance stratification within the unit. Each has important implications for predicting reservoir distribution and lateral facies changes.

KEYWORDS: zircon, geochronology, hydrocarbons, Ordovician, Canning Basin, Willara Formation, Acacia Sandstone Member, Gap Creek Formation, Carranya Formation, Western Australia.

Introduction

The Canning Basin (Fig. 1) is Western Australia's most extensive onshore hydrocarbon province, but is significantly underexplored. The Ordovician strata of this basin (Fig. 2) contains adequate hydrocarbon source rocks and displays significant oil and gas shows, but is yet to produce a commercial field. A major challenge for explorers is locating good quality hydrocarbon reservoirs. One promising reservoir unit is the locally developed Acacia Sandstone Member of the Willara Formation (Fig. 2), from which good reservoir quality and hydrocarbon shows have been reported locally, but its distribution and regional facies trends are poorly constrained.

Detrital zircon dating is an important tool for establishing sediment provenance and distribution pathways. In cases like the Canning Basin sandstone reservoirs, such studies may be able to provide additional constraints on the deposition of these units by linking well or outcrop control points to possible sediment input points along the basin margin. It may also test the continuity of the sandstone unit between control points, for example, determining if it is a single homogeneous entity or, alternatively, several discrete sandstone bodies linked to separate input points. Such techniques have not previously been applied in the Canning Basin.

Acacia Sandstone Member and possible correlative

The Acacia Sandstone Member, a local component of the limestone-dominated upper Willara Formation, is known from several drillholes on the Barbwire Terrace, eastern Broome Platform, and Mowla Terrace of the Canning Basin (Fig. 1). The unit comprises several shallowing- and sanding-upward cycles capped by horizons of clean, well-sorted, and fine- to medium-grained sandstone deposited under energetic shallow-marine conditions. Deposition was probably in response to a relative low stand or series of low stands of sea level, perhaps localized by tectonic activity, allowing basinward progradation of shoreface and shoreline sands. A similar-aged sandstone unit outcropping near the top of the Gap Creek Formation (Prices Creek Group) in the Prices Creek area (Figs 1 and 2) is here considered a possible correlative of the Acacia Sandstone Member.

Samples

Samples of white medium-grained sandstone from the Acacia Sandstone Member were collected from drillcore in petroleum exploration wells Looma 1 (2026.4 – 2028.4 m, GSWA 136069) and Acacia 2 (1174.6 – 1175.3 m, GSWA 136057).

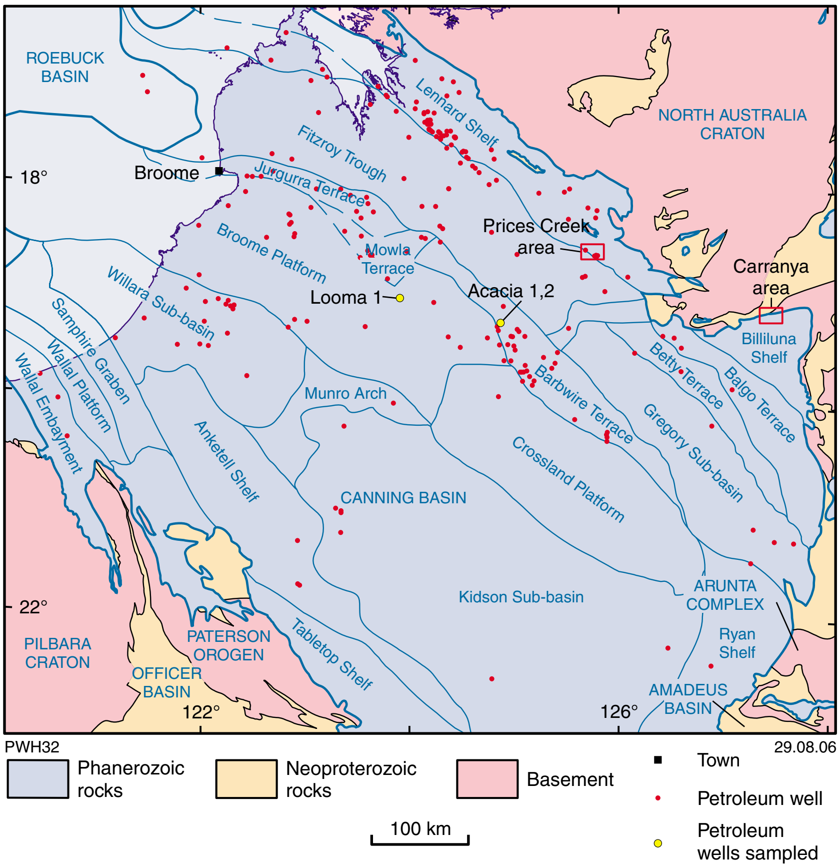

Figure 1. The Canning Basin, showing tectonic elements, petroleum wells intersecting the Acacia Sandstone Member of the Willara Formation, and sample localities in the Gap Creek and Carranya Formations

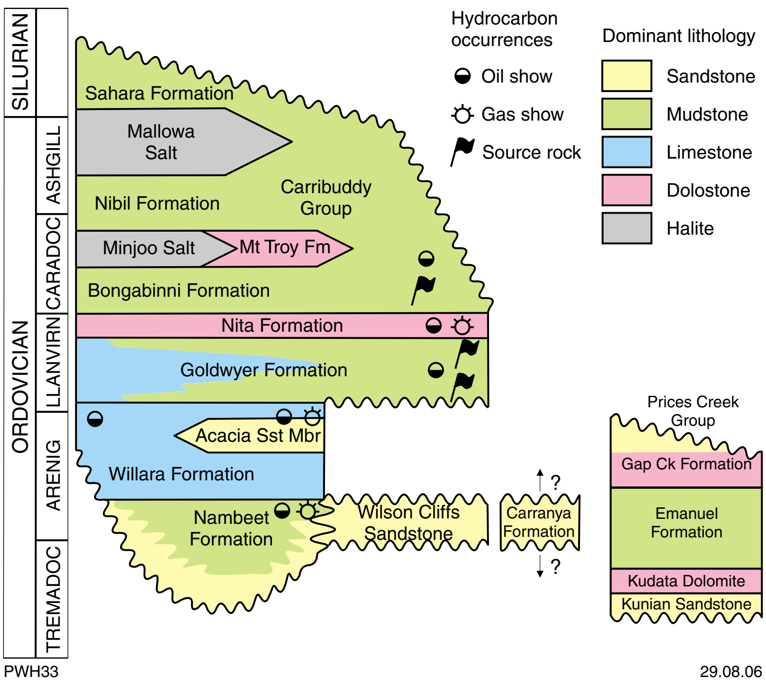

Figure 2. Ordovician–Silurian stratigraphy of the Canning Basin with stratigraphic position of source rocks and major hydrocarbon shows

These wells are 107.5 km apart on the Broome Platform and Barbwire Terrace respectively (Fig. 1). An outcrop sample from near the base of the sandstone unit in the Gap Creek Formation was collected in the Prices Creek area (Fig. 1; 18°37'45.29"S, 125°55'12.14"E; GSWA 184268). Sandstone from outcrop of the Lower Ordovician deltaic Carranya Formation, 15 km northwest of Carranya Homestead on the Billiluna Shelf (Fig. 1; 19°9'52.98"S, 127°39'3.12"E; GSWA 184269), was also collected to provide comparison with a possible Ordovician sediment input point. Although this unit may be of similar age to the Acacia Sandstone Member, it is more likely to be somewhat older based on tentative regional correlations (Fig. 2).

Method and results

Zircons were separated by standard procedures before dating of between 58 and 68 grains per sample with the sensitive high-resolution ion microprobe (SHRIMP) at Curtin University of Technology, Perth. Full analytical results, including data tables, are available in Wingate (in prep.a–d). All plotted data with ages older than 1000 Ma for individual analyses are based on $^{207}Pb/^{206}Pb$ ratios, whereas those younger than 1000 Ma are based on $^{238}U/^{206}Pb$ ratios. Although it was intended that the dated crystals be as representative as possible of the population from each sample, some bias is inevitable because crystals with abundant cracks and inclusions were avoided, and a few very high uranium crystals (>1000 ppm ^{238}U) were not dated because it was likely that they would yield discordant (and unusable) results. With about 60 grains dated per sample, no fraction of a population comprising more than 0.087 of the total will be missed at the 95% confidence level (Vermeesch, 2004).

Of the zircons from Looma 1, 65% plot as a single peak with a weighted mean age of 1850 ± 4 Ma (95% confidence, MSWD = 1.1; Fig. 3a). Similarity in appearance and tightly grouped Th/U ratios of between 0.1 and 0.9 suggest that the majority were

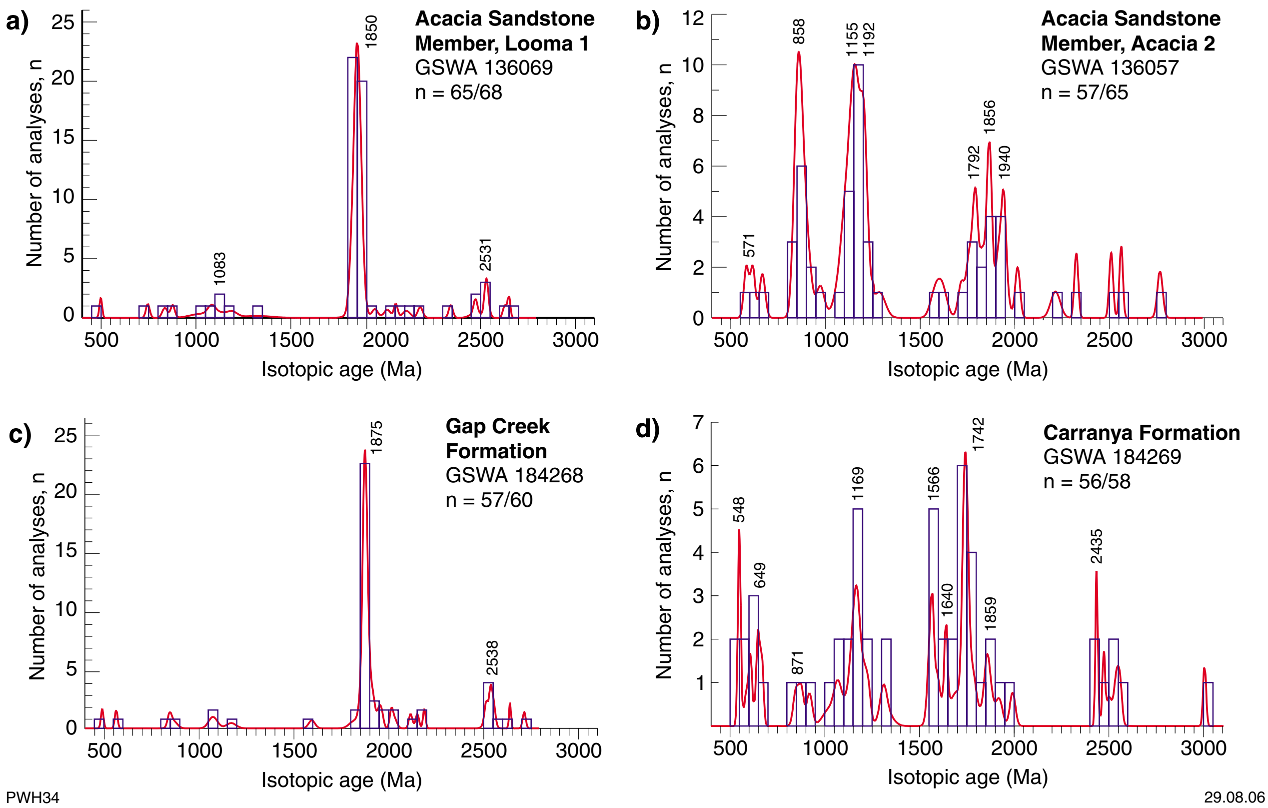

***Figure 3.** Probability density and histogram plots (50 Ma bins) of zircon isotopic ages for samples from a) Looma 1; b) Acacia 2; c) Gap Creek Formation; and d) Carranya Formation. Ages older than 1000 Ma are based on $^{207}Pb/^{206}Pb$ ratios, and those younger than 1000 Ma on $^{238}U/^{206}Pb$ ratios. Data more than 10% discordant are not plotted; n = number of concordant grains/total grains. Mean ages of major probability peaks are indicated*

derived from a single or closely related igneous source(s). Much smaller age components are present at c. 2531 and c. 1083 Ma. The discordant $^{207}Pb/^{206}Pb$ age of c. 2814 Ma is a minimum age for the oldest zircon in this sample, whereas the youngest has a near-concordant $^{238}U/^{206}Pb$ age of c. 498 Ma. Zircons from Acacia 2 show a much broader range of significant age peaks ranging from Neoarchean to latest Neoproterozoic in age. Major age peaks are identified at c. 852, 1155, 1192, 1775, 1792, 1865, and 1940 Ma (Fig. 3b). Of the $^{207}Pb/^{206}Pb$ ages, 29% cluster between 1093 and 1214 Ma. The oldest zircon in this sample has a near-concordant $^{207}Pb/^{206}Pb$ age of c. 2767 Ma.

The Gap Creek Formation sample gives a very similar age distribution pattern to the sample from Looma 1, although the main peak is slightly older at c. 1875 Ma (Fig. 3c). The Carranya Formation sample (Fig. 3d) shows closer similarity to that from Acacia 2, although the ratio of peak heights varies significantly, and the highest peak at c. 1742 Ma is not obvious in the Acacia 2 sample. The c. 852 Ma peak of Acacia 2 is potentially present, but small.

Limited paleocurrent data can be inferred from dipmeter logs over the sampled intervals in both wells (Watson and Derrington, 1982, Appendix VII; Phipps et al., 1998, Appendix 7). In Looma 1 the pattern is bipolar with northwest- and southeast-directed modes, suggestive of tidal channel deposition. In Acacia 2 inferred paleocurrents form a bimodal pattern with transport directions towards the south-southwest and south-southeast over the sampled interval. However, the inferred paleocurrent distribution throughout the entire member is more complex, particularly in the case of Acacia 2, which has currents directed towards all quadrants, with an overall average towards the west. In any case, the complex nature of currents in shallow-marine environments makes it unlikely that there will be any simple relationship between current direction at a particular location and the ultimate source of the sand. No paleocurrent data are available for the Gap Creek Formation, and limited field data for the Carranya Formation show significant variability, but average transport from the north.

Discussion

Igneous rocks dated at c. 1870–1850 Ma are widespread across the North Australia Craton in the Northern Territory and Western Australia. Such basement lies to the north and east of the present (partly tectonic) northeastern margin of the Canning Basin. Detrital zircons in widespread syn- to post-orogenic

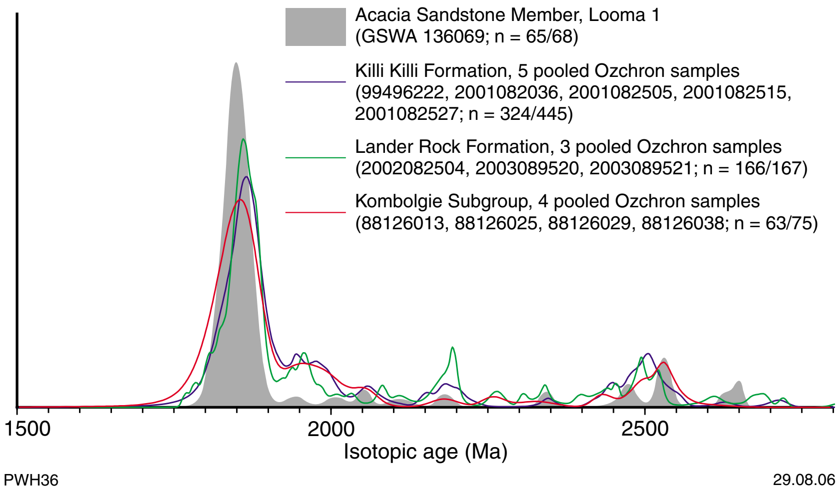

Figure 4. ***Probability density plots for the time interval 1500–3000 Ma, comparing zircon isotopic ages for the Looma 1 sample with pooled results from selected Paleoproterozoic sedimentary and metasedimentary rocks from the North Australia Craton (extracted from OZCHRON; Geoscience Australia, 2006). Ages are based on $^{207}Pb/^{206}Pb$ ratios. Data more than 10% discordant are not plotted; n = number of concordant grains/total grains***

sedimentary and metasedimentary rocks across the North Australia Craton show a remarkably similar age distribution pattern to the older (pre-1700 Ma) components in the Looma 1 and Gap Creek Formation samples. Figure 4 compares the Looma 1 sample to pooled data from the OZCHRON database (Geoscience Australia, 2006) for selected units across the craton, specifically the Lander Rock Formation (western Arunta Orogen, central Australia), Killi Killi Formation (Granites–Tanami Complex), and the Kombolgie Subgroup (basal McArthur Basin), all from within the Northern Territory. The similarity of zircon age spectra across over a thousand kilometres of the North Australia Craton precludes identifying a unique source location or sediment entry point, but strongly supports derivation of these sediments almost exclusively from this craton.

In contrast, the zircon age spectra obtained from Acacia 2 are broadly similar to those previously observed from Neoproterozoic sedimentary rocks of the Amadeus (Camacho et al., 2002; Buick et al., 2005) and western Officer Basins, including deformed equivalents in the Paterson Orogen (Bagas et al., 2001; Bagas, 2003; Geological Survey of Western Australia, 2005). Most samples from these basins have dominant age components of around 1200–1100 Ma, probably derived from the Musgrave Complex and contiguous domains (Camacho et al., 2002), and a complex of smaller upper Paleoproterozoic peaks, with some other peaks important in individual cases. Maximum ages rarely exceed the latest Archean. The main divergence from the common Neoproterozoic pattern in the Acacia 2 sample is the strong 865 Ma peak of unknown provenance, although sparse zircons of near this age are known in some Neoproterozoic samples. Neoproterozoic sedimentary and metasedimentary rocks border the Canning Basin along its southern and southeastern sides, and are likely to lie beneath at least part of the basin. Scattered Neoproterozoic outcrops are also present east of the Canning Basin, but no detrital zircon age data are available from these rocks. Figure 5 compares the Acacia 2 sample to two widely spaced Neoproterozoic samples from the southern Amadeus Basin (Winnall beds) and northwest Paterson Orogen (Choorun Formation). The Carranya Formation sample is interpreted to be derived from a broadly similar, although not identical source. The significant c. 1743 Ma zircons suggest an additional component, possibly from the Arunta Orogen.

The rarity of Archean zircons in all samples indicates that very little, if any, material was derived directly or via reworking from the Pilbara or Yilgarn Cratons, and zircon age spectra are also dissimilar to

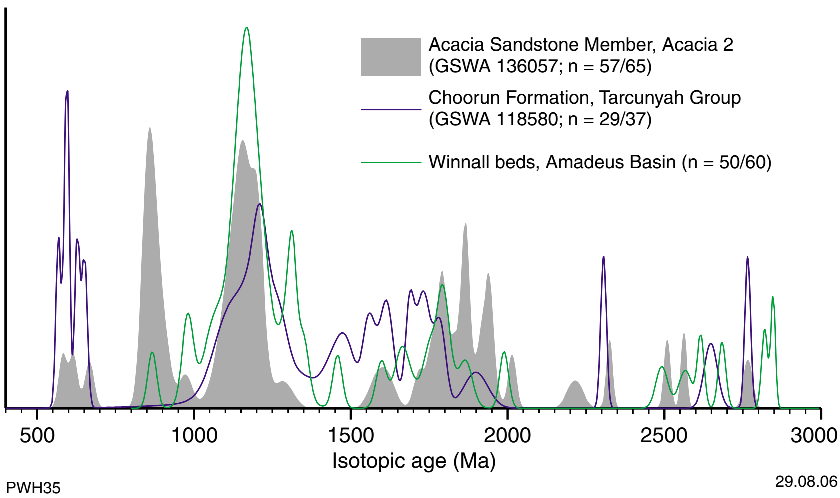

Figure 5. ***Probability density plots comparing zircon isotopic ages for the Acacia 2 sample with Neoproterozoic samples from the Choorun Formation, Paterson Orogen (GSWA 118580, Geological Survey of Western Australia, 2005), and the Winnall beds, Amadeus Basin (Camacho et al., 2002). Ages older than 1000 Ma are based on $^{207}Pb/^{206}Pb$ ratios, those younger than 1000 Ma on $^{238}U/^{206}Pb$ ratios. Data more than 10% discordant are not plotted; n = number of concordant grains/total grains***

those of the Paleoproterozoic and Mesoproterozoic tectonic units lying between these cratons (see data in Geological Survey of Western Australia, 2005). The zircon age profile of the Lower Ordovician Pacoota Sandstone in the Amadeus Basin (Buick et al., 2005) is also dissimilar to both samples, raising questions about the nature or existence of the hypothetical Larapintine Seaway widely believed to have linked the Canning and Amadeus Basins at this time.

Conclusion

Based on our present data the Acacia Sandstone Member has at least two major provenance areas with zircon age spectra similar to the North Australia Craton and adjacent Neoproterozoic basins, respectively, suggesting that sediment was derived from these sources or at least shared common source terrains. Although any further conclusions must be considered preliminary because of the small sample size in this pilot study, one possibility is that the Acacia Sandstone Member is not a single sandstone unit, but several discrete sandstone bodies of similar age feeding from different sediment input points during relative low stand(s) of sea level. This is important to consider when inferring reservoir distribution and making predictions about lateral changes in facies and reservoir properties. An alternate possibility involves switching of sediment sources during deposition, such that the Acacia Sandstone Member is internally stratified with respect to sand source. Further analyses are warranted.

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WINGATE, M. T. D., in prep.d, 184269: quartz sandstone, Carranya Homestead; Geochronology dataset 658: Western Australia Geological Survey.

Geochemical and Nd isotopic signatures of mafic dykes in the western Musgrave Complex

by H. M. Howard, R. H. Smithies, and F. Pirajno

Abstract

Mafic dykes intruding the Mesoproterozoic granulites and gneisses of the Musgrave Complex in central Australia can be divided into at least six geochemical suites. The oldest belongs to the Pitjantjatjarra Supersuite (c. 1170 Ma), related to the Musgravian Orogeny. The Alcurra dykes form part of the 1070 Ma Giles Event, and with the Giles mafic–ultramafic layered intrusions form part of the Warakurna large igneous province. Post-Giles Event mafic dyke suites include unnamed plagioclase-rich dykes, unnamed olivine dolerite dykes (c. 1000 Ma), the Gairdner Dyke Swarm and Amata Dolerite (c. 800 Ma), and unnamed light rare earth element (LREE)-depleted dykes (c. 750 Ma). Secular trends in geochemical composition of the mafic suites show generally decreasing concentrations of incompatible trace elements and increasing ε_{Nd} with decreasing age.

KEYWORDS: mafic rocks, dykes, geochemistry, Western Australia, Musgrave Complex.

Introduction

The Musgrave Complex, in central Australia, is an east-trending belt up to 800 km long and 350 km wide at the junction of the Archean–Proterozoic West, North, and South Australian Cratons. The complex includes gneisses with protolith ages that pre-date the onset of the c. 1225–1160 Ma Musgravian Orogeny and metamorphosed granites that intruded during that orogeny. It was later intruded, during the c. 1070 Ma Giles Event, by ultramafic to mafic intrusions and by granites, which together form the Warakurna Supersuite. The complex is overlain by volcanic and sedimentary rocks of the Bentley Supergroup, which is coeval with the Warakurna Supersuite.

Several different suites of mafic dykes in the Musgrave Complex have been previously documented based on combinations of their field relationships, petrography, and major element, trace element, and isotope geochemistry (Nesbitt et al., 1970; Clarke et al., 1995; Zhao and McCulloch, 1993; Glikson et al., 1996; Scrimgeour et al., 1999). This geochemical and isotopic study has identified several new suites of mafic dykes within the granulite-facies Fregon Domain of the western Musgrave Complex close to the Northern Territory and South Australia borders (Fig. 1).

The oldest dykes (c. 1170 Ma), which belong to the Pitjantjatjarra Supersuite, are the only pre-Giles Event mafic dykes recognized. During the c. 1070 Ma Giles Event, magmatism associated with the emplacement of the Warakurna large igneous province (Wingate et al., 2004) formed layered mafic–ultramafic intrusions, such as the Hinckley Range, Michael Hills, and Bell Rock intrusions, as well as the Alcurra Dolerite (Zhao and McCulloch, 1993; Edgoose et al., 2004).Unnamed plagioclase-rich dolerite dykes clearly post-date the Giles Event intrusions, but their relationship with younger mafic dyke suites is unclear. Other post-Giles Event intrusions include unnamed olivine- and plagioclase-porphyritic dolerite dykes at c. 1000 Ma, 825 Ma quartz dolerite dykes of the Gairdner Dyke Swarm, and c. 800 Ma dykes of the Amata Dolerite (Zhao and McCulloch, 1993; Glikson et al., 1996; Wingate et al., 1998). A further suite of dykes with trace-element-depleted characteristics may be of similar age or younger than the Gairdner Dyke Swarm. Collectively, these groups of mafic dykes provide an opportunity to trace 400 million years of mantle evolution beneath the Musgrave Complex.

Pitjantjatjarra Supersuite mafic intrusions (1207–1170 Ma)

Mafic rocks within the Pitjantjatjarra Supersuite are distributed both north and south of the Mann Fault on the Bates and Bell Rock 1:100 000

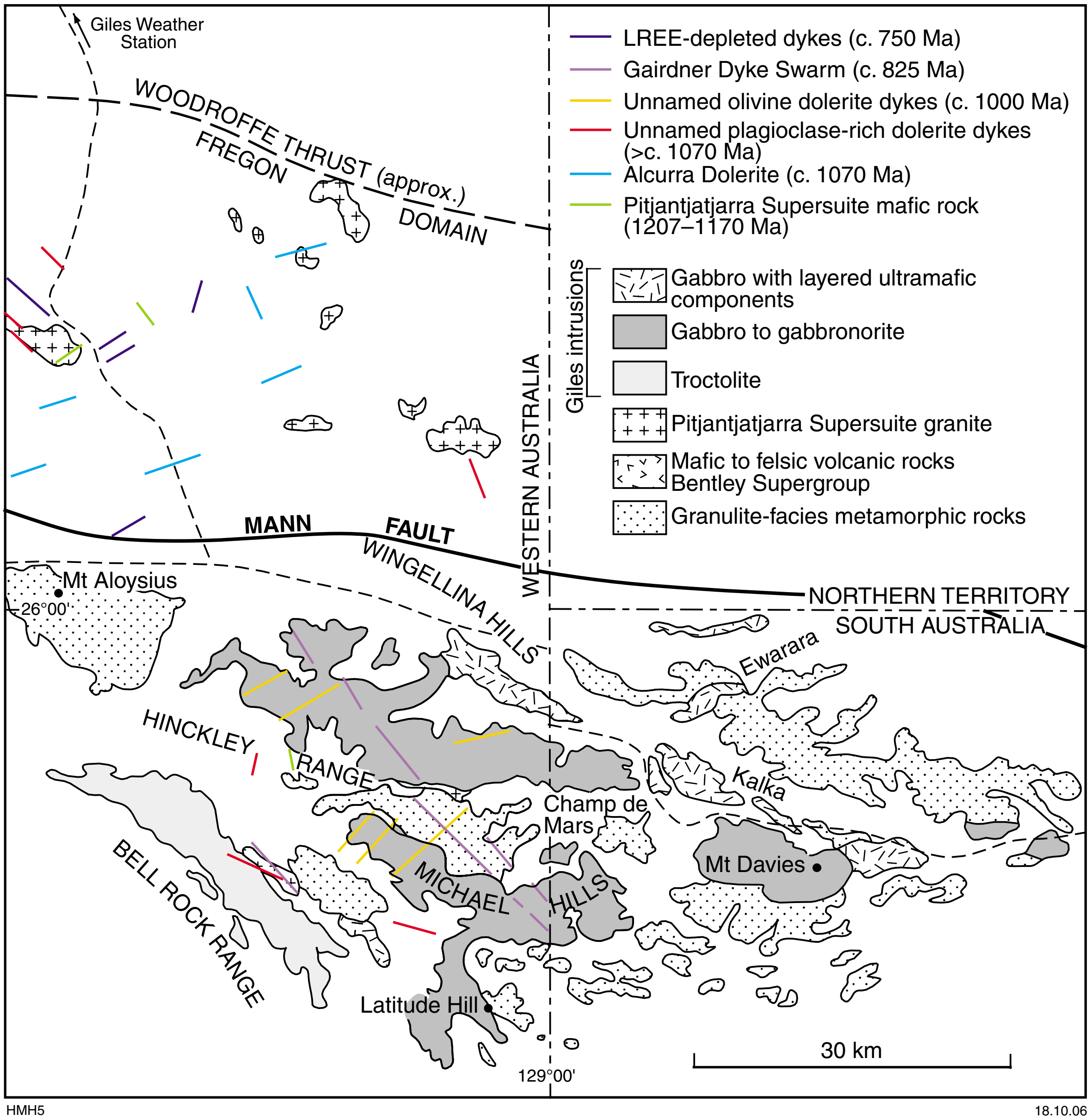

Figure 1. Distribution of mafic dyke suites on the Bates and Bell Rock 1:100 000 map sheets

map sheets. A large biotite gabbro intrusion south of the Hinckley Range yielded a sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon age of 1176 ± 5 Ma (Glikson et al., 1996) and a layered leucogabbro north of the Mann Fault yielded a SHRIMP U–Pb zircon age of 1190 ± 7 Ma (Geological Survey of Western Australia, in prep.). Several mafic dykes are included in this group based on their field relationships. For example, some dykes at Mount Fanny intrude and in places appear to be interleaved with 1207 Ma granites of the Pitjantjatjarra Supersuite, but are also intruded by c. 1170 Ma granite of the Pitjantjatjarra Supersuite. The orientations of the dykes are variable.

The dykes are typically medium grained, massive, and most have a polygonal granoblastic texture. Locally, they contain large (up to 5 mm) clinopyroxene oikocrysts. A typical mineral assemblage consists of plagioclase (45%), orthopyroxene (25%), clinopyroxene (25%), quartz (5%), late-stage brown biotite, green hornblende (replacing pyroxene), and garnet. Some dykes contain abundant disseminated ilmenite grains. Reaction textures include brown biotite and quartz coronas on orthopyroxene, clinopyroxene and garnet coronas on orthopyroxene, and garnet coronas on clinopyroxene and opaque minerals.

The Pitjantjatjarra Supersuite mafic dykes have primitive mantle-normalized incompatible trace-element profiles that are light rare earth element (LREE) enriched, (Table 1, Fig. 2a) with La/Sm values of 4.1 to 4.5 and Gd/Yb values of 1.4

to 1.9. They also have high Th/Nb values, suggesting either enrichment of the mantle source or crustal contamination. Negative titanium anomalies and corresponding low iron contents may reflect ilmenite fractionation. Two Nd isotopic analyses give epsilon Nd (ε_{Nd}) values of –2.42 and –6.20 (calculated at t = 1207 Ma, their maximum age) also suggesting crustal contamination.

Alcurra Dolerite (c. 1070 Ma)

The c. 1070 Ma dykes in Western Australia are contemporaneous with the Alcurra Dolerite and Stuart Pass Dolerite of Northern Territory and show geochemical similarities with the former. In Western Australia the mafic dykes of the Alcurra Dolerite have so far only been identified north of the Mann Fault (on the BELL ROCK 1:100 000 map sheet). They intrude felsic rocks of the Pitjantjatjarra Supersuite, but typically have mylonitic contacts. Most of these mafic dykes are oriented east-southeast and dip 40° to 60° to the south.

The dykes of the Alcurra Dolerite are medium to coarse grained and have a distinctive ophitic texture with oikocrysts several centimetres in diameter. Primary minerals include pink cloudy plagioclase, augite, and minor orthopyroxene symplectite oikocrysts, subhedral olivine, magnetite, and sulfide minerals. Pyrrhotite and pentlandite crystallized in late penetrating fractures in other minerals. Secondary biotite and chlorite rim opaque minerals and garnet forms rims on augite. Olivine has rims of both chlorite and plagioclase or intergrowths of plagioclase–clinopyroxene.

The Alcurra Dolerite has MgO contents of 5.2 to 6.8 wt% and higher TiO_2 and P_2O_5, and lower SiO_2 than the other suites of dykes. They are LREE-enriched (La/Sm = 2.6 to 3.3, Gd/Yb = 1.5 to 2.0) with slight negative Nb anomalies (Fig. 2b). Values for ε_{Nd} range from +0.89 to –0.92 (calculated at t = 1075 Ma), inside the range of +0.1 to –1.3 for Alcurra Dolerites dykes of the Northern Territory (Scrimgeour et al., 1999).

Michael Hills, Hinckley Range and Bell Rock intrusions (c. 1070 Ma)

Most of the large layered Giles Event intrusions, including the Hinckley Range, Michael Hills, and Bell Rock Range intrusions, are south of the Mann Fault. The Hinckley Range and Michael Hills intrusions consist of interlayered gabbros, gabbronorites, and anorthosites, whereas the Bell Rock intrusion is dominantly composed of troctolite and gabbro.

The Michael Hills and Hinckley Range intrusions show a range of trace-element abundance patterns (Fig. 2c), interpreted to be influenced by cumulate processes. Nevertheless, the overall trend shows little to no LREE enrichment compared with the LREE-enriched troctolites and gabbros of the Bell Rock intrusion (Fig. 2d). The trace element profiles for the Hinckley intrusion gabbros and the Michael Hills intrusion gabbronorite are similar. The possibility that these two intrusions might be remnants of a larger igneous body is consistent with gravity data indicating that the two are connected at depth (Shevchenco, S., 2006, written comm.). The ε_{Nd} values for the three intrusions fall within the range 0.89 to –2.75 (calculated at t = 1075 Ma), slightly more negative than the range for the Alcurra Dolerite dykes.

Unnamed plagioclase-rich dolerite dykes (post-c. 1070 Ma)

Northwestly to north-northwesterly trending plagioclase-rich dolerite dykes have been identified both north and south of the Mann Fault. North of the Mann Fault (BATES 1:100 000 map sheet) they intrude granites of the Pitjantjatjarra Supersuite and paragneiss of the Birksgate Metamorphics. South of the Mann Fault they cut the Bell Rock intrusion and c. 1300 Ma granite at Mount West.

The plagioclase-rich dykes are mostly fine to medium grained, either with subophitic to ophitic textures or with polygonal to elongate granoblastic textures where they are foliated. They contain clinopyroxene and a high proportion of plagioclase (60–65%) and opaque minerals. Clinopyroxene has poorly developed coronas of garnet, amphibole, and quartz. This dyke suite is poorly defined, in that the dykes do not have consistent orientations and are of limited distribution.

The dykes have flat, unfractionated, primitive mantle-normalized trace element patterns with generally slightly negative Nb anomalies (Fig. 2e). MgO contents are similar to or higher than those of the other dyke suites, ranging from 7.9 to 10.1 wt%, and Ni contents are similarly high, ranging from 170 to 240 ppm. Two dykes have ε_{Nd} values of 0.58 and –2.06, calculated at t = 1075 Ma (the maximum age of the unnamed plagioclase-rich dolerites).

Unnamed olivine dolerite dykes (c. 1000 Ma)

A suite of unnamed olivine dolerite dykes (referred to by Glikson et al., 1996, as Type C dykes) are mostly northeast trending and are most common in the Michael Hills and the Hinckley Range intrusions. They have so far only been identified south of the Mann Fault. They crosscut the igneous layering of the Giles Event intrusions and are crosscut by 825 Ma dykes of the Gairdner Dyke Swarm. A poorly constrained Sm–Nd mineral isochron age of 1000 Ma was obtained for one of the dykes (Glikson et al., 1996).

The unnamed olivine dolerite dykes have textures that distinguish them from the other dyke suites. They have a fine-grained groundmass and a porphyritic texture, containing phenocrysts of plagioclase (up to 10%) and olivine (5%). The groundmass contains plagioclase (50–60%), clinopyroxene (20–30%), opaque phases (5%), and accessory biotite, Fe–Ti oxides, and spinel. The opaque minerals crystallized late and include ilmentite, pyrrhotite, pentlandite, and pyrite. The texture is dominantly igneous; however,

Table 1. Whole-rock analyses of dolerites dykes, Hinckley Range gabbro and Bell Rock gabbro

Mafic suite	*Pitjantjatjarra Supersuite dolerite*	*Alcurra Dolerite*	*Hinckley Range gabbro*	*Bell Rock gabbro*	*Plagioclase-rich dolerite*	*Olivine dolerite*	*Gairdner Dyke Swarm dolerite*	*LREE-depleted dolerite*
Sample ID	*174793*	*174547*	*183532*	*183431*	*183411*	*174570*	*174564*	*174751*
				Weight percentage				
SiO_2	50.94	48.33	48.43	47.38	47.90	49.05	49.95	48.03
TiO_2	1.03	2.11	0.55	0.46	0.85	1.33	1.38	0.86
Al_2O_3	15.73	15.45	19.37	22.00	17.37	16.71	14.08	16.55
Fe_2O_3	2.07	1.97	1.58	1.44	2.25	2.10	2.17	1.84
FeO	8.69	11.47	6.15	7.08	9.31	8.60	9.67	7.74
MnO	0.19	0.20	0.12	0.11	0.19	0.17	0.20	0.17
MgO	7.62	6.07	8.58	7.59	8.31	8.06	8.11	9.42
CaO	9.77	8.32	11.68	10.57	10.68	9.90	12.04	12.06
Na_2O	2.49	2.79	2.25	2.57	2.24	2.66	1.91	1.86
K_2O	0.82	1.09	0.36	0.24	0.24	0.66	0.21	0.21
P_2O_5	0.16	0.42	0.06	0.05	0.10	0.31	0.11	0.08
LOI	-0.74	0.21	-0.14	-0.46	-0.81	-0.94	-1.07	0.04
SO_3	0.22	0.10	0.15	0.03	0.20	0.24	0.03	0.15
Total	**98.99**	**98.53**	**99.14**	**99.06**	**98.83**	**98.85**	**98.79**	**99.01**
				Parts per million				
Ag	0.2	0.23	0.01	0.18	0.46	0.05	0.2	0.1
As	2.7	4.9	0.9	3.5	5.4	1.9	2.9	1.9
Ba	255	400	173	71	94	297	44	26
Be	0.6	1.4	1.0	0.3	0.8	0.4	0.3	0.3
Cr	188	60	260	232	176	288	149	332
Cs	0.22	0.68	0.01	0.03	0.03	0.07	0.12	0.11
Cu	55	76	96	42	132	68	184	120
Ga	16.3	20.9	16.6	22.4	17.5	18.2	18	14.7
Ge	1.4	1.4	1.1	1	1.7	1.1	1.7	1.5
Hf	2.9	4.1	0.9	0.4	1.5	2.5	2.1	1.4
Mo	0.9	1.2	0.5	0.6	0.8	1.1	0.6	0.4
Nb	3.9	10.8	1.0	0.8	2.2	6.3	4.5	1.1
Ni	98	108	248	269	173	132	115	193
Rb	26.2	31.1	7.1	5.0	6.9	14.8	11.1	15
Sb	0.2	0.1	–	0.2	0.3	5.4	0.2	3.3
Sc	28	22	24	8	27	22	32	33
Sr	155.1	267.1	371.8	385.2	185.2	348.8	165.6	151.2
Th	3.4	2.8	0.4	0.4	0.3	1.8	1.2	0.5
Ti	6 186	12 678	3 282	2 730	5 082	7 968	8 292	5 160
V	200	234	108	87	206	204	347	248
Y	31.2	24.5	12.9	4.3	11.7	29.3	26.4	23.7
Zn	90	128	54	56	78	87	82	66
Zr	128.1	160.1	30.2	17.3	51.5	125.3	82.9	51.4
La	16.42	19.47	4.92	2.78	4.79	15.84	5.97	2.71
Ce	33.42	45.16	9.37	5.66	11.56	32.39	14.28	6.73
Pr	4.13	5.81	1.38	0.75	1.57	4.23	2.15	1.06
Nd	17.43	26.29	5.85	3.41	7.42	19.08	10.64	5.64
Sm	3.74	5.87	1.72	0.76	2.14	4.13	3.31	2.01
Eu	1.122	1.971	0.751	0.643	0.837	1.541	1.164	0.769
Gd	3.77	5.95	1.9	0.72	2.54	4.31	3.64	2.71
Tb	0.68	0.97	0.3	0.12	0.47	0.75	0.68	0.50
Dy	4.33	5.85	1.94	0.73	2.97	4.38	4.00	3.36
Ho	0.92	1.16	0.4	0.13	0.65	0.86	0.86	0.73
Er	2.89	3.42	1.18	0.40	1.95	2.52	2.49	2.22
Yb	2.70	2.83	1.13	0.31	1.64	2.21	2.02	1.99
Lu	0.41	0.42	0.16	0.04	0.26	0.34	0.31	0.31
La/Sm	4.39	3.32	2.86	3.66	2.24	3.84	1.80	1.35
Gd/Yb	1.40	2.1	1.68	2.32	1.55	1.95	1.80	1.36
La/Nb	4.21	1.8	4.92	3.48	2.18	2.51	1.33	2.46
ε_{Nd}	-6.43	-0.34	-2.65	0.59	0.58	-2.84	2.39	4.58
Age	1 180	1 075	1 075	1 075	1 075	1 000	800	750

NOTES: ε_{Nd} calculated using the crystallization age (T) of the mafic suite. Analytical procedures are outlined in Morris and Pirajno (2005)

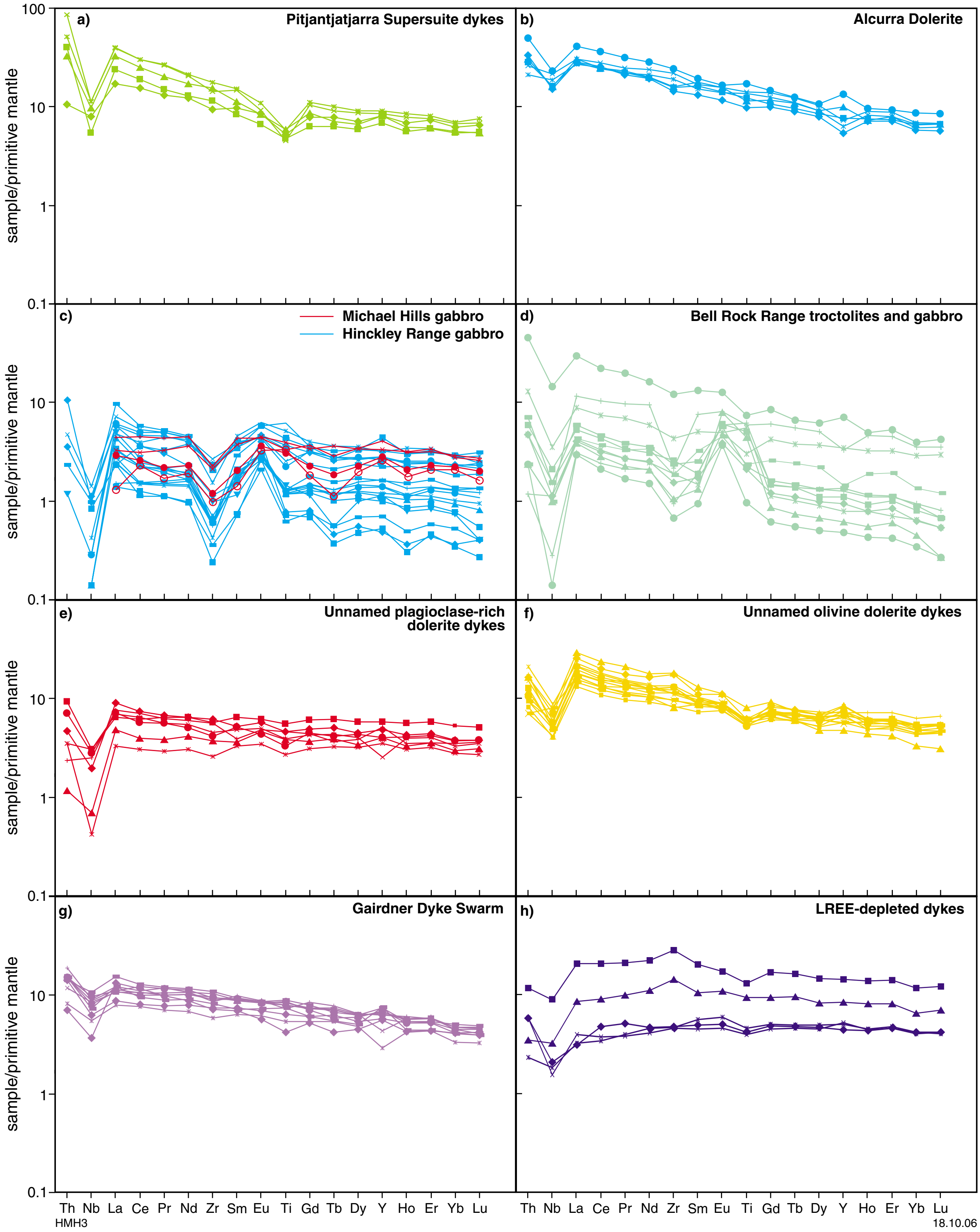

Figure 2. (a–h) Primitive mantle-normalized trace element plots for the mafic dyke suites, and the Hinckley Range and Bell Rock intrusions of the western Musgrave Complex. Normalizing values from Sun and McDonough (1989).

many of the dykes show recrystallized clinopyroxene, and in some cases where the entire groundmass has been recrystallized, a polygonal granoblastic texture is seen. Plagioclase coronas on olivine phenocrysts are common.

The dykes are chemically more primitive than many of the other suites, with high MgO (mostly 9 to 13 wt%), and Ni (132–291 ppm) reflecting their high olivine content. They nevertheless have LREE-enriched profiles [La/Sm = mostly 2.8 to 3.5, slightly lower than that of the Alcurra Dolerite], high Gd/Yb ratios (1.6 to 2.0), but at significantly lower REE abundances than the Alcurra Dolerite (Fig. 2f). They have a slight negative Nb anomaly, suggesting limited crustal contamination. The olivine dolerite dykes have ε_{Nd} values ranging from 0.65 to –2.84 when calculated at t = 1000 Ma.

Gairdner Dyke Swarm and Amata Dolerite dykes (c. 825 Ma)

The Gairdner Dyke Swarm (Type B dykes of Glikson et al., 1996) contains mostly northwest- to north-trending dykes that so far have only been identified south of the Mann Fault. One dyke in Western Australia yielded a zircon U–Pb age of 824 ± 4 Ma (Glikson et al., 1996), similar to the baddeleyite U–Pb age of 827 ± 6 Ma for a Gairdner Dyke Swarm dyke on the Stuart Shelf (Wingate et al., 1998). An Amata Dolerite dyke gave a less precise Sm–Nd age of 790 ± 40 Ma (Zhao et al., 1994). The Gairdner Dyke Swarm, Type B dykes and Amata Dolerite dykes have been linked on the basis of their similar ages and chemistry (Glikson et al., 1996). They crosscut the unnamed olivine dolerite dykes and Giles Event intrusions such as the Hinckley Range and Michael Hills intrusions. They are composed of medium-grained, intergranular to subophitic dolerite, but where recrystallized show polygonal granoblastic textures. The dolerite consists of pink cloudy plagioclase (labradorite, 55–60%), augite (30–40%), and late sulfide minerals (up to 5% pyrrhotite with accessory pyrite). Augite is commonly altered to amphibole and biotite is associated with the sulfide phases. In zones of deformation the dolerite is variably recrystallized, and contains micromylonite zones and warped plagioclase.

The dykes have slightly enriched primitive mantle-normalized incompatible trace-element profiles (La/Sm = 1.8 to 2.9) and a slight negative Nb anomaly (Fig. 2g).

Neodymium data for two dykes show ε_{Nd} values of +2.39 and +3.81 (calculated at t = 800 Ma), generally lower than the range of +3.1 to +4.9 for these dykes in the Northern Territory (Scrimgeour et al., 1999), but consistent with the ε_{Nd} values of +2.4 to +4.3 for the Amata Dolerite and the Gairdner Dykes Swarm of South Australia (Zhao et al., 1994).

LREE-depleted dykes (c. 750 Ma)

There are several metamorphosed mafic dykes north of the Mann Fault (BATES 1:100 000 map sheet) that are characterized by distinctive depleted incompatible trace-element geochemistry and high ε_{Nd} values. Their orientation varies where deformed, from east-northeast to northwest.

The dykes are medium grained, massive, ophitic to subophitic metagabbros. The well-preserved igneous textures are, however, accompanied by high-grade metamorphic reactions. Recrystallized dykes have polygonal granoblastic textures and well-foliated or mylonitic dykes have elongate granoblastic textures.

The major mineral assemblage consists of green clinopyroxene (sometimes as oikocrysts), orthopyroxene, euhedral plagioclase (30–35%), green hornblende, quartz (<5%), with or without garnet (porphyroblasts). Rutile, biotite, pentlandite, and pyrrhotite are accessory minerals. Fine-grained sulfides extend along grain boundaries, enclose plagioclase grains, and are common inclusions within garnet porphyroblasts. Metamorphic reactions include hornblende rims on clinopyroxene, biotite rims on opaque phases, and polygonal aggregates of biotite–garnet–clinopyroxene surrounding orthopyroxene.

The LREE-depleted dykes (Fig. 2h) have La/Sm ratios of 0.8 to 1.5 and flat heavy rare earth element (HREE) profiles (Gd/Yb = 1.3–1.7), compared with the other suites of dykes. They also have a slightly negative Nb anomaly and ε_{Nd} values ranging from +4.58 to +4.60.

A three-point Sm–Nd age determination yielded an age of 747 ± 48 Ma (GSWA unpublished data) suggesting that they are either a depleted component of the c. 800 Ma magmatic event that produced the Gairdner Dyke Swarm and Amata Dolerite of South Australia (Zhao et al., 1994) or a slightly younger suite, possibly contemporaneous with the 755 Ma Mundine Well dyke swarm of northwestern Australia (Wingate and Giddings, 2000). If the former is true, then they were extracted from a source that was more melt depleted than other dykes of that age. The LREE-depleted dykes show contrasting trace element characteristics to the LREE-enriched 755 Ma Mundine Well Dyke Swarm (Morris and Pirajno, 2005; Li et al., 2006).

Discussion

The trace element and isotope geochemistry of the six mafic dykes suites suggests that they were derived from distinct magma sources or incorporated distinct source components. All suites have higher La/Nb ratios than primitive mantle, in particular the Pitjantjatjarra Supersuite, the plagioclase-rich dykes, and the olivine dolerite dykes, which have the highest La/Nb ratios of more than 2. These high ratios indicate the involvement of either crustal contamination or subduction-enriched mantle sources.

Secular trends in composition towards generally decreasing concentrations of incompatible trace elements with decreasing age are evident from the trace element profiles of most dyke suites at a given MgO content and these trends most probably reflect differences in the magma sources. The Pitjantjatjarra Supersuite mafic intrusions show very LREE enriched trace element patterns and have high La/Nb ratios (3.2 to 4.2) indicative of a significant crustal component. The Alcurra Dolerite dykes show slightly less LREE enrichment, but significantly lower La/Nb ratios (1.3 to 1.8), suggesting more extensive fractionation of a less enriched source or of a relatively uncontaminated magma.

The difference in composition between the Alcurra Dolerite dykes and the unnamed plagioclase-rich dolerite dykes is the only exception to the secular enrichment trend. The plagioclase-rich dykes were either intruded in the latter stages of or after the Giles Event. Their low REE abundances, high MgO and Ni contents, and flat REE profiles may be due to a higher degree of melting of a slightly more refractory mantle source, following the extraction of large amounts of mafic magma from the mantle during the Giles Event. The relatively high La/Nb ratios of 2.1 to 7.6 still require the involvement of a crustal component, either in the mantle source or as a later magma contaminant.

The unnamed olivine dolerite dykes are LREE enriched with La/Nb ratios ranging from 2 to 4 and were possibly generated from a similar source to the plagioclase-rich dykes. However, the dykes of the Gairdner Dyke Swarm show no or only very slight LREE enrichment and much lower La/Nb ratios of 1.2 to 1.4, suggesting that their chemical characteristics reflect their mantle source and melting conditions and have not been significantly modified by crustal contamination. The large spatial extent of the Gairdner Dyke Swarm and Amata Dolerite dykes (and their extrusive equivalents) and their consistent geochemistry, (also supported by these data) are consistent with derivation from the uniform asthenospheric mantle plume proposed by Zhao et al. (1994). The LREE-depleted 750 Ma dykes have similar HREE abundances to the Gairdner Dyke Swarm and low La/Nb ratios, but are significantly LREE depleted. These dykes may have been produced from either a depleted component of the same mantle plume source or an unrelated mantle source.

The Nd isotope chemistry shows secular trends towards increasing ε_{Nd} values with decreasing age. The Pitjantjatjarra Supersuite mafic intrusions show ε_{Nd} values from –6.2 to –2.4 consistent with generation from a highly enriched mantle source or extensive crustal contamination, or both. The La/Nb values in the dykes overlap with or exceed those of average Pitjantjatjarra Supersuite granites (~3.2), suggesting that either the voluminous suite of granites was not the sole crustal contaminant or that an enriched (high La/Nb) mantle source is required, or both. Successively more positive ε_{Nd} from the Alcurra Dolerite dykes compared to the unnamed olivine dolerite dykes suggests derivation from either a successively less enriched mantle source, or successively less crustal contamination of mantle-derived magma, or some combination of these two processes. The most significant change in the Nd isotope chemistry is in the dykes of the Gairdner Dyke Swarm, which have significantly more positive ε_{Nd} values of +2.4 to +4.3. This change suggests that they were derived from a significantly less enriched source and is consistent with a mantle plume model. The LREE-depleted dykes have similar to slightly more positive ε_{Nd} values of +4.6, again reflecting a similar primitive, although slightly more depleted, source.

Many of the older mafic suites are exposed both north and south of the Mann Fault, such as the Pitjantjatjarra Supersuite dykes, the Giles Event-age layered intrusions and Alcurra Dolerite dykes, and the post-Giles Event plagioclase-porphyritic dykes. In contrast, the younger suites appear to be more provincial. For example, the Gairdner Dyke Swarm and unnamed olivine dolerite dykes are only exposed south of the Mann Fault (on BELL ROCK), whereas the LREE-depleted 750 Ma dykes appear to be confined to the area north of the Mann Fault (on BATES). This suggests that the younger dykes have intruded to very specific crustal levels and so their present distribution is controlled by the extensive post-Giles Event vertical displacements along the Mann Fault.

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A new lithostructural framework for the central Yilgarn Craton

by A. Riganti, S. Wyche, and S. F. Chen

Abstract

A new lithostructural framework for the central Yilgarn Craton has been introduced following completion of the GSWA mapping program in the region. Discrete greenstone belts with common stratigraphic elements and structural histories are the building blocks in the new scheme, and have been assigned unique codes within the GSWA State-wide map units database.

KEYWORDS: Archean, greenstone, structural terranes, Yilgarn Craton.

Introduction

Since 1997, new mapping by the Geological Survey of Western Australia (GSWA) in the central Yilgarn Craton has resulted in the production of fifteen 1:100 000-scale map sheets with Explanatory Notes and associated publications and presentations, along with a large volume of newly acquired geophysical, geochemical, and geochronological data. All available geological information has been incorporated into the first edition of the Central Yilgarn Geological Information Series (GIS) digital package (Geological Survey of Western Australia, 2006a).

The lithostructural framework for the central Yilgarn Craton, developed during the course of this work, provides a new context for the understanding of geological relationships and tectonic evolution gained during detailed mapping of the region. Lithostructural units have been defined for the area to allow a unique set of codes to be developed accordingly for use in a digital environment.

Geological setting of the central Yilgarn

The area covered by the Central Yilgarn GIS dataset falls within the northern part of the newly defined Southern Cross Domain of the Youanmi Terrane (Fig. 1; Cassidy et al., 2006). The Youanmi Terrane combines the Southern Cross and Murchison Granite–Greenstone Terranes of Tyler and Hocking (2001), which are now recognized to have a broadly similar lithostratigraphy, geochronology, and tectonic history (e.g. Chen et al., 2003), as well as an isotopically distinct signature from the other terranes of the Yilgarn Craton based on neodymium and hafnium isotope depleted-mantle model ages (e.g. Barley et al., 2003; Griffin et al., 2004). The Southern Cross Domain is separated from the Murchison Domain (formerly the Murchison Granite–Greenstone Terrane) by major shear zones such as the Youanmi shear zone, and is bounded to the east by the Ida and Waroonga fault systems (Fig. 1) — structures that have been extensively obscured by later granite intrusions.

The northern part of the Southern Cross Domain is characterized by a number of discrete greenstone belts with overall common lithostratigraphic elements and structural histories. The age of the greenstones is not well constrained but the major, mafic-dominated successions were probably deposited at about 3.0 Ga (e.g. Chen and Wyche, 2001). The structural complexity, lack of key geochronological data from the mafic sequence, and absence of regional stratigraphy have obstructed direct correlations between greenstone belts in the central Yilgarn Craton. Strong deformation and poor exposure effectively preclude the establishment of detailed stratigraphic successions within most belts. However, their common lithological associations and deformational histories distinguish them from the c. 2.7 Ga greenstones of the adjacent Eastern Goldfields Superterrane (Fig. 1). A representative stratigraphic sequence for the greenstones in the northern part of the Southern Cross Domain has quartzite and quartz–mica schist at the base of the succession. These quartzites contain 4.2 to 3.1 Ga detrital zircons indicating greenstone deposition on, or adjacent to, continental crust (Wyche et al., 2004). The majority of the greenstone belt successions are dominated by mafic rock types, mostly tholeiitic basalts with some spinifex-textured komatiitic basalts and gabbroic units, with subordinate ultramafic rocks. Banded iron-formation (BIF) and chert are dominant at lower to middle stratigraphic levels. The abundance of BIF and paucity of ultramafic lavas are characteristic of the Southern Cross greenstone belts, and contrasts with

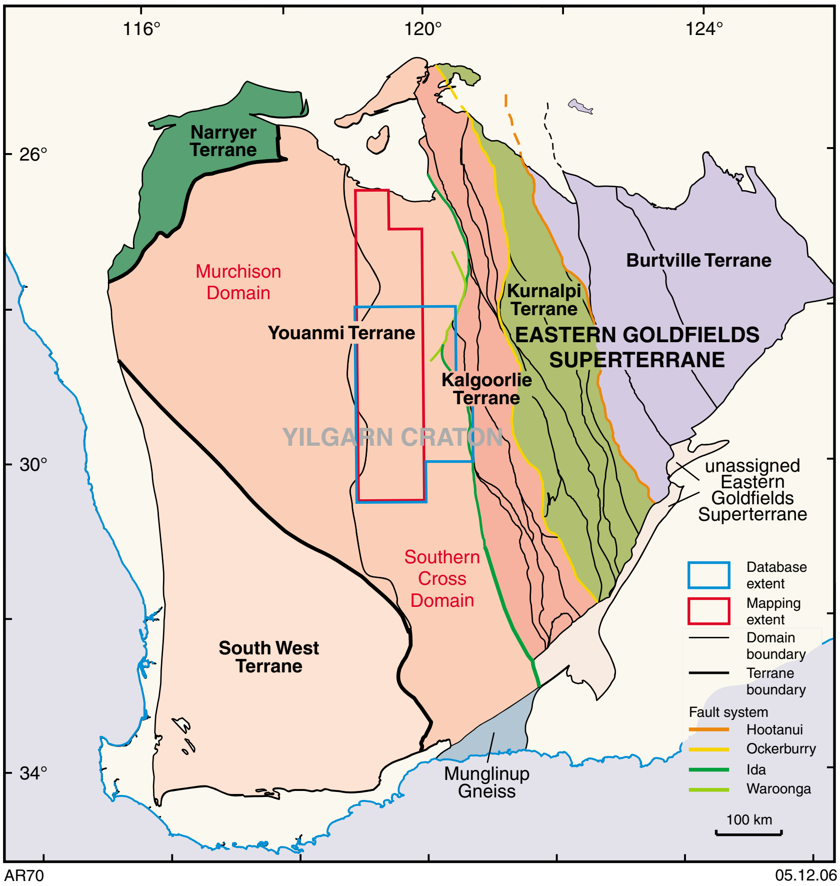

Figure 1. ***Tectonic subdivisions of the Yilgarn Craton, showing terrane and domain boundaries, as well as the areal extent of GSWA mapping (red box) and the Central Yilgarn GIS dataset (blue box). Modified after Cassidy et al. (2006)***

the scarcity of BIF and abundance of ultramafic rocks in greenstone sequences of the adjacent Eastern Goldfields Superterrane.

In parts of the northern Southern Cross Domain the c. 3.0 Ga mafic-dominated succession is unconformably overlain by a sequence of weakly metamorphosed felsic to intermediate volcanic rocks, followed by weakly metamorphosed clastic sedimentary rocks. In the Marda–Diemals greenstone belt (Fig. 2), this upper sequence is represented by the felsic to intermediate calc-alkaline Marda Complex in which basal conglomerates and sandstones that were derived from the underlying greenstones are overlain by andesite, rhyolite, and rhyolitic ignimbrite, dated at c. 2732 Ma (Geological Survey of Western Australia, 2006b). The clastic sedimentary rocks are represented by the Diemals Formation, which has a maximum age of c. 2729 Ma (Geological Survey of Western Australia, 2006b). In the Gum Creek greenstone belt, just north of the area embraced by the first edition of the Central Yilgarn GIS, the poorly exposed upper succession also contains c. 2720 Ma felsic volcanic rocks and clastic sedimentary rocks, including abundant carbonaceous shales (Chen et al., 2006).

The greenstone belts in the northern part of the Southern Cross Domain share a common structural history (Chen et al., 2004). D_1 north–south shortening produced low-angle thrusts, isoclinal folds, and a gently dipping foliation, with a locally pronounced down-dip mineral lineation. D_1 structures are only locally preserved, and are commonly represented by a folded foliation and F_1 folds refolded by D_2. D_2 deformation was dominated by east–west shortening, with the formation of large, originally north-trending, upright folds with an axial-planar foliation that overprinted D_1 structures. Inhomogeneous east–west compression during D_3 resulted in impingement of competent granitic blocks into less competent, north–south-oriented greenstone belts. This led to development of northwest-trending sinistral and northeast-trending dextral regional-scale shear zones along the margins of the granitic blocks. These shear zones are linked by northerly trending zones of intense deformation, in which shortening is accommodated by the formation of folds and reverse faults in the greenstones, and by a coaxial flattening fabric in granitic rocks. Lateral escape of the greenstones is indicated by the progressive rotation of early macroscopic folds into parallelism with the strike-slip shear zones. Brittle deformation later than D_3 is also present in the northern part of the Southern Cross Domain, but is poorly constrained in age.

Greenstone belts of the Southern Cross Domain are surrounded by granite and gneiss ranging in age from c. 2810 to 2635 Ma (Geological Survey of Western Australia, 2006b). The majority of granite plutons were probably intruded pre- to syn-D_2, because some contain a north-trending gneissic banding and foliation. Granites are strongly deformed in D_3 shear zones and preserve well-developed shear-sense indicators such as S-C fabrics and rotated porphyroclasts. Granitic gneisses, on the other hand, are commonly slightly older than the deformed and undeformed granites (Geological Survey of Western Australia, 2006b), and preserve an earlier, northerly trending D_2 fabric both adjacent to, and away from, the greenstone belts.

Southern Cross Domain lithostructural units

No formal stratigraphy has been established for the mafic-dominated portion of the greenstone succession

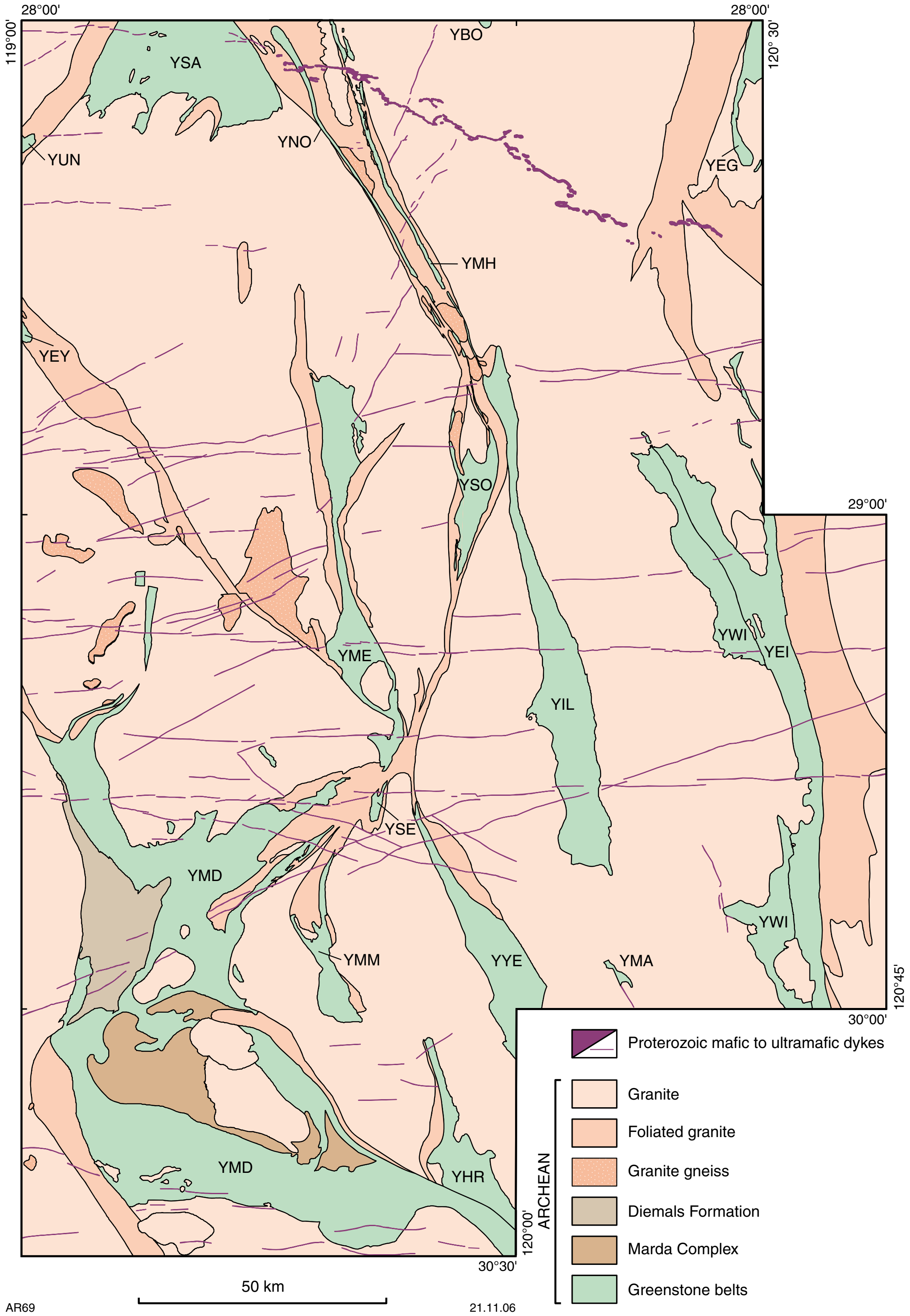

Figure 2. Simplified interpreted bedrock geology for the area covered by the Central Yilgarn GIS dataset, depicting the lithostructural units identified to date. Acronyms for greenstone belts: YBO = Booylgoo Range, YEI = East Ida, YEY = East Youanmi, YHR = Hunt Range, YIL = Illaara, YMA = Maninga, YMD = Marda–Diemals, YME = Mount Elvire, YMH = Maynard Hills, YMM = Mount Manning, YNO = North Cook Well, YSA = Sandstone, YSE = South Elvire, YSO = South Cook Well, YWI = West Ida, YUN = Unaly Hill, YYE = Yerilgee. YEG indicates undifferentiated greenstones from the Eastern Goldfields Superterrane

in the northern part of the Southern Cross Domain, due to a lack of dateable horizons and marker beds. Nonetheless, the occurrence of greenstone belts as spatially discrete entities, together with their lithological similarities and shared deformational histories, makes individual greenstone belts the most suitable building blocks for a new lithostructural framework in the central Yilgarn Craton (cf. Van Kranendonk, 1998).

Seventeen greenstone belts of variable areal extent have been named in the area covered by the first edition of the Central Yilgarn GIS digital dataset (Fig. 2), and rock types are now described according to the greenstone belts in which they occur. This allows a better characterization of lithologies from different areas and within individual belts (both in terms of variations or similarities), and represents a first step towards the definition of a formal stratigraphy and a more comprehensive tectono-stratigraphic framework for the region. In addition to naming litho-structural units, lithological codes have been modified from the original published 1:100 000-scale maps to be consistent with the new GSWA coding scheme (Tyler et al., 2004) that closely follows international guidelines on rock nomenclature. In this scheme, more emphasis is given to metamorphic rock codes (particularly in rocks metamorphosed to upper greenschist or amphibolite facies), and mineralogical, textural, and structural features of the rocks are listed in consistent order (unlike previously published codes). Therefore, in the central Yilgarn dataset, each rock type is characterized by a code that defines its age, lithology, and the lithostructural affiliation for any particular outcrop. For example, 'A-bb-YSA' defines an Archean basalt of the Sandstone greenstone belt of the Yilgarn Craton, whereas 'A-mtq-YMH' refers to a metamorphosed quartz arenite in the Maynard Hills greenstone belt. Lookup tables in the database provide a full tectono-stratigraphic characterization of individual rock units (e.g. terrane, domain, age, etc.). The system, as designed, is flexible and open to further updates. In particular, it allows more detailed breakdown of stratigraphy, including the introduction of more formal nomenclature, as more data become available.

Formal stratigraphic units have been defined wherever possible for this part of the central Yilgarn Craton. The volcanic rocks of the Marda Complex have been assigned group status, and their high-level intrusive equivalent, the Butcher Bird Monzogranite, has been correspondingly included in the formal stratigraphy of the complex. Metasedimentary rocks of the Diemals Formation have also been formally described, as have some mafic units such as the Forest Belle Gabbro in the East Ida greenstone belt. For granite intrusions with boundaries clearly outlined by outcrop distribution, aeromagnetic images, or geochemistry, formation names have been introduced (e.g. 'A-_pr-gm' for the Pigeon Rock Monzogranite, the underscore indicating that a suite has not been formally identified yet). For all units where formal names have been assigned, the naming conventions and descriptions conform with those used by GSWA throughout Western Australia. The large majority of granitic rocks in the central Yilgarn have poorly defined intrusion boundaries, and some post-date accretion of the Youanmi Terrane with the Eastern Goldfields Superterrane. For this reason, only their affiliation to the Yilgarn Craton is recognized in their characterization (e.g. 'A-gm-Y' for a monzogranite). Similarly, the boundaries of gneissic units that might precede accretion are commonly difficult to define due to poor exposure and outcrop fragmentation, and for this reason these rocks have also simply been assigned to the Yilgarn Craton.

Conclusions

The establishment of a lithostructural framework for the central Yilgarn Craton in a GIS environment provides a powerful tool for geologists working in the region. The approach allows particular lithologies to be better characterized according to their distribution and relationships. The resulting detailed breakdown of greenstone successions will allow spatial analysis to be carried out that will improve our understanding of the geological evolution of these sequences, as future mapping or analytical work that leads to the establishment of a formal stratigraphy can easily be accommodated within the structure of the database. Finally, spatial analysis of lithostructural units in relation to the distribution of known mineralized occurrences (also provided in the Central Yilgarn GIS package) may lead to advances in our understanding of tectono-stratigraphic controls on different styles of mineralization.

The implementation of a new lithostructural scheme for the Southern Cross Domain in the Central Yilgarn GIS dataset has already provided the framework for a fresh look at structural and stratigraphic problems, such as the correct positioning of the Ida Fault relative to the surface geology, and the consequent subdivision of the Mount Ida greenstone belt into components of the Youanmi Terrane and Eastern Goldfields Superterrane (Geological Survey of Western Australia, 2006a). Future expansion of the database will include more recent mapping, and detailed notes and descriptions covering the entire region. Ultimately, the Central Yilgarn GIS will be integrated with other databases covering the east Yilgarn Craton and Murchison regions to provide a fully integrated tectono-stratigraphic framework embracing the whole of the Yilgarn Craton.

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The Mount Belches Formation — Black Flag Group, a late basin, or something else?

by C. Hall

Abstract

New data and field observations suggest that sedimentary rocks of the younger-than-2666 Ma Mount Belches Formation in the Eastern Goldfields Superterrane are not part of the late-basin succession (Penny Dam conglomerate) or a lateral equivalent of the upper part of the Black Flag Group, but rather a separate unit that underlies the late-basin successions, analogous to the Porcupine assemblage in the Abitibi Province of Canada. Regional mapping has increased the known extent of the Mount Belches Formation, with outcrops on either side of the Kalgoorlie–Kurnalpi terrane boundary, indicating that the Kalgoorlie and Kurnalpi Terranes amalgamated before c. 2666 Ma. New SHRIMP U–Pb zircon data suggest a correlation between deformation in the Mount Belches Formation and a D_2 extensional event described in the Kurnalpi Terrane to the north.

KEYWORDS: Mount Belches Formation, Black Flag Group, sedimentary basins, Porcupine Assemblage, terranes.

Introduction

Late-basin successions of the Eastern Goldfields Superterrane (Cassidy et al., 2006) commonly contain conglomerates and sandstones deposited in basins that are locally fault bound or lie within synclines parallel to the regional north-northwest structural trend. These units rest unconformably on older greenstone successions such as the Black Flag Group (Kalgoorlie Terrane), and are regarded as having been deposited after north–south thrusting and recumbent folding associated with D_1, but before the main regional east–west shortening event of D_2 that produced the north-northwest structural trend (Swager et al., 1995; Swager, 1997; Krapez et al., 2000; Brown et al., 2001, Weinberg et al., 2003). In the Kurnalpi Terrane (Fig. 1), late-stage sedimentary rocks include the Penny Dam and Yilgangi conglomerates, which are successions of polymictic conglomerates and intercalated sandstones (Krapez et al., 2000; Brown et al., 2001). The Mount Belches Formation (Fig. 1), a thick sequence of quartzofeldspathic sandstones, mudstones with minor pebbly conglomerates, and banded iron-formation (Ahmat, 1995; Krapez et al., 2000; Brown et al., 2001), has been mapped as a lateral facies equivalent of the Penny Dam conglomerate (e.g. Swager et al., 1995). Krapez et al. (2000) constrained the maximum depositional age of the Mount Belches Formation to c. 2666 Ma by sensitive high-resolution ion microprobe (SHRIMP) U–Pb analysis of detrital zircons, and included the Mount Belches Formation and Penny Dam conglomerate in their ‘Kurrawang Sequence’, which they suggested was a submarine fan within a remnant-ocean basin, deposited before 2655 Ma, prior to the D_2 regional compressional event.

In contrast, Painter and Groenewald (2001) argued that the Mount Belches Formation has undergone at least two deformation events, with pre-D_2 folds (west-northwesterly trend) folded by north-northwesterly trending F_2 folds. Evidence cited by Painter and Groenewald (2001) for the earlier folding included a bedding-parallel foliation, irregularities in facing direction in the Mount Belches Formation, and regional-scale fold-interference patterns indicated by aeromagnetic traces of the iron-rich Santa Claus Member of the Mount Belches Formation. These features, resulting from the development of the Randall Dome, indicate that the Mount Belches Formation has undergone a more complex deformation than is commonly observed in the late-basin successions.

In this paper the Mount Belches Formation and its relationship to the late-basin successions and the Black Flag Group are discussed in terms of their significance with respect to the structural and stratigraphic subdivisions of the Eastern Goldfields Superterrane.

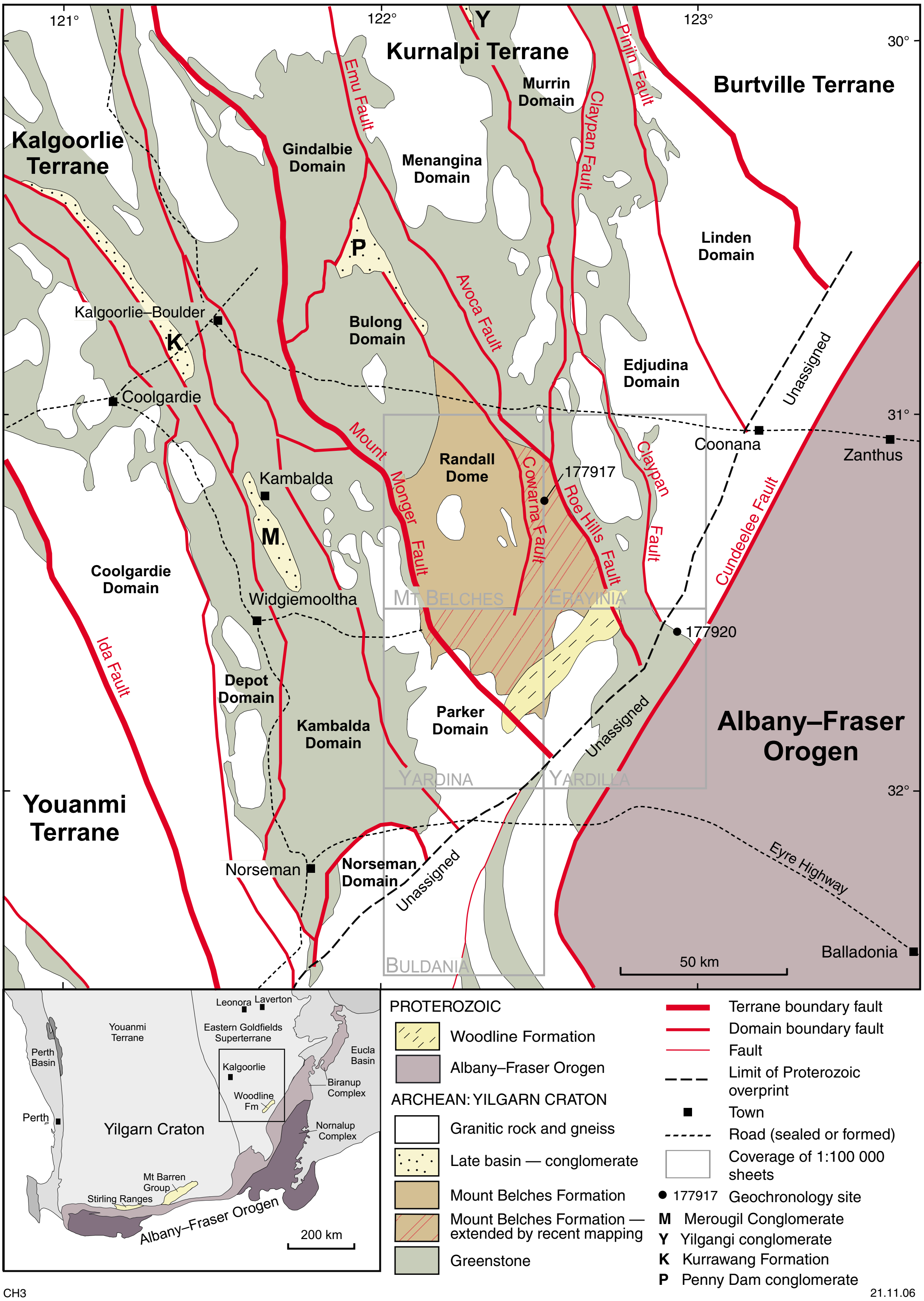

Figure 1. Locality guide and simplified geology showing the position of the Mount Belches Formation with respect to late-basin sedimentary units

Mount Belches Formation

The Mount Belches Formation is a sequence of metamorphosed fine- to coarse-grained sandstones interbedded with siltstones and mudstones, minor chert, banded iron-formation, and granular to pebbly conglomerate. The sandstone–mudstone sequences commonly display normal grading, scours, parallel- and cross-laminations, and soft-sediment deformation, indicative of turbidity current deposition according to Krapez et al. (2000). Petrographically, the sandstones contain relict detrital quartz grains interspersed with biotite clots and poikiloblastic plagioclase, with subordinate amounts of amphibole, chlorite, muscovite, and carbonate, and accessory amounts of magnetite, zircon, titanite, and apatite. A similar mineral assemblage is present in the mudstone layers, but staurolite, andalusite, and garnet are also present where the metamorphic grade reaches amphibolite facies.

The Mount Belches Formation, the late basins, and the Black Flag Group

Recent 1:100 000-scale mapping on MOUNT BELCHES* (Painter and Groenewald, 2001), ERAYINIA (Jones, 2006), YARDINA (Hall et al., 2006), and YARDILLA (Jones and Ross, 2005) to the east and south of the area studied by Krapez et al. (2000) has increased the known extent of the Mount Belches Formation (Fig. 1) so that: (1) the eastern margin of the Mount Belches Formation is now known to be bound to the east by the Roe Hills Fault rather than the Cowarna Fault (Jones, 2006); (2) the unit extends 20 km farther south than had previously been recognized; and (3) exposure includes a large anticlinal structure called the Randall Dome (Painter and Groenewald, 2001). In contrast, late-basin siliciclastic sedimentary rocks of the Kurrawang Formation and Merougil Conglomerate in the Kalgoorlie Terrane, and the Yilgangi and Penny Dam conglomerates in the Kurnalpi Terrane, lie in narrow north-northwesterly trending, elongate, regional 'D_2' synclinal basins (Fig. 1).

In the northwestern part of YARDINA (Hall et al., 2006) the Mount Belches Formation is exposed on both sides of the interpreted Mount Monger Fault (Fig. 1), which forms the boundary between the Kalgoorlie and Kurnalpi Terranes (Cassidy, 2004; Cassidy et al., 2006). Rocks of the Mount Belches Formation at the southern end of the Randall Dome are well-bedded siliciclastic sandstones and mudstones that have been metamorphosed to amphibolite facies (Hall et al., 2006). The sedimentological and mineralogical characteristics of the Mount Belches Formation in this area are very similar to sandstones and mudstones that have been metamorphosed to amphibolite facies in the southwestern corner of YARDINA, regarded by Hill et al. (1992) and Krapez et al. (2000) as a lateral equivalent of the Black Flag Group of the Kalgoorlie Terrane.

Late-basin sedimentary units are typically bound to the west by observed or interpreted faults (e.g. Merougil Conglomerate of Swager et al., 1995). The Mount Monger Fault is not exposed on either MOUNT BELCHES or YARDINA, but has been inferred from interpretation of aeromagnetic data and intersection of a fault zone from a drillhole in the northwest corner of MOUNT BELCHES (Painter and Groenewald, 2001). If the Mount Belches Formation-like rocks in southwestern YARDINA are actually part of the Mount Belches Formation rather than the Black Flag Group, then deposition of the Mount Belches Formation must post-date the amalgamation of the Kalgoorlie and Kurnalpi Terranes.

Deformation in the Mount Belches Formation

Early deformation (D_1) in the Eastern Goldfields Superterrane is poorly defined, but has been identified by bedding-parallel S_1 foliations associated with refolded F_1 folds and local thrust stacking (Swager, 1997). In the Mount Belches Formation, Painter and Groenewald (2001) identified folding of a pre-D_2, bedding-parallel foliation by open F_2 folds. Although Painter and Groenewald (2001) made the comment that the relationship of this early fabric in the Mount Belches Formation to the regional D_1 event is unclear, it suggests deposition earlier than the late-basin successions which do not have a pre-D_2 fabric.

The maximum depositional age for the Mount Belches Formation of c. 2666 Ma post-dates the minimum age of D_1 (Kalgoorlie Terrane), which has been interpreted as c. 2675 Ma (Kent and McDougall, 1995; Swager, 1997; Nelson, 1997). However, Blewett et al. (2004) described an extensional event within the D_2 deformational regime (D_{2E}) in the Kurnalpi Terrane to the north as having occurred at c. 2662 Ma. According to their scheme, this was followed by D_{2b} east–west shortening. A microgranite that lies about 15 km east of the southern end of the Roe Hills Fault and eastern margin of the mapped Mount Belches Formation (Jones and Ross, 2005; Jones 2006) has a strong early lineation folded by D_2 east–west compression. SHRIMP U–Pb zircon dating of the microgranite yielded a crystallization age of 2664 ± 3 Ma (Wingate and Bodorkos, in prep., GSWA 177920). Thus the earliest recognized deformation in the southwestern part of the Kurnalpi Terrane appears to correspond to the D_{2E} extensional deformation of Blewett et al. (2004).

A Canadian analogue of the Mount Belches Formation

In the Abitibi Province of Canada the Timiskaming assemblage is a suite of rocks similar in character and setting to the late basins in the Eastern Goldfields (e.g. Blewett et al., 2004). This assemblage, also found in narrow elongate corridors, is dominated by clastic sedimentary rocks (polymictic conglomerates and sandstones) with subordinate volcanic rocks that have a depositional age range from 2687 to 2675 Ma (Ayer et al., 2002). Unconformably beneath the Timiskaming assemblage, but above the Archean granite–greenstone basement, are rocks of the Porcupine assemblage (Ayer et al., 2002). This assemblage, dominated by sandstones and siltstones displaying Bouma cycles, is interbedded with minor

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

conglomerates and iron formation (Ayer et al., 2002). The characteristics and relative abundance of the different units in the Porcupine assemblage are very similar to those described for the Mount Belches Formation (Painter and Groenewald, 2001), suggesting that the Mount Belches Formation lies in a similar stratigraphic setting within the Eastern Goldfields Superterrane.

Conclusion

New geochronological data and field observations suggest that the Mount Belches Formation is not part of the late-basin sequence (Penny Dam conglomerate) or the Black Flag Group, but is a separate turbidite-dominated unit similar in character to the Porcupine assemblage in the Abitibi Province of Canada. If the Mount Belches Formation is a much more widespread unit than has previously been described, then the fact that it has been deposited on both sides of the Mount Monger Fault constrains the age of major movement on this terrane boundary to before c. 2666 Ma. Earlier interpretations of the Mount Belches Formation as a lateral equivalent of the Penny Dam conglomerate, or rocks that may belong to the Mount Belches Formation as lateral equivalents of the upper Black Flag Formation, highlights a problem in the definition of what constitutes a 'late basin' in the Eastern Goldfields Superterrane.

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Coyote gold deposit, Granites–Tanami Orogen, Western Australia

by L. Bagas[1,2], D. L. Huston[3], J. A. C. Anderson[4], and F. P. Bierlein[2]

Abstract

The Coyote gold deposit, hosted by graded turbidite units of the Paleoproterozoic (c. 1835 Ma) Killi Killi Formation of the Tanami Group, comprises a number of ore lenses localized along the limbs of the Coyote Anticline, a structure formed during the Paleoproterozoic Tanami Orogeny. The main ore lenses are along the steeply dipping south limb of this fold, just to the north of the Gonzales Fault. The Coyote Anticline was refolded about north-trending fold axes and the Gonzales Fault reactivated as a dextral transpressive structure during late (c. 1800 Ma) easterly directed compression. Dilational zones that formed in and adjacent to an approximately 10 m-thick siltstone unit controlled the movement of mineralizing fluids at moderate temperatures (~350°C) by a pressure gradient. These dilational zones formed in response to the compression.

An implication of this preliminary study is that gold mineralization in the Coyote deposit was multistage and can be temporally linked to a combination of tectonism, metamorphism, and granite emplacement, similar to the genesis of many orogenic gold deposits worldwide.

KEYWORDS: Paleoproterozoic, Tanami Group, Killi Killi Formation, Tanami Orogeny, Coyote, gold.

The Coyote gold deposit is concealed by both in situ and transported regolith to a depth of 15 m, and the base of weathering extends to a depth of up to 200 m. As a consequence of the regolith cover, AngloGold Ashanti and Tanami Gold NL have delineated the geological structure of the area with detailed lithological and structural logging of drillholes.

Coyote, Kookaburra, and Sandpiper are the only gold deposits in the western part of the Paleoproterozoic Granites–Tanami Orogen for which resources have been established, but there are other significant prospects in the area (Fig. 1).

The auriferous veins are interpreted to have been emplaced during and after the Tanami Orogeny between 1835 and 1800 Ma. The orogeny is a major tectonic event that is characterized by southeast- to east-trending folds and faults.

Between c. 1835 and 1795 Ma the region was characterized by extensive magmatism accompanied by folding. The magmatism may be associated with post-collisional extension after docking of the Halls Creek Orogen to the northwest and is broadly coeval with most of the gold deposits in the Tanami region (Huston et al., 2006).

Structural setting

The Coyote deposit is hosted by the c. 1835 Ma Killi Killi Formation of the approximately 5 km-thick Tanami Group (Huston et al., 2006). The formation is interpreted to be up to 4 km thick and comprises fine- to medium-grained, immature sandstone interbedded with lesser (10–30%) siltstone, and rare carbonaceous shale, and mafic intrusive rocks. A distinctive finer, approximately 10 m-thick siltstone-dominated sequence, locally called the 'Marker siltstone', has been used as a stratigraphic marker within the mine sequence to delineate the structure of the deposit (Fig. 2).

The Coyote deposit consists of a number of ore lenses that are within the F_{C1}* Coyote Anticline associated with the Tanami Orogeny. The deposit comprises one main (Buggsy–Gonzales) and several satellite lenses (e.g. Speedy) that form ruler-shaped lodes plunging 10–15° to the southwest (parallel to the fold axis). The Buggsy–Gonzales lode is about 1 m thick and extends 150 m down-dip and up to 300 m along strike, and the Speedy lode is about 2 m thick, and extends 40 m down-dip and 80 m along strike.

1 This contribution forms part of a PhD thesis project at:
2 Centre for Exploration Targeting, University of Western Australia, Crawley, W.A. 6009.
3 Geoscience Australia, GPO Box 378, Canberra, A.C.T. 2601.
4 Tanami Gold NL, PO Box 1892, West Perth, W.A. 6872.

* 'C' refers to deformation events in the Coyote area.

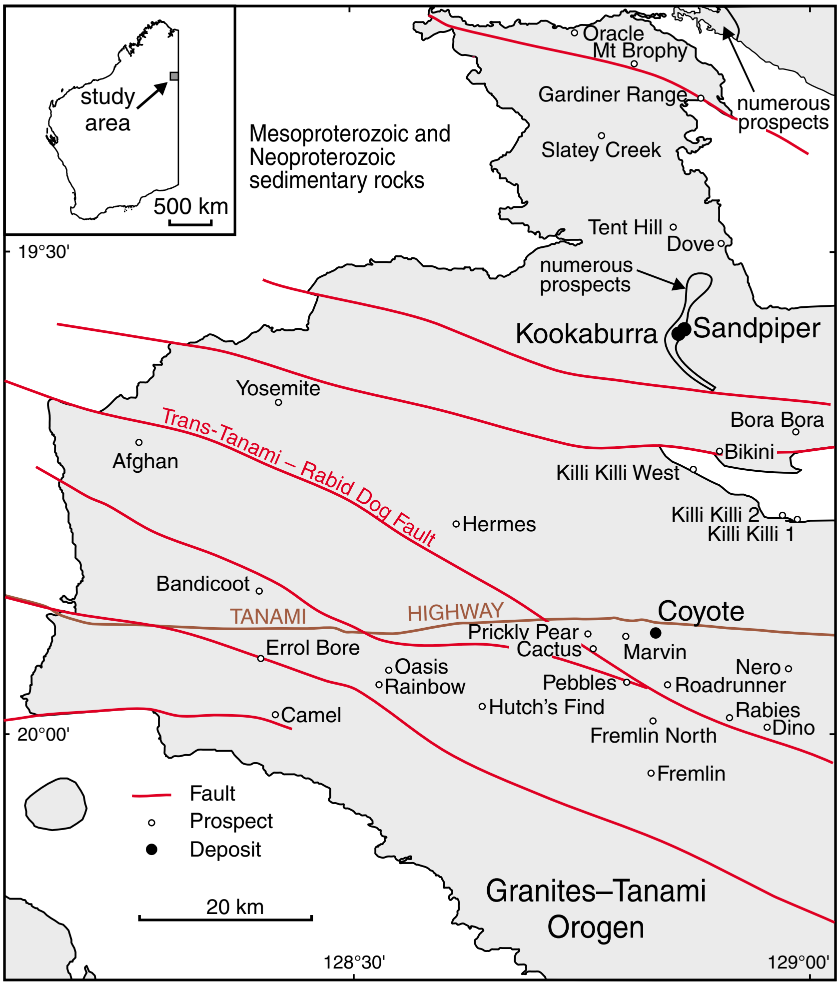

Figure 1. Mineral deposits and prospects in the western part of the Granites–Tanami Orogen, Western Australia

A major, near-vertical to steeply north-dipping fault, the Gonzales Fault (Bagas et al., 2006), is subparallel to the southern limb of the anticline (Fig. 2). The orientation of the Gonzales Fault, in combination with the angular, asymmetrical, and overturned shape of the Coyote Anticline, suggests that both the fold and fault formed during the same tectonic event. The Gonzales Fault cannot pre-date the Coyote Anticline because similar structures have not been observed at the same stratigraphic level on the northern limb of the fold. However, some of the bedding-parallel foliation in the area may be associated with earlier (pre-D_{C1}) structures, and is the subject of further investigations. In addition, local changes in the sense of movement along the Gonzales Fault, including extensional (south-side-down) and transpressional dextral movements observed along the fault, indicate that the fault has been reactivated several times.

The southeast-striking sinistral faults in the eastern part of the Coyote Anticline and the curved trace of the Coyote Anticline suggest refolding around northerly trending axes that indicate compression (D_{C2}) in an easterly direction (Fig. 2). During this easterly directed compression the Gonzales Fault was reactivated as a transpressional fault with dextral movement. Dilational zones would have formed at local perturbations along the fault during this movement, such as at the Gonzales ore lens (or lode). The structural controls on the Gonzales lode are not fully understood, but appear to have involved a complex interrelationship between faulting and parasitic folding in the limbs of the Gonzales Anticline.

The late (D_{C3}) Trans-Tanami – Rabid Dog Fault is between 1 and 4 km southeast of the Coyote deposit. The structure is a late approximately 125° trending, brittle, dextral strike-slip fault that hosts massive (2–3 m-thick) quartz veins.

Veining and mineralization

At least three sets of quartz veins are recognized at the Coyote deposit. These are described here as the early, quartz–chlorite, and late vein sets.

The early veins are bedding parallel, and are commonly in siltstone beds adjacent to the contacts with more competent sandstone beds. The location of these veins suggests that a competency contrast developed between the siltstone and sandstone during deformation, consistent with a flexural-slip folding mechanism.

The veins consist of quartz, and minor chlorite and carbonate, and are associated with narrow (<5 mm) chloritic wallrock alteration haloes. This veining appears to be more prevalent near parasitic anticline hinges and perturbations developed within the Coyote Anticline. In places these early veins are folded or modified within narrow bedding-parallel shear zones. The folding and shearing is consistent with continuing flexural slip during the progressive deformation that formed the Coyote Anticline. As a result of continuing deformation the early bedding-parallel veins are strongly recrystallized with fibrous textures, with laminated and boudinaged morphologies.

The early vein set is crosscut by quartz–chlorite veins that are orientated at high angles to bedding

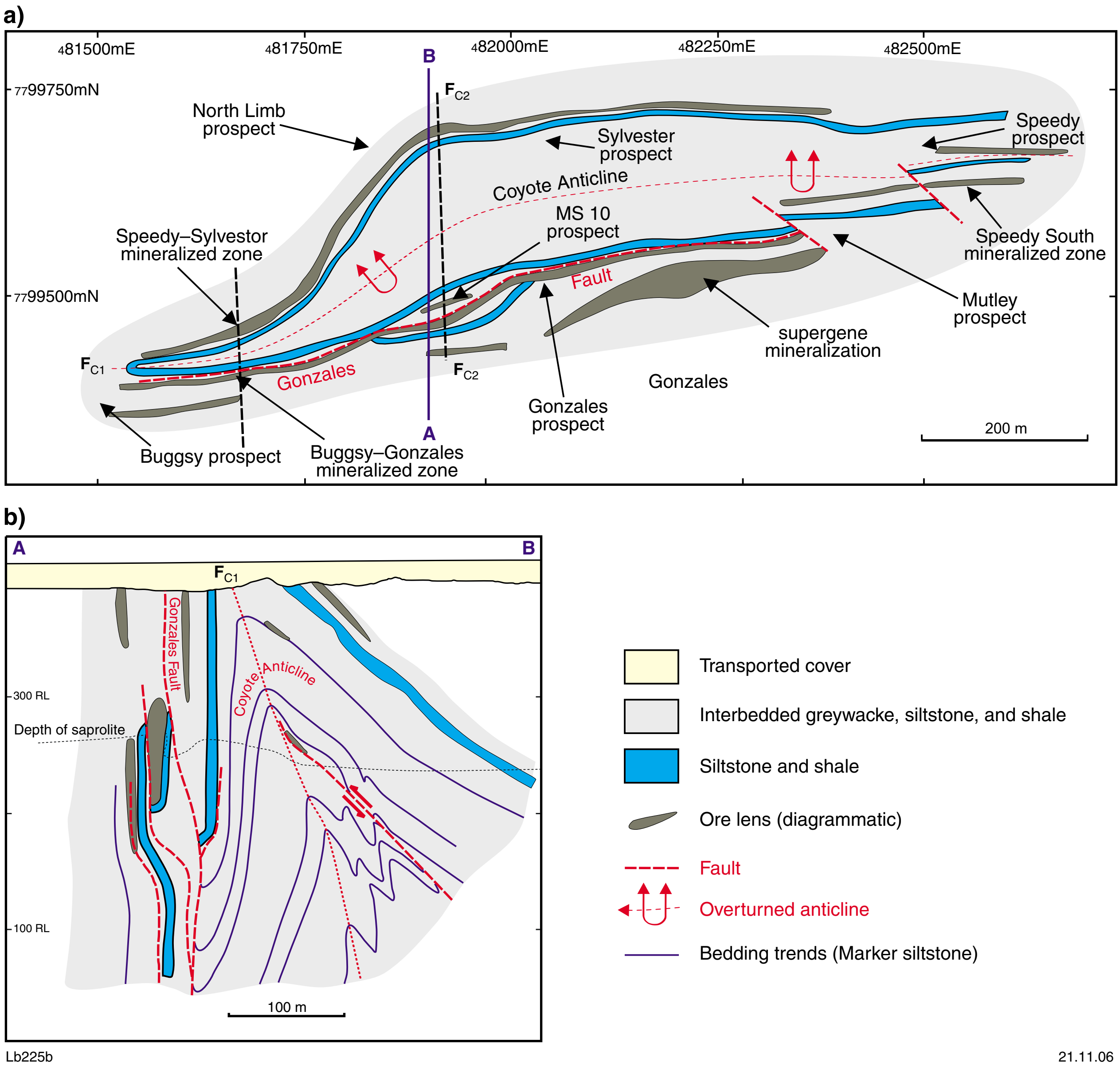

Figure 2. a) Generalized geological map of the Coyote area; b) cross section A–B of the Coyote Anticline (modified after maps provided by AngloGold Ashanti and Tanami Gold NL)

and have well-developed, 2–10 mm-thick chloritic selvages. These either represent link structures that accommodated flexural slip between bedding planes during regional folding or they constitute a later vein set. In addition, the early bedding-parallel veins are crosscut by small-scale gash or tension veins. These crosscutting veins formed across the width of the host veins and frequently propagate a short distance into the surrounding wallrock. Chloritic alteration selvages less than 10 mm wide and asymmetric in places are normally present where these veins propagate into wallrock.

Within the deposit gold is only associated with quartz veining, and the majority of the visible gold is associated with the small-scale gash or tension veins that formed within and across the early vein set. These crosscutting veins are quartz dominated, but also contain chlorite–carbonate(–sericite after biotite) with minor (<1%) pyrite–chalcopyrite–arsenopyrite–sphalerite–galena–bismuth species, and free gold.

Near the mineralization there is a second set of patchy retrogressive chlorite(–sericite–biotite) alteration that extends at most 20 mm into the wallrock. In addition, visible gold is associated with some early veins formed within sandstone units with almost no sulfides and weak silica–chlorite wallrock alteration.

The exact timing of the auriferous, bedding-parallel 'early' veins is unclear and has been complicated by the progressive style of deformation. However, this change in auriferous vein style suggests that there may be a continuum or multiple episodes of gold deposition between D_{C1} and D_{C2}. The late veins include massive white quartz and effervescent carbonate veins without significant alteration. These are not auriferous and are interpreted to have formed during D_{C3}.

Genetic model

Data collected in this preliminary study place some constraints on models for the genesis of gold at Coyote. Figure 2 illustrates the two major structural elements (folding and faulting) at Coyote. Even though these two types of structures may have formed during the same deformation event (D_{C1}), faults in the area were reactivated several times and folds were refolded during later deformational events.

We interpret the Coyote Anticline and the Gonzales Fault as having formed during the Tanami Orogeny, which is characterized by southeast- to east-trending angular folds (Huston et al., 2006). The earliest generation of folded quartz veins most likely formed at this time along bedding-parallel faults or shears. These veins were probably progressively folded to accommodate bedding-slip as the anticline tightened during the D_{C1} event. Because the fold is angular and generally lacks a pronounced axial-planar foliation, we interpret that it either formed at a relatively high structural level or its shape is a function of lithology.

As discussed above the gold appears to have been deposited during a protracted period between D_{C1} and D_{C2}. During this period competency contrasts between siltstone and sandstone beds promoted and localized dilation, and allowed emplacement of quartz–chlorite–pyrite–chalcopyrite(–arsenopyrite–galena–bismuth minerals–gold) veins. The association of these veins with biotite-bearing alteration selvages, and the results of fluid-inclusion studies by T. Mernagh (2006, written comm.) suggest that the veins formed at temperatures around 350°C. This protracted mineralization between D_{C1} and D_{C2} suggests that the gold mineralization was multi-phase and may have been related to both the Tanami Orogeny as well as deformation processes leading to the emplacement of the c. 1800 Ma granites in the region (Fig. 3; Bagas et al., 2006). This hypothesis is supported by preliminary sensitive high-resolution ion microprobe (SHRIMP) analyses of hydrothermal xenotime that is paragenetically associated with gold at Coyote, and gives an age of 1791 ± 8 Ma (Bagas et al., 2006). However, it must be pointed out that this date is regarded as a minimum age for gold mineralization because of possible resetting by thermal perturbations associated with the emplacement of c. 1800 Ma granites in the region.

Gold deposition and granite emplacement probably occurred as the stress field associated with deformation relaxed, with the associated pressure release allowing gold to be deposited and granite to be emplaced (Fig. 3). Moreover, the decrease in pressure allowed the auriferous fluids to effervesce, as indicated by fluid-inclusion studies, causing gold deposition as H_2S partitioned into a CO_2-rich vapour (Mernagh, T., 2006, written comm.). It is likely that the regional relaxation was accompanied by a regional decrease in temperature, which may be reflected in the replacement of biotite by chlorite in the late-stage paragenesis of the auriferous veins. If gold deposition occurred slightly after arsenopyrite deposition, the distribution of gold and arsenic would not exactly coincide, matching geochemical observations at Coyote and other gold deposits in the region (Huston et al., 2006), as well as similar observations in analogous terrains elsewhere (e.g. central Victoria; Bierlein et al., 2000).

This model implies that similar processes enhancing gold deposition may have also occurred in other areas of low pressure that developed towards the end of the D_{C2} event (Fig. 3). The Gonzales Fault as a whole appears to define a significant although narrow mineralized corridor. Gold is also present on the northern limb of the Coyote Anticline in late bedding-parallel veining adjacent to the sheared contact between the Marker siltstone and the overlying turbiditic sandstone.

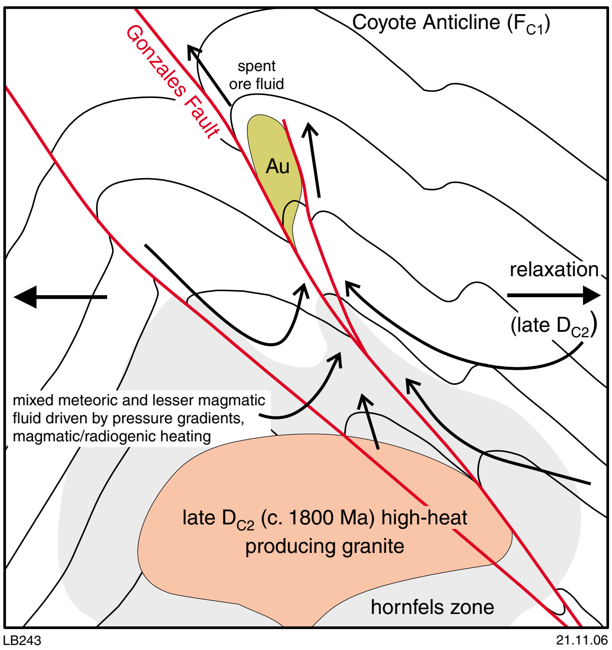

Figure 3. Genetic model for the Coyote gold deposit

Such bedding contacts represent zones with significant competency differences and are commonly brecciated or faulted, forming dilation zones where gold is deposited.

The lack of a clear lithogeochemical control at Coyote, such as that interpreted at The Granites goldfield in the Northern Territory (Huston et al., 2006), suggests that structural traps were important in localizing gold in the Coyote deposit. Such structural control may be the most important factor for gold deposition in the Killi Killi Formation in both Western Australia and the Northern Territory. These turbiditic units generally lack the chemically reactive rocks that are highly effective gold traps elsewhere in the region (Huston et al., 2006). In this respect, Coyote has many similarities with 'slate belt-hosted' orogenic gold deposits in the western Lachlan Orogen of Australia, and in Alaska in the United States of America (Goldfarb et al., 2001).

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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 2005–06

The focus of activities during 2005–06 was in the Canning Basin. Other basins are under a watching brief. Detailed studies of the Canning Basin continued. Some of the highlights were:

- Publication of a compendium of all basic petroleum geochemistry analytical data for the Canning Basin as Record 2006/7;
- Compilation for release, early in 2006–07, of the first public-domain workstation-ready seismic and well log dataset for the Canning Basin. This release will include over 37 000 km of SEGY seismic data and 179 wells with partial wireline log suites. Shotpoint locations for over 50 000 km of seismic data and locations for 256 wells are included, comprising the entire Canning Basin seismic shotpoint and petroleum well-location dataset. Datasets are available in Landmark and SMT Kingdom Suite formats through the online Western Australian petroleum information management system (WAPIMS) database;
- Commencement of the first study on the potential for Hot Dry Rocks (HDR) geothermal energy developments in parts of Western Australia;
- Oral presentations were made at the Petroleum Open Day, Offshore Europe, AAPG International, the Central Australian Basins Symposium, the North American Prospect Exposition, and the Australian Petroleum Production and Exploration Association conference;
- Exhibitions of the petroleum opportunities in Western Australia were provided for the Good Oil Conference and Exhibition in Fremantle, the Petroleum Open Day in Fremantle, Offshore Europe in Aberdeen, AAPG in Paris, the North American Prospect Exposition Houston, and APPEA Gold Coast;
- One-on-one presentations of petroleum opportunities in Western Australia were provided to companies in Australia, Canada, the UK, and France;
- Following on from the Central Australian Basins Symposium (CABS), a GSWA paper examining evidence for the possible existence of the Larapintine Seaway was completed for publication in the CABS Symposium volume to be published by the Northern Territory Geological Survey;
- Staff led an excursion for industry personnel to the Canning Basin.

2005–06 publications and products

- Record 2006/7: *Petroleum geochemistry of the Canning Basin, Western Australia: basic analytical data 2004–05*;
- Prospectivity of State Acreage Release Areas L05-7 and L05-8, Lennard Shelf, Canning Basin (in conjunction with the Petroleum and Royalties Division);
- Prospectivity of State Acreage Release Areas L05-5 and L05-6, Fitzroy Trough and Pender Terrace, Canning Basin (in conjunction with the Petroleum and Royalties Division);
- Eighteen external papers were published.

Future work

Future studies will continue to focus on petroleum systems analysis of the Canning Basin. Future products from the Canning Basin studies and others will consist of basic and interpretative data packages, papers, and presentations including:

- Four papers and one poster session at AAPG 2006 Perth;
- A paper presented at Global Infracambrian Hydrocarbon Systems London;
- Workstation-ready seismic and wireline log data for part of the Canning Basin;
- Sedimentology and stratigraphy from outcrop and subsurface studies;
- Stratigraphy and sedimentology of the Carribuddy Group;
- Structure and sequence stratigraphy from seismic interpretation;
- Petroleum geochemistry and thermal history 2D modelling;
- Fluid flow modelling (getting the lead out of petroleum systems);
- Potential source rocks and their maturation histories from organic geochemistry, organic petrology, and apatite fission-track analysis studies;
- Potential reservoir rocks from sequence stratigraphy and numerical modelling (SedSim in conjunction with CSIRO) 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;
- Potential for Hot Dry Rocks geothermal energy developments in Western Australia.

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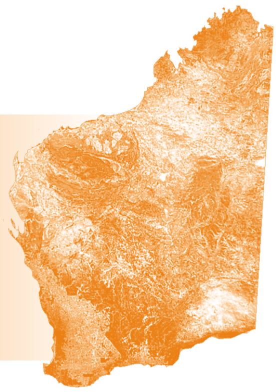
Petroleum exploration reports and data



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 2005–06

The program of scanning well completion reports from hard-copy to PDF and TIFF formats continued with a total of 775 reports, completing the onshore and starting in the territorial seas of the Carnarvon Basin, being scanned and loaded onto the WAPIMS system for online web viewing.

As part of the WAPIMS database program, well log curves for a further 167 wells (giving a total of 1048 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, Perth, Carnarvon and Bonaparte Basins from nine-track reels to 3590 cartridges (15 324 tapes from 39 surveys) continued to reduce the number of 'old' tapes in the archive and move these valuable data to new and more reliable media. All seismic data in the Bonaparte Basin have been transcribed.

Upgrades to the WAPIMS public interface were completed, with extra features of the database delivered early in 2005–06.

A total of 306 Gb of data are now available online through WAPIMS, with 34.6 Gb of online seismic SEGY data for 143 surveys, 16.2 Gb of online log data for 426 wells, and 38.2 Gb of well completion reports for 435 wells added in 2005–06.

WAPIMS database

During 2005–06 a total of 21 342 new data items received from industry were loaded into the system.

Data release

During 2005–06, 3817 edited and unedited reports were released. Industry requests consisted of 104 requests for loans of seismic and well, digital field, and processed data for 143 seismic surveys and 397 wells. In addition, 104 requests for sampling or borrowing slides from 174 wells were processed.

Future work

- Complete the scanning of well completion reports for the State and scanning of well log headers for the State;
- Continue adding well log data and seismic post-stack data to that already available online;
- Continue the transcription program — working primarily in the western and central Canning Basin, with some surveys in the Perth and Carnarvon Basins;
- Specific Area Gazettal data packages for areas to be determined.

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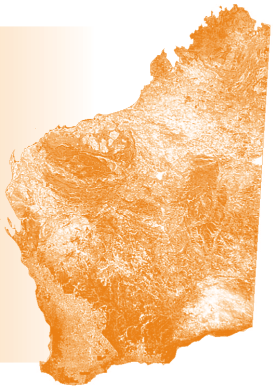
MINERAL RESOURCES ASSESSMENT AND MINERAL EXPLORATION DATA

Mineralization and exploration assessment

Objective: *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 published as data packages comprising GIS-compatible databases on CD-ROM. Some of this information is also included in GSWA's internet-based map viewer GeoVIEW.WA.*



Highlights and activities 2005–06

Two mineral prospectivity data packages on the west Hamersley and Mid West coast areas were released during the year. A data package is nearing completion for the Gascoyne area. Compilation of databases and digitizing of spatial data for mineral occurrences and mineral exploration activities continued for the north Murchison area and commenced for the Peak Hill area (Fig. 1).

Each data package is presented as a CD-ROM of digital data containing the following datasets available in GeoVIEWER.WA format: 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; aeromagnetics; radiometrics; gravity; topographic and cultural features.

2005–06 publications and products

Report 97: *Mineral occurrences and exploration potential of the Paterson area*;

Record 2006/5: *Mineral occurrences and exploration activities of the Mid West coast area*;

Record 2006/12: *Mineral occurrences and exploration activities of the west Hamersley area*.

Future work

A data package for the Gascoyne area is in preparation for release in 2007.

Database compilation and digitizing will continue for the north Murchison and Peak Hill areas (Fig. 1).

The WAMIN database (currently available only on CD-ROMs in prospectivity data packages and the DVD for the East Yilgarn 1:100 000 Geological Information Series data package) is to be integrated with the MINEDEX database and will be available in late 2007.

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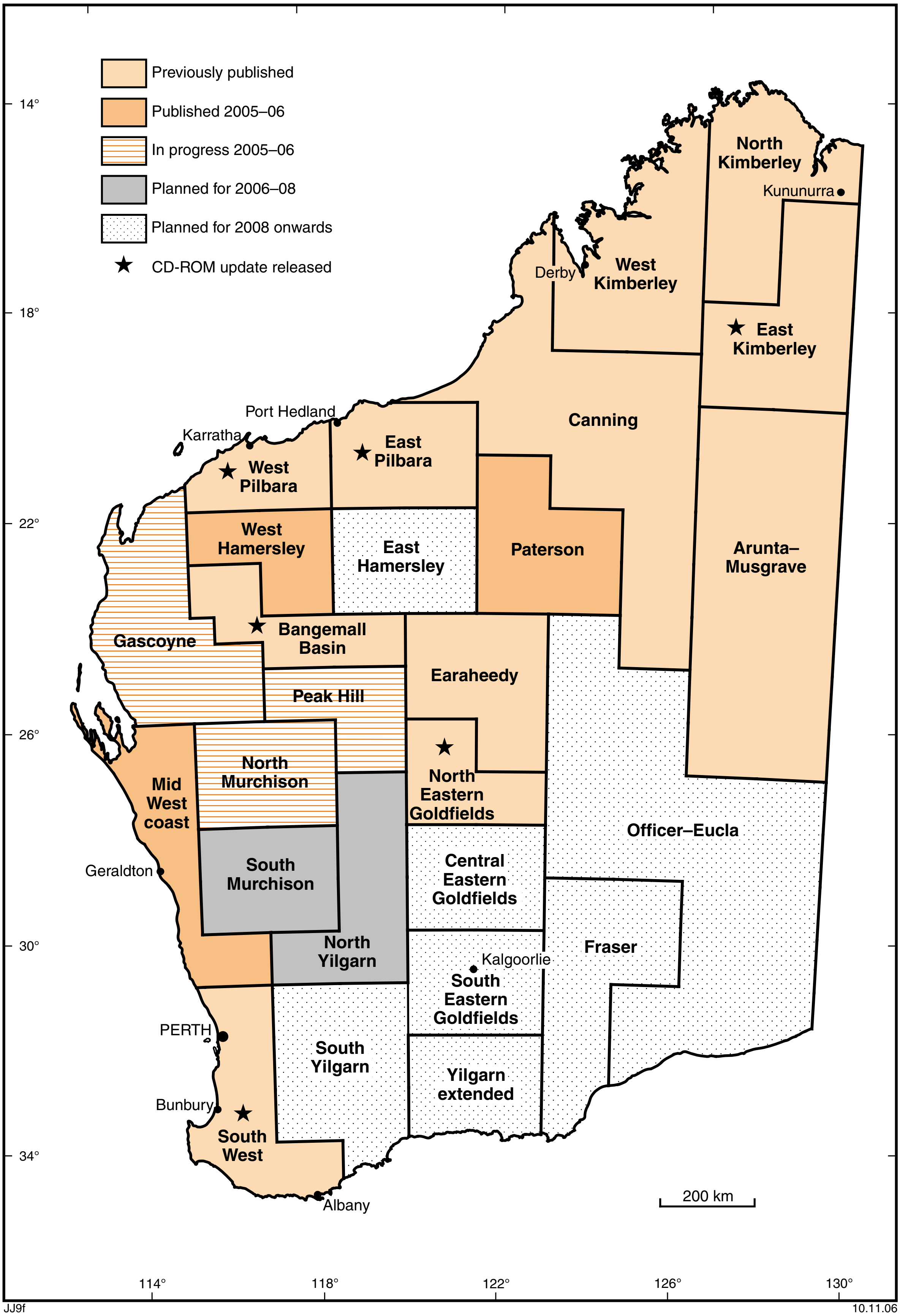
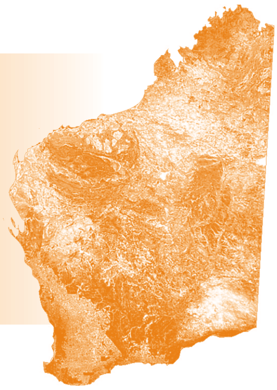


Figure 1. Progress of regional mineralization mapping projects

Commodity and industry analysis



Objective: *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).*

Highlights and activities 2005–06

The ongoing data capture into DoIR's Western Australian mines and mineral deposits information database (MINEDEX) formed an important part of the function of this section. A total of about 350 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. Work has commenced on integrating three of the Geological Survey's minerals databases (MINEDEX, WAMIN, and WABMINES).

Draft commodity reviews (including updates) were prepared for nickel, copper–lead–zinc, diamonds, manganese, vanadium, and chromium.

Compilation continues of the first part of a major publication covering dimension stone in Western Australia, with publication intended as a two-part Mineral Resources Bulletin. Several articles on dimension stone in Western Australia were prepared and published.

2005–06 publications and products

- Western Australian mines — operating and under development, 2006 map;
- Major resource projects, 2006 map;
- Iron ore deposits of the Pilbara Craton, 2005 map and CD;
- Iron ore deposits of the Yilgarn Craton, 2006 map;
- Record 2006/6: *Nickel–cobalt in Western Australia: commodity review for 2004*;
- Record 2006/13: *Copper–lead–zinc in Western Australia: commodity review for 2003 and 2004*;
- Overview of mineral exploration in Western Australia for 2004–05.

Future work

Continued integration of the Geological Survey's minerals databases (MINEDEX, WAMIN, and WABMINES). 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.

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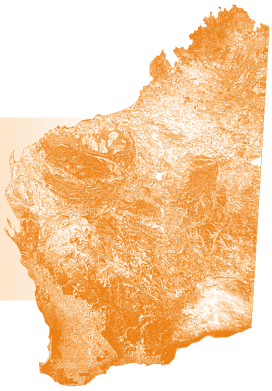
Inventory of abandoned mine sites



Objective: *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 2005–06

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. The selective extraction and processing of bedrock gold-mineralization features from the WABMINES database has enabled the generation of three-dimensional pseudocolour drapes that highlight the gold mineralization patterns within historic mine sites.

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 21 450 mine site features were added to the inventory during 2005–06, resulting in a total of 166 425 features at 30 June 2006 (Fig. 2).

Priority for field inspection is now being given to abandoned mine sites within 10 km of major towns, 1 km of main roads and selected tourist routes, and within 5 km of smaller towns and communities. About 44% of all abandoned mine sites are in this high-priority category. At 30 June 2006, approximately 76% of these higher

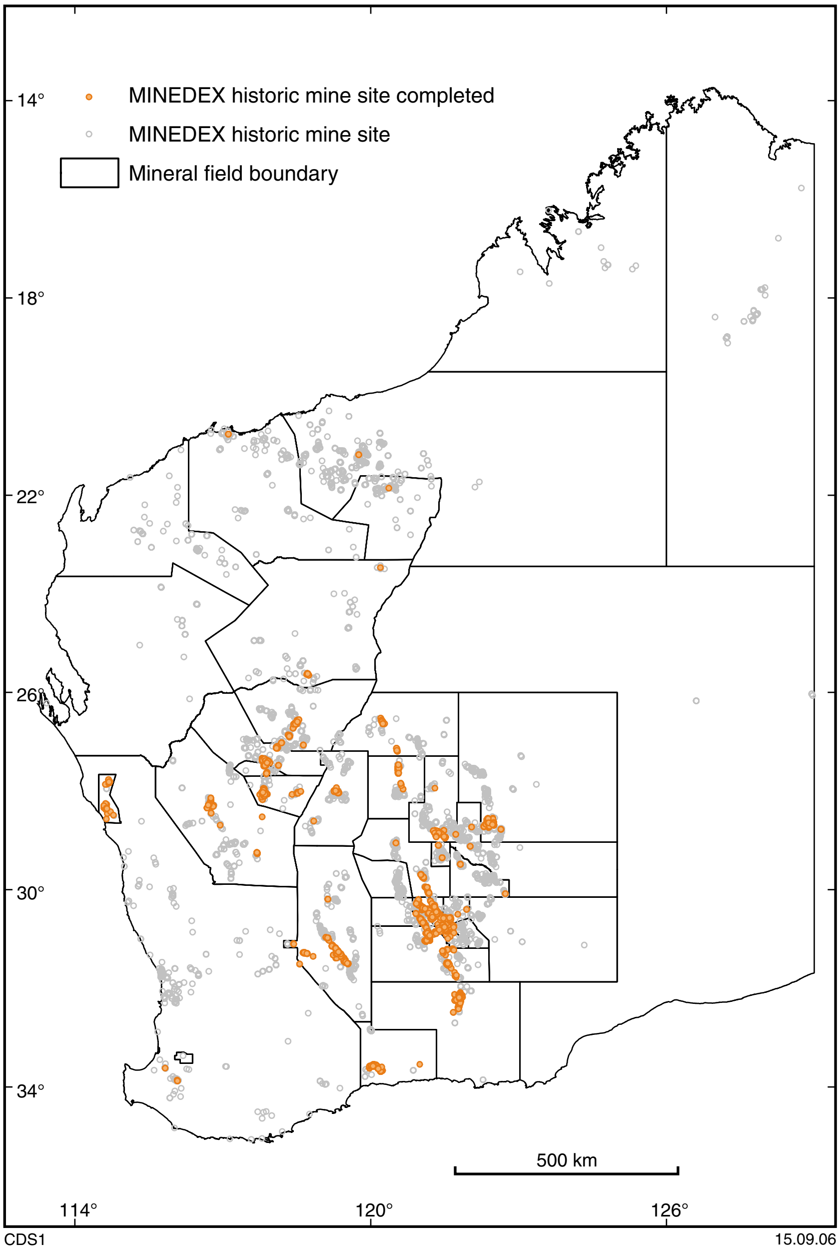


Figure 2. Status of the inventory of abandoned mine sites — MINEDEX sites completed as at 30 June 2006

priority production sites had been inspected during the program.

Fieldwork during 2005–06 was conducted along the southeastern section of the Golden Quest Discovery Trail, including Ora Banda, Siberia, Goongarrie, Comet Vale, and Menzies.

2005–06 publications and products

- Digital datasets on DVD: *Inventory of abandoned mine sites: progress 1999–2005*;
- A technical paper in the 2004–05 GSWA Annual Review: *Spatial analysis of gold mineralization information from GSWA's abandoned mine site database*;
- An article in the Australian Centre for Geomechanics April 2006 Newsletter: *Field inventory of abandoned mine sites in Western Australia*.

Future work

The team will complete working along the Golden Quest Discovery Trail in the Menzies, Kookynie, Murrin Murrin, and Copperfield areas.

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Resource assessment and land access

Objective: *To carry out assessments of the economic geology of areas proposed for land title and land use changes, and thereby provide advice on the impact on future exploration and resource development. This advice is provided to other divisions of the Department, other Government agencies, resource companies, and the community.*

Highlights and activities 2005–06

The primary function of the group is to estimate the economic value of known mineral and petroleum resources, as well as the potential for additional discoveries in areas proposed for changes in land tenure. Based on these resource assessments, advice is given to other divisions of the Department, other Government agencies, resource companies, and the community. During 2005–06, advice was given on 1032 requests for land title or land use changes. This number is similar to the previous year and reflects, in part, the buoyant economy in Western Australia and the resulting increase in land development activities in urban, regional, and rural areas.

Detailed advice on the economic geology was carried out on:

- The geological distribution of the Donnybrook Sandstone in the Donnybrook Shire;
- Conservation reserve proposals for the Forest Management Plan in the Swan Coastal Plain;
- Local government town-planning schemes and local planning strategies;
- Proposed expansion of the town of Ravensthorpe.

Future work

Work will continue on providing resource assessments and advice with respect to land title and land use changes so as to avoid conflict with land access for exploration or the sterilization of known and potential mineral resources. 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 sand at the Baldivis Explosive and Buffer Reserve south of Perth;
- Publication of a series of maps showing the distribution of Ti mineralization (heavy mineral sands) on the Swan Coastal Plain.

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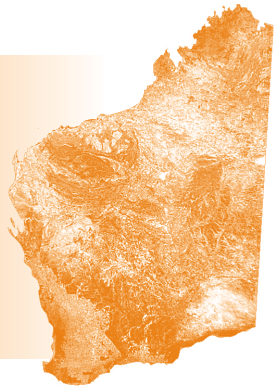
Industry and community liaison



Objective: *To improve access for exploration and development of mineral, petroleum, and building materials on all lands in the State through provision of information and advice to Government authorities, the resource 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.*

Highlights and activities 2005–06

Conservation issues

- The Southwest Forest Management Plan, as identified in the Government's 'Protecting Old Growth Forest Policy', proposes numerous new conservation reserves. Mineral resource assessments have been carried out on the proposed reserves, with discussions taking place with the Department of Environment and Conservation (DEC; previously the Department of Conservation and Land Management) with the goal to minimize the impacts on future resource access.
- The impact on the exploration, mining, and petroleum industries of the creation of a large number of proposals for the extension and creation of national parks and nature reserves has required resource assessments and negotiations with other Government departments. Proposals include expansion of the Kennedy Range National Park, and the creation of the Koolanooka Nature Reserve and Dampier Archipelago National Park.
- The development of major iron ore deposits in the Mid West region has been hampered by the lack of knowledge of native flora and fauna in the mineralized areas, which has delayed approval by the Environmental Protection Authority, and the proposal of DEC to create conservation parks. Discussions have take place with companies and DEC to progress the proposed mining developments.

Community liaison

- Assistance, by way of information on the geology and mineral resources, has been provided on a range of planning schemes related to Town Planning Schemes and Local Planning Strategies for local Government.
- The buoyant demand for residential land has led to a number of conflicts between the protection of limesand resources and proposals for new residential land developments. Extensive discussions have taken place with various stakeholders regarding the proposals to expand the Dongera and Lancelin townsite areas.

Planning initiatives

- Compiling maps for the titanium mineral deposits in the Swan Coastal Plain continued. These maps will inform land use planners and others of the location of deposits and will hopefully lead to less conflict over land usage.
- Limestone is an important basic raw material that has numerous applications. There is increasing demand for limestone in road construction; as a construction material, both for lime blocks and cement manufacture; in mineral processing of gold ores, nickel laterite, and bauxite; and as agricultural lime. However, most limestone occurs in coastal areas where there is high land-use conflict, particularly from environmental issues and residential housing developments. The 'Towards the State Lime Supply Strategy' will propose methods to develop strategies to ensure that Western Australia has lime resources for the next fifty years.
- Similar to limestone, sand is a basic raw material that is affected by planning issues. The shortage of sand south of Perth has resulted in the need to utilize the resources located on the Baldivis Explosive Reserve and Buffer. The Geological Survey, ReadyMix, LandCorp and Main Roads are working together to maximize the value to the State of this strategic sand resource and to ensure sequential use of the land for residential development.

Geological initiatives

- Progress has been made on finalizing a management policy of the Western Australian Register of Geoheritage Sites. A compilation of geoheritage sites will shortly be released to the public.

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.

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Geoscientific advice relating to exploration

Objective: *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 2005–06

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 2215 mineral tenements (Table 1) was reviewed during 2005–06 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 195 applications in 2004–05 to 333 in 2005–06). Exploration expenditure for iron (as reported on Form 5) has increased by 40% from 2004–05 to over $66 million in 2005–06 (this figure does not include exploration expenditure within State agreements).

The number of applications for exemption from exploration expenditure determined by the Department during 2005–06 has increased by about 5% to 3606 (after a 35% decrease in the previous year to 3437 from 5211 in 2003–04). However, it should be noted that there has been a 9% increase in the number of tenements in force in the same period. In addition, dollar amounts exempted overall have shown a downward trend over the last three years.

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 are 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 recommended in lieu of forfeiture where an expenditure exemption has been refused (the Minister imposed fines on 309 tenements in lieu of forfeiture during the 2005–06 period). The number of exemption applications refused constitutes about 23% of total applications in 2005–06 (down

Table 1. Tenement reviews

Geological advice provided	*Number of tenement actions*					
	2000–01	*2001–02*	*2002–03*	*2003–04*	*2004–05*	*2005–06*
Expenditure exemption	1 569	1 962	2 362	2 406	2 146	1 543
Extension of term of Exploration Licences	394	411	369	323	286	237
Dealings in first-year Exploration Licences	75	42	43	30	67	80
Iron ore authorization (Exploration Licences)	16	32	30	90	195	333
Iron ore drop offs (Exploration Licences)	2	0	0	8	15	20
Retention Licence applications	6	6	5	5	2	1
Special Prospecting Licence applications	4	4	4	6	2	1
Total	**2 066**	**2 457**	**2 813**	**2 868**	**2 713**	**2 215**

from 25% in 2004–05). This figure includes lapsed applications where tenements have been surrendered before the intent to refuse could be carried through.

Exemption applications for the 2006–07 period may be expected to increase as changes to the Mining Act, introduced in February 2006, are taking effect. Exemptions under Section 102(2)(h) — that aggregate expenditure on a project basis has been met—can no longer include the costs of mining activities in the calculation of aggregate expenditure for a project.

The number of granted exemptions seems high, but most are for partial amounts. Also, the majority of exemptions are still being sought on a project basis under Section 102(2)(h). This reflects the fact that currently 63% of tenements in force are part of projects (904 combined reporting groups in total). Overall expenditure by industry as claimed on Form 5 operations reports* is currently 21 times the expenditure commitment under the Act; an increase of 76% from 2004–05 to about $6.3 billion in 2005–06. Expenditure on mineral exploration activities (as a subset of total expenditure) increased by 72% to $633 million during the same period. It should be noted, however, that minimum expenditure commitments have not been increased since the introduction of the Mining Act 1978.

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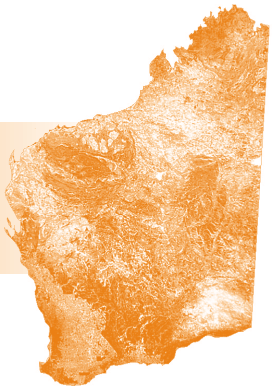
* Expenditure includes costs of exploration activities, mining and development, heritage surveys, rates and rents, overheads and administration.

Mineral exploration reports and data



Objective: *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 project covers all aspects of the submission, management and release of mineral exploration data through WAMEX (Western Australian mineral exploration database).

Highlights and activities 2005–06

- The 'Sunset Clause' amendment to the Mining Act, which allows for the release of reports five years after submission, came into force in February 2006. The first release of 7000 reports commenced in April 2006. By July 2007 all 21 000 'Sunset Clause' reports will have been released.
- The scanning of over 7000 reports, previously only available as microfiche, was completed for release via the web. Until late 1999, all exploration reports were released to open file as microfiche. A concerted effort was made in 2005–06 to backscan about 6900 reports that had previously only been available as microfiche. These scanned reports will be available for use and downloading from the web.
- 1878 mineral exploration reports (3336 volumes) were received, representing industry activity on 8968 tenements. The total number of volumes held is now 90 444. Submission of data in digital form continues to increase, with approximately 75% of all reports submitted during the year containing some digital data and 71% of all reports being fully digital.
- 9598 volumes were released to open file, bringing the total number of open-file mineral reports to 38 816.
- 2005–06 was 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. Quality-control checking by Departmental staff found that about 16% of the hardcopy reports did not comply with the reporting guidelines. 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. GSWA has updated a software application, available on the Departmental website, to facilitate the generation of metadata header information for digital tabular-data files.

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 the 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 release of the 'Requirements for the submission of mineral exploration data in digital format';
- Progressively acquire in digital format legacy tabular data previously submitted in hardcopy reports;
- Capture attribute information for legacy minerals 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 mandatory submission of exploration reports in digital form.

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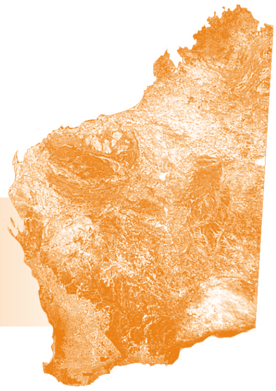
REGIONAL GEOSCIENCE MAPPING

Regolith–landform mapping



Objective: *To provide regolith–landform maps in a land systems context as a component of GSWA's program of regional and detailed geological mapping and analysis.*

Highlights and activities 2005–06

In 2005–06, after a number of years undertaking 1:50 000-scale regolith–landform mapping primarily for environmental and resource-definition objectives in selected urban and development areas of the State, GSWA initiated a systematic program of regional regolith–landform mapping to complement the regional bedrock mapping program at 1:100 000 scale.

The approach being taken is to map the regolith in terms of its variation in landform, surface material, and process of formation (weathering, erosion or deposition) through interpretations of topographic and remotely sensed spectral and radiometric data. The mapping is complemented by field observations to confirm the typical characteristics of the interpreted regolith–landform units. A land-systems classification scheme is used to place the regolith–landform units in a hierarchical context that enables further analysis of the landscape at a range of scales. The methodology both contributes to and uses State and National standards.

During the year, work continued on mapping the Blackstone* 1:100 000 map sheet area in the western Musgrave, and commenced on 1:100 000 map sheet areas in the Murchison and the western Tanami regions, where GSWA is a partner with industry, NTGS and CRC LEME in the Exploring through cover in the Tanami project. The mapping progress as at 30 June 2006 is summarized in Figure 3.

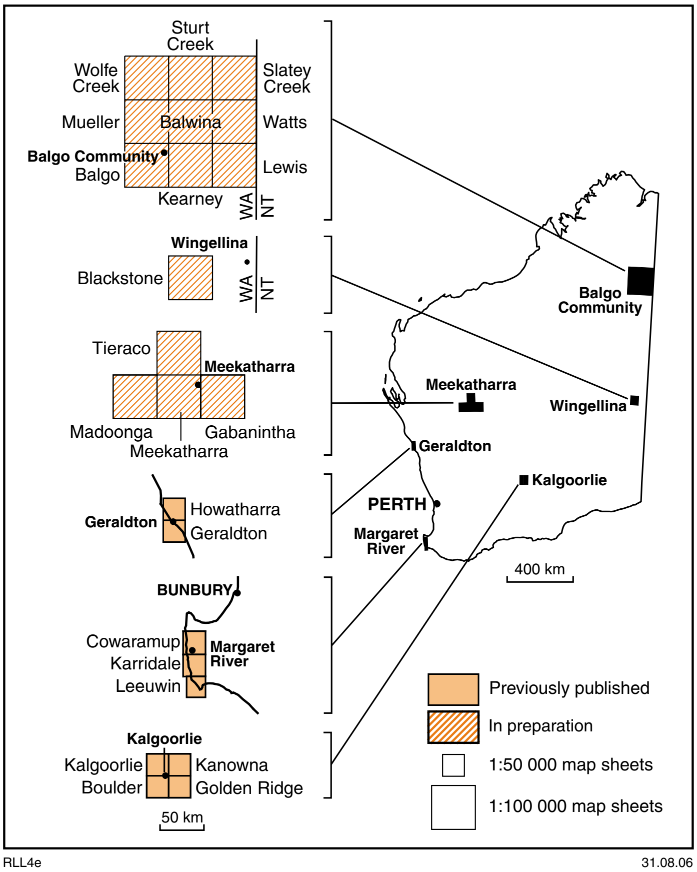


Figure 3. Progress of regolith–landform mapping projects

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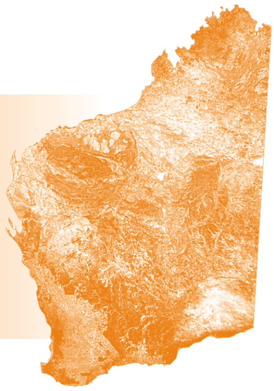
* Capitalized names refer to standard 1:100 000 map sheets, unless otherwise indicated.

King Leopold and Halls Creek Orogens project



Objective: *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 2005–06

During 2005–06 progress was made towards the completion of Bulletin 143 and the Explanatory Notes for TURKEY CREEK, with the writing up of the Proterozoic basin units in the Osmand Range.

A talk on the 'Tectonic significance of detrital zircon age profiles across Paleoproterozoic orogens in the Kimberley region of northern Australia' was presented at the Supercontinents and Earth Evolution Symposium held in Fremantle in September 2005.

Future work

Bulletin 143 and the Explanatory Notes for TURKEY CREEK will be completed for release in 2008. Writing of Explanatory Notes for the MCINTOSH and MOUNT RAMSAY 1:250 000 maps will commence for release in 2009.

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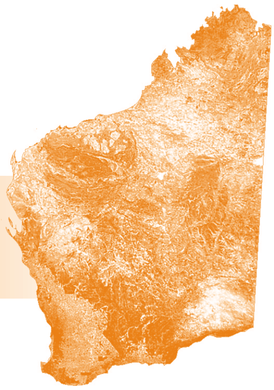
Lennard Shelf project



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 been published. The eighth map, at a scale of 1:500 000, was compiled in 2006.

Highlights and activities 2005–06

Compilation of Bulletin 145 on Devonian reef complexes of the

Canning Basin has continued. The text of most chapters has been completed in draft form by Phillip Playford, Roger Hocking, Gil Klapper, Thomas Becker, and Geoffrey Playford.

Future work

Still to be prepared for Bulletin 145 are chapters on diagenesis and the zinc–lead deposits (Malcolm Wallace). The Bulletin will be released in 2007.

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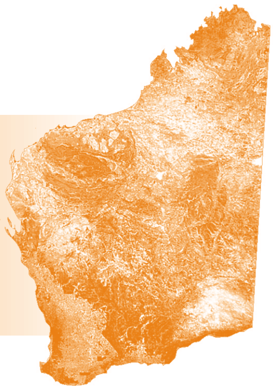
Pilbara Craton project



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 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 the remaining 1:100 000-scale and 1:250 000-scale maps and accompanying reports. During 2006, the first Pilbara GIS package was released and work continued towards the release of a larger GIS package, covering the entire east Pilbara, in 2006–07.

The project has provided a major reinterpretation of the geology and crustal evolution of the northern Pilbara Craton, with important implications for future mineral exploration. This new interpretation, published in GSWA Record 2006/15, will assist industry selection of the most appropriate exploration programs and metallogenic models for individual areas.

Highlights and activities 2005–06

Release of GSWA Record 2006/15 provided a new geological interpretation of the northern Pilbara Craton, and laid the foundation for future research and mineral exploration. Crustal evolution from 3.52 to 2.90 Ga is related to specific thermotectonic events in which the intrusion of major igneous suites and supersuites is correlated with volcanism and sedimentary deposition.

Project activities during 2005–06 included extensive recoding of 25 previously released 1:100 000 maps to comply with recently revised GSWA map codes, and to accommodate stratigraphic revisions in the Pilbara Craton. Project members continued to be involved in collaborative projects with various external research organizations.

2005–06 publications and products

- MOUNT MARSH and EASTERN CREEK (v. 2) 1:100 000 maps;
- PORT HEDLAND – BEDOUT ISLAND 1:250 000 map;
- Interpreted bedrock geology of the northwestern Pilbara Craton (1:250 000 scale) map;
- Asteroid impact signatures of the Pilbara Craton (1:1 000 000 scale) map;
- Pilbara 1:100 000 Geological Information Series (WARRIE, MOUNT MARSH and NOREENA DOWNS) digital dataset on DVD;

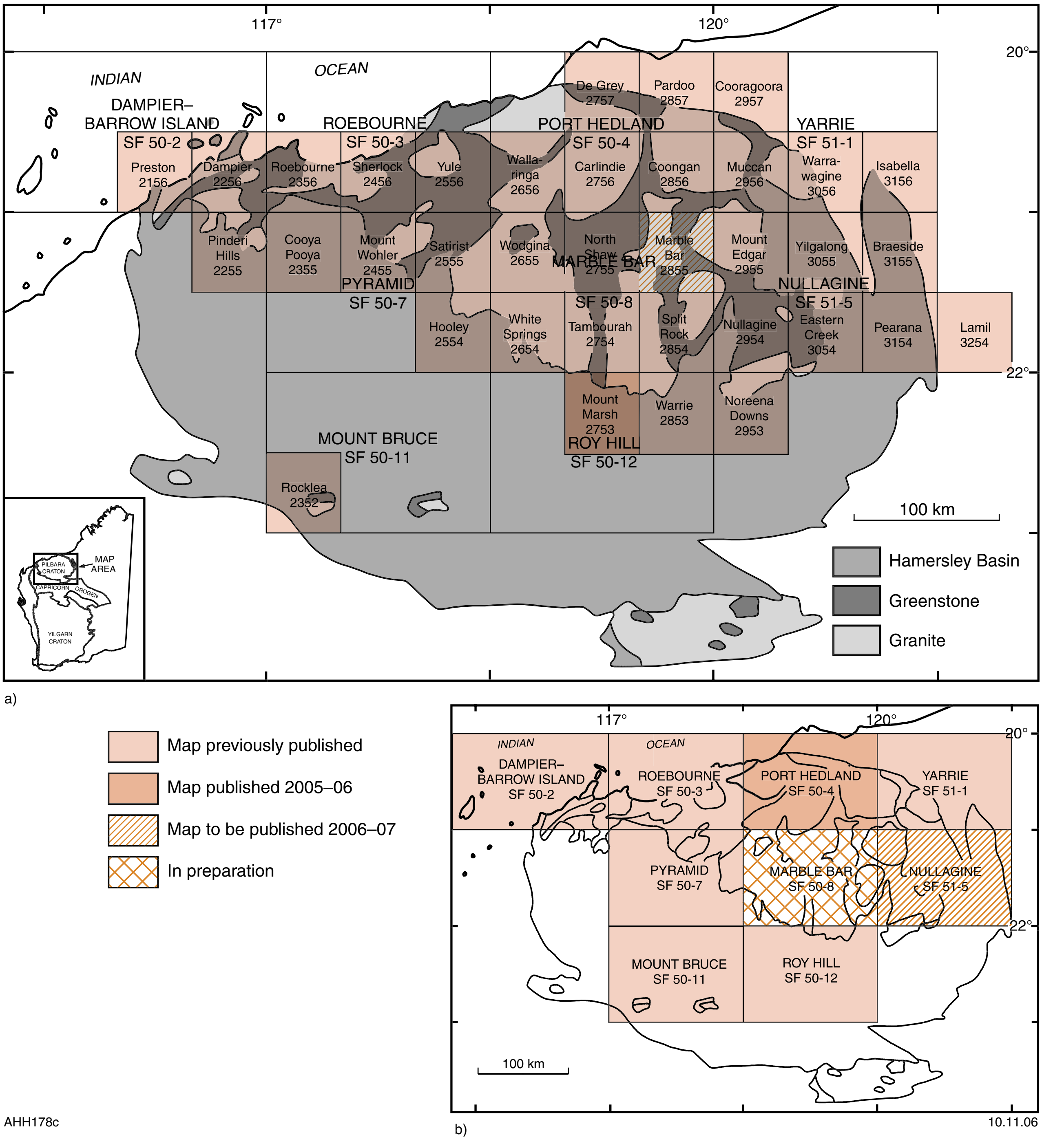


Figure 4. Progress of recent regional mapping in the Pilbara Craton: a) 1:100 000 map sheets; b) 1:250 000 map sheets

- WODGINA and EASTERN CREEK 1:100 000 Explanatory Notes;
- Report 101: *Archean volcanic and sedimentary rocks of the Whim Creek greenstone belt, Pilbara Craton, Western Australia*;
- Record 2006/14: *The Pilbara drilling project: c. 2.72 Ga Tumbiana Formation and c. 3.49 Ga Dresser Formation, Pilbara Craton, Western Australia*;
- Record 2006/15: *Revised lithostratigraphy of Archean supracrustal and intrusive rocks in the northern Pilbara Craton, Western Australia*;
- Geoscientific papers in the Annual Review and external journals, and public presentations.

Future work

The 2006–07 year will see the release of the MARBLE BAR 1:100 000 map, the NULLAGINE 1:250 000 map, a detailed 1:50 000 interpretative bedrock geology map on the Lalla Rookh – Western Shaw structural corridor, and the second Pilbara 1:100 000 Geological Information Series DVD (23 maps in the east Pilbara). Work will commence on compilation of the MARBLE BAR 1:250 000 map. Reports will be produced on the geology of the west Pilbara and on asteroid impact beds in the Pilbara Craton and Hamersley Basin. Records will be released on the Strelley Pool Chert and on putative microfossils in chert of the Apex Basalt. Explanatory Notes will be released for the YILGALONG 1:100 000 map, and compiled for the COONGAN 1:100 000 map and the NULLAGINE 1:250 000 map.

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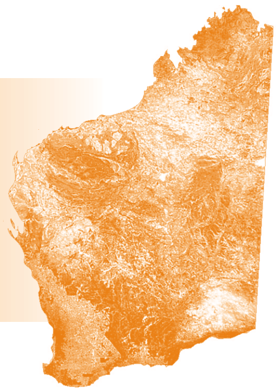
Earaheedy Basin project



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 integrating 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 late 2005. Since 1997, one 1:250 000-scale and fourteen 1:100 000-scale geological maps (Fig. 5) and five sets of Explanatory Notes have been published, as well as four peer-reviewed publications in international journals and a number of presentations at national and international conferences. Two additional 1:100 000-scale geological maps are at the compilation stage.

The Earaheedy Basin contains the Paleoproterozoic 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 Earaheedy Group is a 5 km-thick succession of shallow-marine clastic and chemical sedimentary rocks that are divided into two subgroups — the Tooloo Subgroup and the overlying Miningarra Subgroup. The age of the Earaheedy Group is constrained by the age of the c. 1.84 Ga Maraloou Formation (Yerrida Basin) and by the c. 1.99 Ga Imbin Inlier. Mineral potential of the Earaheedy Basin comprises the extensive iron formations of the Frere Formation, base metals, gold, diamonds and possibly uranium.

Highlights and activities 2005–06

During this period field checks were carried out in parts of the Earaheedy Basin. Compilation work was completed for the COLLURABBIE and VON TREUER 1:100 000 map sheets.

2005–06 publications and products

COLLURABBIE 1:100 000 map sheet.

Future work

Compilation of the CARNEGIE 1:100 000 map sheet will be completed, and a Report on the geology and mineral systems of the Earaheedy Basin is in progress

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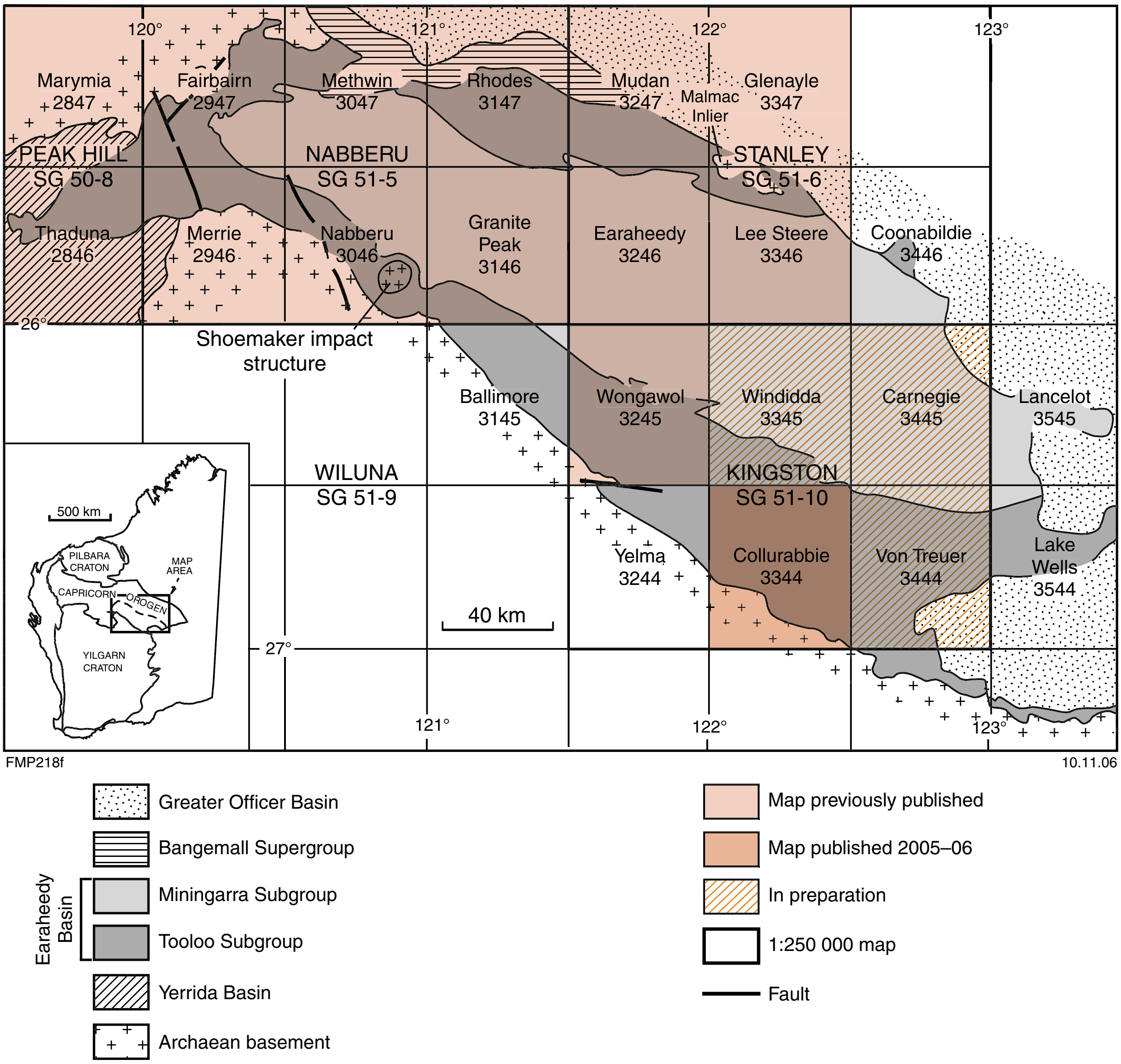
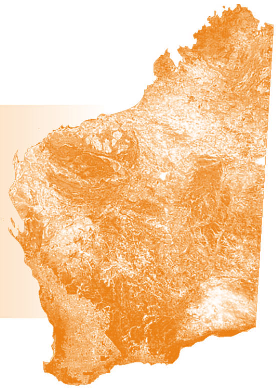


Figure 5. Progress of 1:100 000-scale geological mapping for the Earaheedy Basin project

Edmund and Collier Basins



Objective: *To increase the 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 2005–06

During 2005–06, fieldwork activities focused on detailed mapping of the Bangemall Supergroup rocks on PEEDAWARRA (Fig. 6). There has also been a joint geochronological and provenance study of detrital zircon populations taken from sandstone units throughout the Edmund and Collier Groups. This has been conducted in collaboration with staff from Geoscience Australia and the University of Western Australia.

The provenance history of the Bangemall Supergroup can be divided into two discrete stages that reflect the changes in paleogeography between the Edmund and Collier Groups. The Edmund Group records erosion of the Gascoyne Complex and progressive unroofing of early to late Paleoproterozoic supracrustal rocks on the southern margin of the Pilbara Craton. During this time, the paleogeography of the Edmund Basin evolved from a horst-and-graben terrain, with significant detrital contribution from localized sources, to an extensive east–west-trending intracratonic basin, with the Pilbara Craton to the north providing the main source of detritus. In contrast, the Collier Group records unroofing and reworking of successively lower levels of the underlying Edmund Group, with possible additional contribution from the Paterson Orogen. This change in provenance is accompanied by the formation of a regional unconformity at the base of the Collier Group, and a progressive change in paleocurrent direction from south-southwesterly to west-

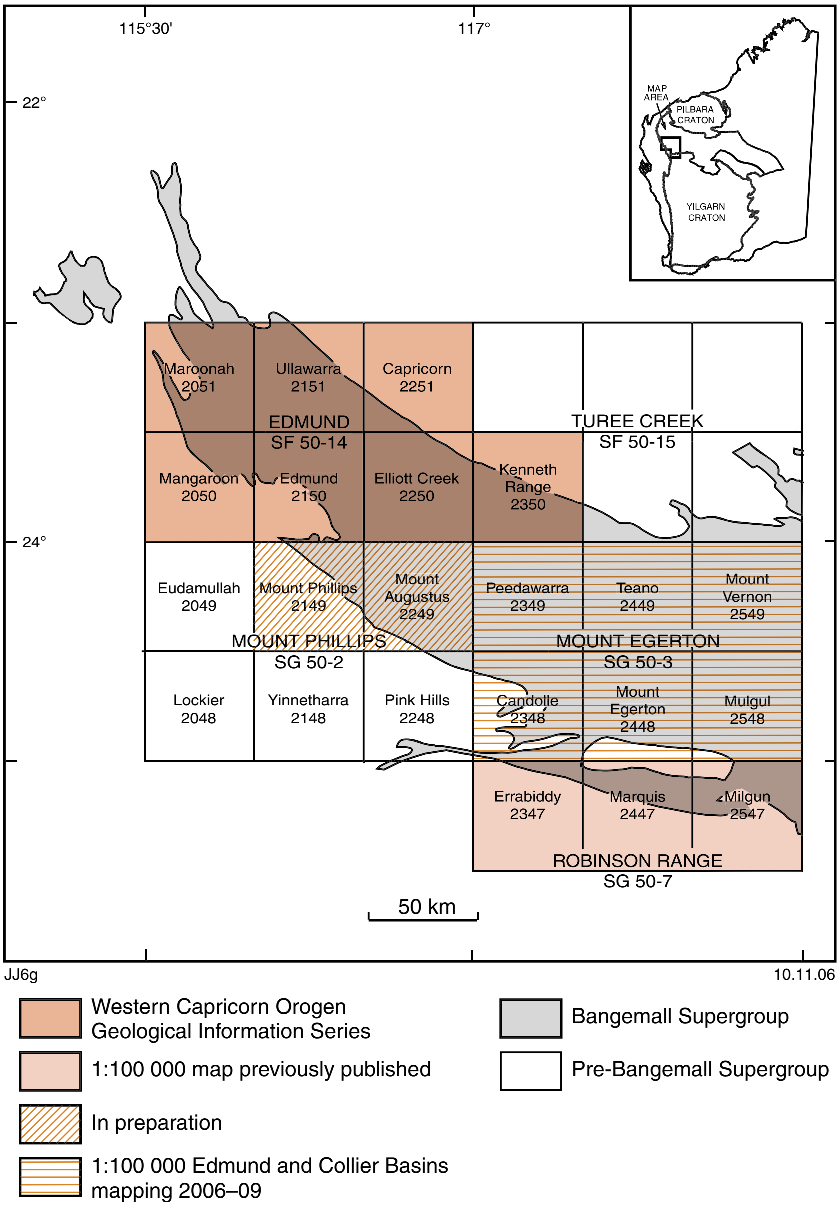


Figure 6. Progress of recent mapping for the Edmund and Collier Basins

northwesterly, consistent with uplift to the southeast of the Collier Basin. The present distribution of rocks in the Gascoyne Complex and Pilbara Craton was therefore already in existence by the Mesoproterozoic and, when integrated with paleocurrent data, can adequately explain the provenance history of the Bangemall Supergroup.

Much of the office activity during 2005–06 has centred on the compilation of Bangemall Supergroup rocks on Mount Augustus and Mount Phillips. Digital data from Kenneth Range have also been prepared for inclusion in the 2005–06 update of the Western Capricorn Orogen 1:100 000 Geological Information Series digital package. A second edition of the Edmund 1:250 000 map sheet was compiled and released and a regional aeromagnetic interpretation of the Bangemall Supergroup outcrop was also compiled and integrated with the 1:500 000-scale State geology map.

2005–06 publications and products

- Edmund 1:250 000 map;
- Western Capricorn Orogen 1:100 000 Geological Information Series, June 2006 update comprising data from the Maroonah, Ullawarra, Capricorn, Mangaroon, Edmund, Elliott Creek, and Kenneth Range 1:100 000 map sheets.

Future work

Work to be carried out during 2006–07 includes mapping and compilation of the Bangemall Supergroup on Peedawarra and Candolle and updating the Western Capricorn Orogen 1:100 000 Geological Information Series to include Explanatory Notes and geological linework and data from Mount Augustus and Mount Phillips. A 1:500 000-scale 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 2005–06

During 2005–06, fieldwork on the Gascoyne Complex rocks on Eudamullah, Mount Phillips and Mount Augustus was completed. Eudamullah and Mount Augustus were compiled, and compilation for Mount Phillips is nearly finished (Fig. 7). Mapping on the southern part of Mount Phillips shows that medium-grade metasedimentary rocks in the Morrissey Hill area consist of two separate packages: the c. 1680 Ma Pooranoo Metamorphics and, to the south, the less than 1840 Ma Morrissey Metamorphics. Field relationships suggest that the Pooranoo Metamorphics are the higher grade equivalents of the Mount James Formation.

A collaborative study with Drs B. Rasmussen, J. R. Muhling, and I. R. Fletcher at the University of Western Australia was initiated during 2005–06. The project involves U–Pb SHRIMP analysis of metamorphic monazite and xenotime present in situ in pelitic schists in the central part of the Mount Phillips 1:250 000 sheet area. Preliminary indications are that the medium-grade metamorphism in the Morrissey Hill area is Neoproterozoic, rather than Paleoproterozoic as previously thought. A manuscript on the age of the metamorphism and its tectonic implications is in preparation.

During 2005–06, a collaborative project with Dr Marc Norman at the Research School of Earth Sciences at the Australian National University aimed to date molybdenite from probable porphyry-molybdenum mineralization at the Minnie Springs prospect. A preliminary Re–Os age of c. 1775 Ma was obtained from disseminated molybdenite, strongly suggesting that mineralization is related to the late stages of the Minnie Creek batholith.

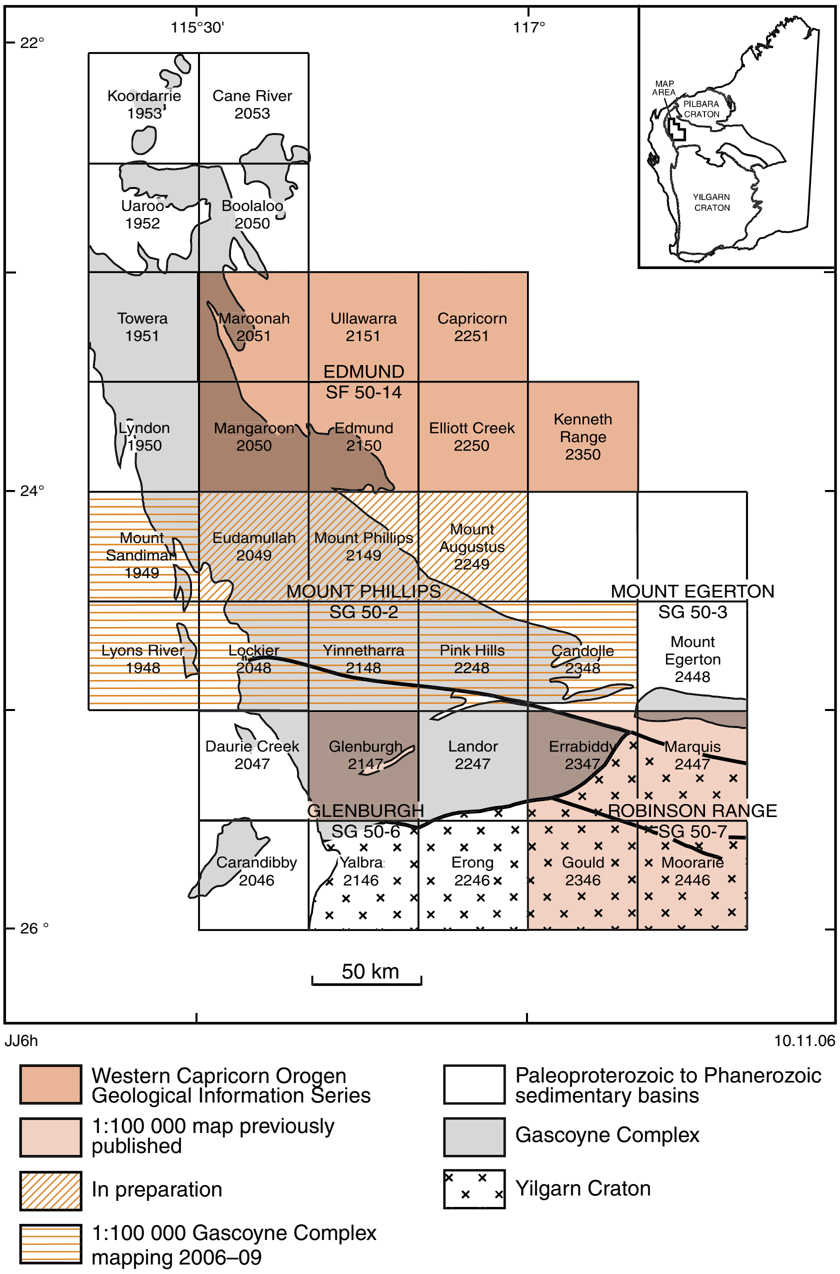

Figure 7. Progress of recent geological mapping for the Gascoyne Complex

Two papers dealing with Gascoyne Complex geology were published in the 2004–05 GSWA Annual Review. One by GSWA staff examined enigmatic aegerine-augite bearing meta-leucogabbros in the central part of the complex, and another written by Debbie Shewfelt from the University of Saskatchewan and co-authors presented preliminary findings on the origin of tourmaline nodules from a granite in the southern part of the complex.

2005–06 publications and products

- Western Capricorn Orogen 1:100 000 Geological Information Series 2006 update comprising data from the MAROONAH, ULLAWARRA, CAPRICORN, MANGAROON, EDMUND, ELLIOTT CREEK, and KENNETH RANGE 1:100 000 map sheets;
- EDMUND 1:250 000 map (2nd edition).

Future work

Work to be carried out during 2006–07 includes mapping on YINNETHARRA; updating the Western Capricorn Orogen Geological Information Series to include Explanatory Notes and geological linework and data from MOUNT AUGUSTUS, MOUNT PHILLIPS and EUDAMULLAH. A solid geology interpretation, derived using aeromagnetic data integrated with first- and second-edition geology maps, of the western Capricorn Orogen will also be produced. Follow-up studies on the nature of the metamorphism in the central Gascoyne Complex are planned, as is a paper on the age of the molybdenite mineralization in the Minnie Creek batholith.

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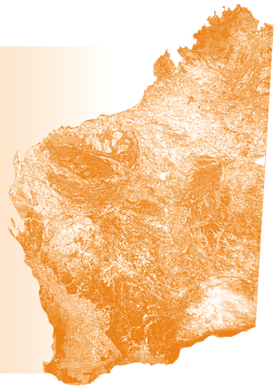
West Tanami project



Objective: *As part of a cooperative project, including the Geological Survey of Western Australia, Geoscience Australia, and the Centre of Exploration Targeting at the University of Western Australia, to increase geoscientific knowledge of the western part of the Paleoproterozoic Granites–Tanami Orogen 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.*

Field mapping continued in the west Tanami during 2005–06.

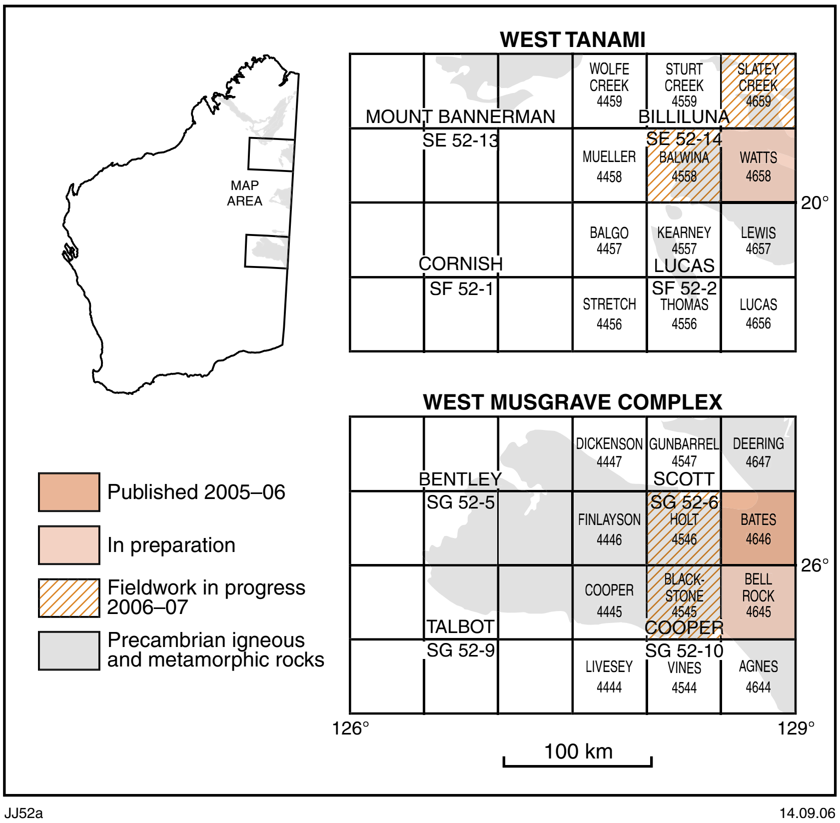


Figure 8. Recent geological mapping for the west Tanami and west Musgrave Complex projects

Highlights and activities 2005–06

Some of the highlights for the year include:

- BALWINA and SLATEY CREEK (Fig. 8) were partially mapped and will be compiled during 2006–07;
- The major seismic survey conducted by Geoscience Australia, in conjunction with the Geological Survey of Western Australia and the Northern Territory Geological Survey in 2004–05, was interpreted and released.

2005–06 publications and products

Publications produced during the year include:

- A paper on gold deposits in the Granites–Tanami Orogen in Western Australia that was submitted to Mineralium Deposita for publication;
- A paper on the Coyote gold deposit is included in this volume.

Future work

Field mapping and GIS-based compilation will continue on BALWINA, SLATEY CREEK, LEWIS, and KEARNEY during 2006–07.

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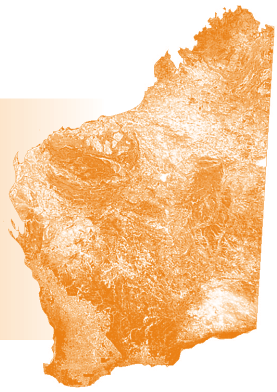
West Musgrave Complex project



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 2005–06

The 2005–06 period saw the release of BATES and the first release of the West Musgrave 1:100 000 Geological Information Series. Field mapping and map compilation of BELL ROCK was completed and the majority of BLACKSTONE was mapped (Fig. 8).

Collaboration with Adelaide University was extended to include two Honours projects — one each on BATES and BELL ROCK — aimed at constraining the timing of major mylonitic deformation.

Geophysical studies have highlighted the importance of gravity surveys in identifying unexposed mafic rocks that show similar magnetic intensities to the iron-rich granitic rocks that dominate the region. Geochronology continues to prove a crutial tool in separating geochemically and structurally similar granitic rocks belonging to distinct orogenic events and has identified at least two discrete events within the Mesoproterozoic Musgravian Orogeny.

2005–06 publications and products

- BATES 1:100 000 map;
- West Musgrave 1:100 000 Geological Information Series digital dataset on DVD.

Future work

The 2006–07 period will see the release of BELL ROCK and the second release of the West Musgrave 1:100 000 Geological Information Series. Mapping of BLACKSTONE will be completed and progress will be made on HOLT. A series of gravity traverses will be completed across the northern part of BLACKSTONE.

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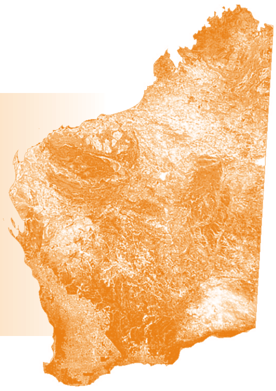
East Yilgarn project



Objective: *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 Eastern Goldfields Superterrane 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 2005–06

A GSWA Record was published in which the proposed new Terrane/ Superterrane subdivisions of the Yilgarn Craton were outlined. These subdivisions will be used in future editions of the East Yilgarn 1:100 000 Geological Information Series to provide the basis of detailed stratigraphy in the Eastern Goldfields Superterrane as it is developed.

The current East Yilgarn 1:100 000 Geological Information Series is being updated and expanded to include recently completed YARDINA and ERAYINIA (Fig. 9), and will be re-released in late 2006. The area covered will include sixty 1:100 000-scale geological map sheets as a seamless digital coverage of most of the Eastern Goldfields Superterrane.

BULDANIA – FRASER RANGE, COWALINYA – MOUNT ANDREW, and MINERIE have been compiled. Field mapping on NEARANGING and DUNDAS is complete. All of these maps will be integrated into future editions of the East Yilgarn 1:100 000 Geological Information Series. Twelve new U–Pb zircon SHRIMP ages were published for the Eastern Goldfields Superterrane, mainly in the southeast.

A new bedrock geology interpretation was completed for the northeastern Yilgarn Craton, and was included in the update of the geological exploration package for that area. Field mapping commenced on MULGABIDDY CREEK and TOPPIN.

The Joe Lord Core Library continues to assist the mining and exploration industry through the acquisition, storage, and display of drillcore. The hyperspectral scanning of drill-core program was extended and now includes infrared scans. Regional mapping geologists at the Kalgoorlie regional office routinely provide advice and information to the general public, mining companies, and others about the geology of the Eastern Goldfields and adjacent areas.

In May 2006 the Geological Survey, in conjunction with industry geologists, conducted a three-day field excursion across the central part of the Eastern Goldfields Superterrane. The 30 geologists who attended the excursion were shown well-preserved mafic and felsic volcanic facies, late-basin sedimentary rocks, and were given a detailed overview of AngloGold Ashanti's Sunrise Dam gold deposit.

2005–06 publications and products

- Record 2006/4: *Northeastern Yilgarn geological exploration package, April 2006 update*;
- Record 2006/8: *A revised geological framework for the Yilgarn Craton, Western Australia*;
- Record 2006/11: *Stratigraphy and physical volcanology of the Archean Kurnalpi Terrane, Yilgarn Craton — a field guide*;
- ERAYINIA 1:100 000 map;
- YARDINA 1:100 000 map.

Future work

Fieldwork will continue on BLAXLAND, JUTSON, STRAWBRIDGE, YAMARNA, DOROTHY HILLS, TOPPIN, BAILEY, LIGHTFOOT, and MINIGWAL. New editions of the East Yilgarn 1:100 000 Geological Information Series will include new mapping as it is generated, and comprehensive Explanatory Notes. New interpretation of the bedrock geology will allow the inclusion of detailed stratigraphy for the Eastern Goldfields Superterrane.

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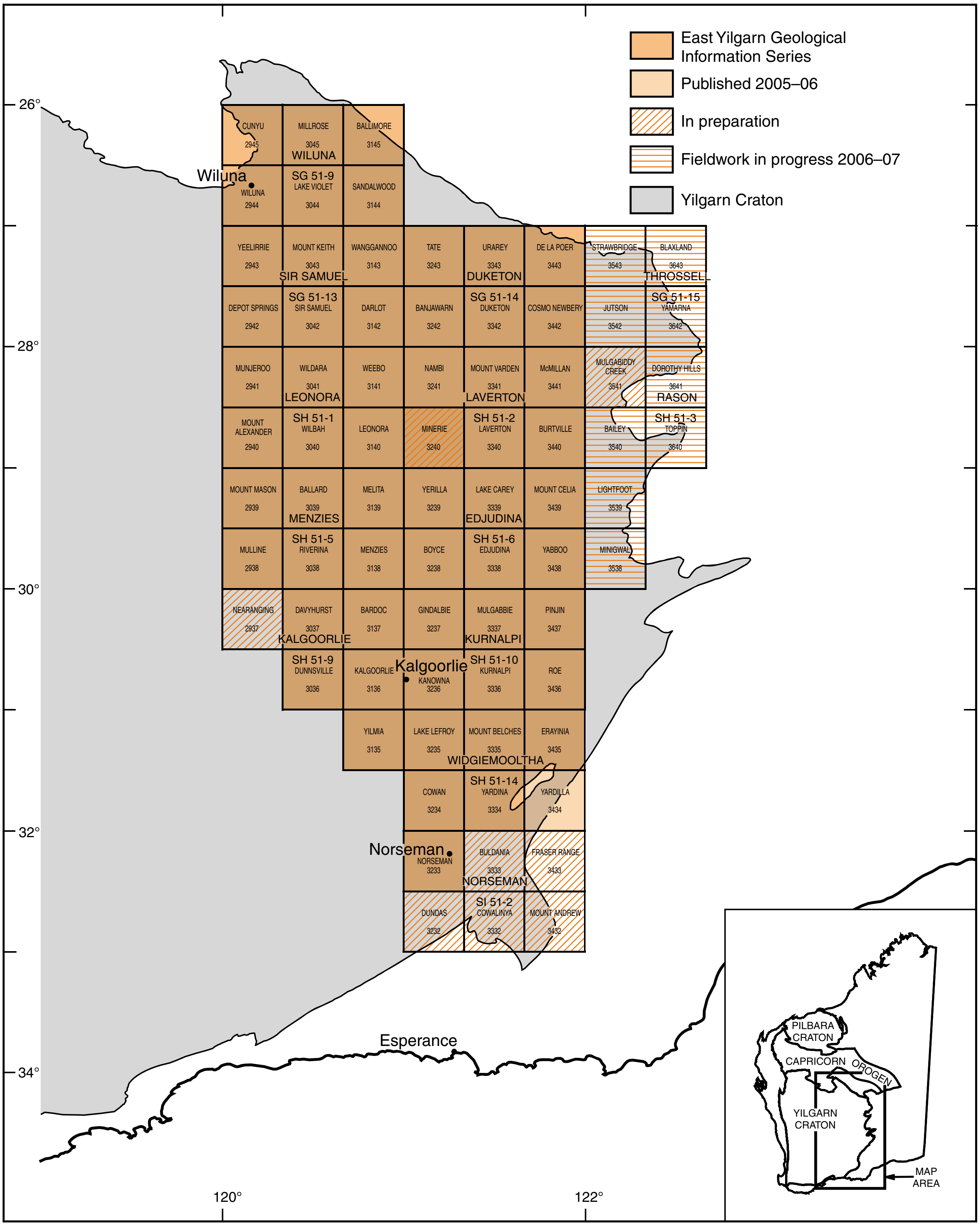

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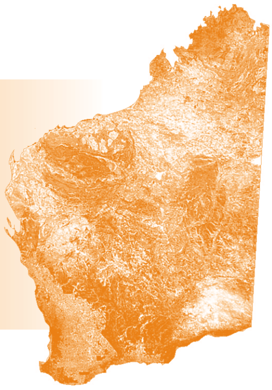
Figure 9. Progress of recent geological mapping in the east Yilgarn region and progress towards the GIS-based seamless digital database

Central Yilgarn project



Objective: *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 in the Southern Cross Domain of the Youanmi Terrane of the Yilgarn Craton began in late 1997, and fourteen 1:100 000 sheets have been published to date (Fig. 10).

Highlights and activities 2005–06

In 2005–06, YOUNO DOWNS was compiled and published; and the first edition of the Central Yilgarn 1:100 000 Geological Information Series, covering all previously released 1:100 000-scale mapping south of the SANDSTONE 1:250 000 sheet, was assembled and released. Three new U–Pb zircon SHRIMP geochronology dates were published for felsic volcanic and granitic rocks from MONTAGU.

2005–06 publications and products

- Central Yilgarn 1:100 000 Geological Information Series (1st edition) digital dataset on DVD;
- YOUNO DOWNS 1:100 000 map.

Future work

Maps for MONTAGU and YAGANOO will be published in 2006–07 and the second edition of the Central Yilgarn 1:100 000 Geological Information Series will be released as a GIS package on DVD.

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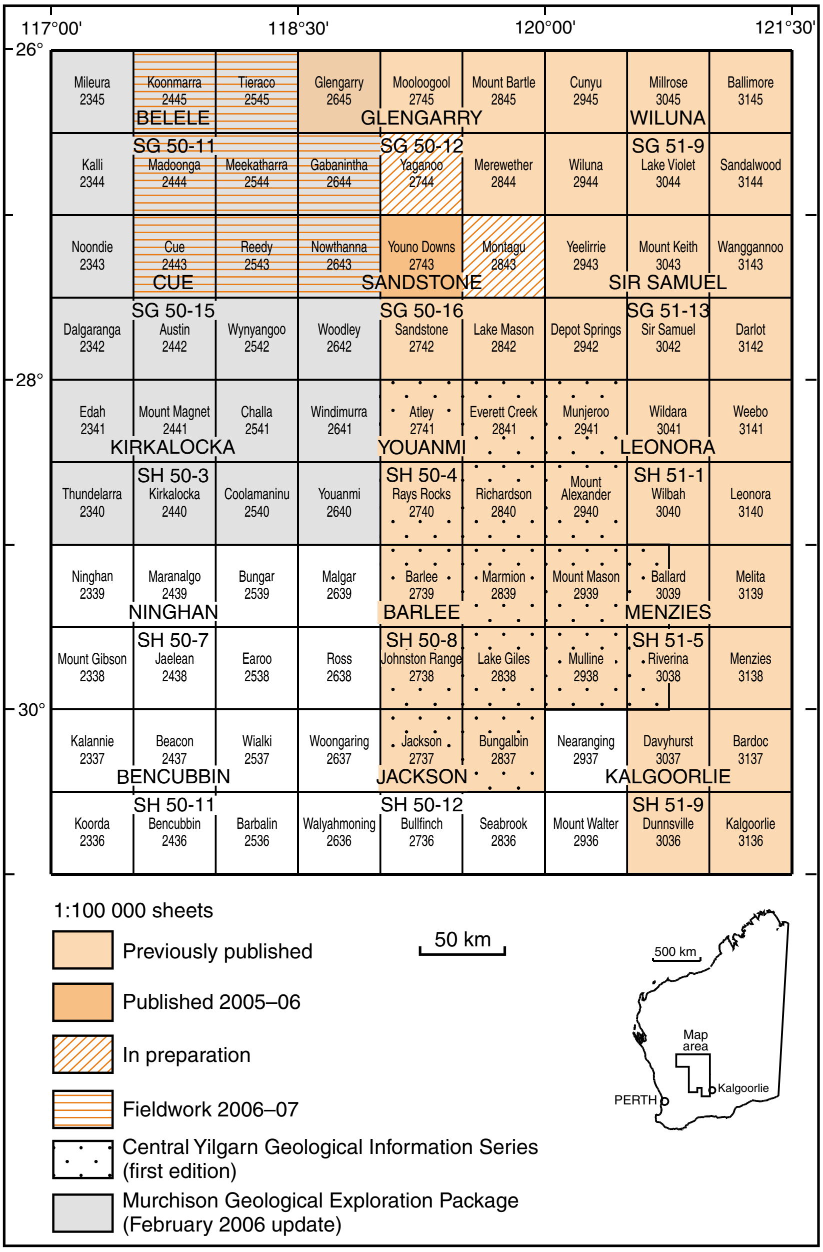
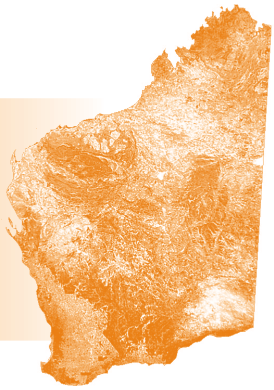


Figure 10. Progress of recent geological mapping for the central Yilgarn and Murchison projects

Murchison project



Objective: *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 Domain of the Youanmi Terrane in the Yilgarn Craton in 2004–05.

Highlights and activities 2005–06

In 2005–06, new field mapping in the Meekatharra–Wydgee, Abbotts, Mingah Range, and Weld Range greenstone belts covered parts of TIERACO, MEEKATHARRA, GABANINTHA, REEDY, CUE, and KOONMARRA (Fig. 10). A new regional geological interpretation was included in an update of the Murchison geological exploration package. The explanatory note for the interpretation has been released as a GSWA Record.

New mapping in the Meekatharra region has delineated the distribution of major shear zones and is being used to review published stratigraphy.

New geochronological samples have been collected to test structural and stratigraphic models.

2005–06 publications and products

- Record 2006/2: *Murchison geological exploration package, February 2006 update*;
- Record 2006/10: *Interpreted bedrock geology of the northern Murchison Domain, Youanmi Terrane, Yilgarn Craton*.

Future work

Field mapping and GIS-based compilation will continue in the Meekatharra–Wydgee, Abbotts, Mingah Range, and Weld Range greenstone belts on TIERACO, MEEKATHARRA, GABANINTHA, REEDY, NOWTHANNA, CUE, MADOONGA, and KOONMARRA. A first edition of the Murchison 1:100 000 Geological Information Series will be released in 2007.

A gravity survey covering parts of the BELELE, CUE, GLENGARRY, and SANDSTONE 1:250 000 sheets will be carried out in early 2007.

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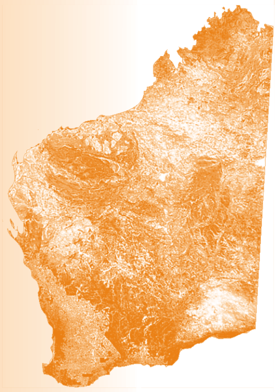
SCIENTIFIC, TECHNICAL AND FIELD SUPPORT

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 to local, national, and international explorers and researchers.*



Highlights and activities 2005–06

The review and approval of all manuscripts and map products is a major ongoing task to ensure the quality of their content and the consistency of presentation.

The first phase of the redevelopment of WAROX — GSWA's field observation database — was completed with WAROX8 entering production, and data being routinely captured at the outcrop. A new position of Specialist Database Geologist was created, reporting to the Chief Geoscientist. This position is responsible for maintaining and upgrading the quality of data already within the database, and for developing a program for the capture of 'legacy' field observations and sample information from existing first and second edition geological maps. The Specialist Database Geologist will also liaise with the database administrators to ensure that the database functions efficiently and that the integrity of the data is maintained.

A major activity for the year was the updating of the digital State 1:500 000 interpreted bedrock-geology map and the development of associated standard map-unit attribute look-up tables for the Archean, Proterozoic and Phanerozoic. The tectonic unit nomenclature for the Archean Yilgarn Craton was revised in consultation with researchers from Geoscience Australia (GA) and the University of Western Australia and the nomenclature of the Pilbara Craton was revised to be consistent with this. The standard attribute look-up tables are now applied to map units in all published digital map datasets at all scales and were developed as part of a review of all mapped geological units in Western Australia. From this review, the structure for an Explanatory Notes Database was developed that will provide up-to-date geological descriptions for all geological and tectonic map units in Western Australia. This database will be the basis for a new initiative — *WA Geology Online*.

Four geoscientific data layers covering Western Australia (1:250 000 geology, 1:250 000 topography, magnetic intensity, and Bouger gravity) were made available in NASA's open-source virtual globe program, World Wind. The release of linked geoscientific layers as a collaborative effort with the World Wind open-source community is believed to be a world-first.

One of the roles of the Chief Geoscientist and the Terrane Custodians is to maintain and improve GSWA's understanding of the geology of Western Australia in areas where mapping programs are not currently being carried out. Sampling for geochemistry, geochronology, and isotopic analysis has been carried out along the southern margin of the Hamersley Basin, in the Albany–Fraser Orogen, and in the upper Neoproterozoic to lower Paleozoic successions of the Officer Basin, Perth Basin and the Badgeradda Group. Logistical support is being provided to a PhD project based at the University of Texas at Austin on the structural and metamorphic evolution of the Albany–Fraser Orogen between Bremer Bay and Esperance.

The Chief Geoscientist and the Proterozoic Terrane Custodian attended a three-day conference on the Evolution and Metallogenesis of the North Australian Craton held in Alice Springs in June 2006, at which an invited talk was presented on the geology and mineralization of the King Leopold and Halls Creek Orogens. The meeting represented the wrap-up of Geoscience Australia's North Australian Project, conducted with the cooperation of the Northern Territory Geological Survey (NTGS) and GSWA and included the presentation of the results of the joint GA–NTGS–GSWA Tanami Seismic Survey. The meeting reinforced the linked nature of deformation, magmatic, and basin-forming events throughout the Proterozoic of northern and western Australia. A session on Assembling Australia at the Supercontinents and Earth Evolution Symposium held in Fremantle in September 2005, hosted by the Tectonics Special Research Centre (TSRC), the WA Division of the Geological Society of Australia and GSWA, emphasized the importance for greenfields mineral exploration of a coordinated approach between GA, the State Geological Surveys and academic researchers to synthesize data for the Australian Proterozoic.

The Chief Geoscientist and the Archean Terrane Custodian attended a meeting of the predictive mineral discoveries Cooperative Research Centre (pmd*CRC), of which GSWA is a sponsor, held in Perth in April 2006. Results were presented from the Y4 project, which has been developing a scale-integrated understanding (from mantle lithosphere to ore shoot using multiple datasets) of the orogenic gold mineral systems of the Eastern Goldfields Superterrane of the Yilgarn Craton. The aim is to generate exploration targets both undercover and at depth. GSWA will continue to provide logistical support to Y4 and to research at Monash University on the late basins in the Eastern Goldfields Superterrane.

The Archean Terrane Custodian continues to act as Vice Chair of the IUGC Subcommission on the Subdivision and Calibration of the Precambrian Timescale, which held an informal workshop prior to the Fremantle Supercontinents and Earth Evolution Symposium. He is also acting as chief editor for a book on the Earth's Oldest Rocks, in which Western Australia geology features prominently, to be published by Elsevier.

The Chief Geoscientist and Terrane Custodians 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. A review and critique of the proposed Western Australia High School Curriculum was undertaken by the Archean Terrane Custodian and submitted on behalf of the Executive Director to the Curriculum Council. GSWA has also contributed to NASA's Virtual Field Trip, a multimedia educational program developed jointly by NASA and Macquarie University's Australian Centre for Astrobiology. The program features two localities in the Pilbara, as well as Hamelin Pool, within the theme of early life on Earth, and is designed to allow students to undertake a scientific investigation remotely.

2005–06 publications and products

- Record 2005/11: *Geology of the western Albany–Fraser Orogen, Western Australia — a field guide* by I. C. W. Fitzsimons and C. Buchan of the Tectonics Special Research Centre, Curtin University of Technology for the Supercontinents and Earth Evolution Symposium held in Fremantle in September 2005, and hosted by the TSRC, the WA Division of the Geological Society of Australia, and GSWA;
- Record 2006/8: *A revised geological framework for the Yilgarn Craton, Western Australia* by K. F. Cassidy, D. C. Champion, and R. S. Blewett from Geoscience Australia, B. Krapez, M. E. Barley and S. J. A. Brown from the School of Earth and Geographical Sciences, University of Western Australia, and B. Groenewald and I. M. Tyler from GSWA.

Future work

The Chief Geoscientist and Terrane Custodians will be involved in the assessment of pen-tablet PCs in the field to enable geoscientists to view all their data at the outcrop, to enter data, and make preliminary map compilations.

The various GSWA geological datasets will continue to be improved to ensure a genuine seamless coverage is achieved across the State with the development of a program for the capture of legacy field observations and sample information from existing first and second edition geological maps. The Chief Geoscientist and Terrane Custodians will have a major role in the development and testing of the *WA Geology Online* initiative.

The revised State 1:500 000 digital interpreted-bedrock geology map will be completed and new State 1:2 500 000 digital geological and tectonic units maps will be derived from it, and from the State 1:500 000 regolith map. A process will be developed to revise the State digital geology-map datasets as new digital-map datasets are released from individual mapping project areas.

Geoscience Australia has been compiling a 1:1 000 000-scale digital map of the surface geology of Australia. During 2005–06, work began on compilation in Western Australia, concentrating on areas along the border with the Northern Territory. During 2006–07, the Chief Geoscientist and Terrane Custodians will review the GA compilation to ensure that both the GSWA and GA datasets are consistent.

In collaboration with Professor Peter Cawood at UWA, a submission to ANSIR (National Research Facility for

Earth Sounding) is being developed as part of the NCRIS Auscope project. The submission is for a series of integrated geophysical and geological transects across the West Australian Craton and its margins. These transects would include seismic reflection, seismic refraction, passive seismic, and magnetotelluric surveys that will provide insight into the geological evolution of the Australian lithosphere over some four billion years of Earth history and an understanding of the localization of mineral systems within the upper crust.

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Geochronology

Objective: *To augment the geological knowledge of Western Australia by the acquisition and dissemination of geochronological data, as a complement to other geological information in support of geoscience initiatives.*

Geochronology is a fundamental part of geological understanding, particularly in terms of elucidating 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 2005–06

A total of 61 samples were dated by 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 (East Pilbara Terrane), the Yilgarn Craton (Eastern Goldfields Superterrane and Youanmi Terrane), the Capricorn Orogen (Gascoyne Complex), the Musgrave Complex, the Officer Basin, and the Canning Basin.

The latest release of geochronology data is a digital compilation (on CD) of data acquired by GSWA between 1994 and 2004, 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.

2005–06 publications and products

- *Compilation of geochronology data, June 2006 update* (CD containing GSWA geochronology data obtained between 1994 and 2004).

Future work

Geochronology in the Pilbara Craton (East Pilbara Terrane), the Yilgarn Craton (Eastern Goldfields Superterrane and Youanmi Terrane), the Capricorn Orogen (Gascoyne

Complex), the Musgrave Complex, and the Officer Basin will continue in 2006–07, together with a new project in the Albany–Fraser Orogen. The U–Pb zircon geochronology program will be accompanied by an assessment of the viability of routine dating of mafic igneous rocks using the U–Pb system in zircon and/or baddeleyite.

An update of the Compilation of geochronology data CD will be released in May 2007, and new data will be released on the GSWA website as soon as it is available.

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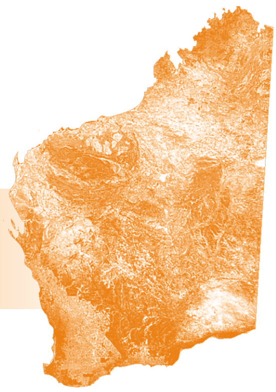
Geochemistry



Objective: *To acquire and collate geochemical data for regolith and various bedrock lithologies in a central repository, and disseminate these data, in order to enhance the prospectivity of the State.*

Highlights and activities 2005–06

An orientation stream-sediment geochemistry program continued in the State's southwest. Various grain size fractions of 64 stream-sediment samples were analysed using three different digestions in order to evaluate the most appropriate approach for detecting areas of known mineralization, and to establish regional geochemical backgrounds. Five samples were examined in terms of heavy mineral chemistry and modal mineralogy.

The structure of the corporate geochemical database (WACHEM) was modified in order to store information dealing with the screening, crushing, and milling of samples. Population of the database continued with loading of current and legacy datasets. Extraction tools were developed to extract locational and compositional information based on simple search criteria, and another tool reports on batch analysis characteristics. Both tools are being trialled.

Regional geochemical datasets provided by exploration companies for the Yamarna and Capricorn areas were made available using GSWA's GeoVIEW.WA portal. Another comprehensive company-sourced dataset is being prepared covering parts of the Capricorn Orogen, and extensions to the Pickands-Mather Kimberley stream-sediment dataset are being sought.

The collaborative venture with CRC LEME and CSIRO to compile a geochemical map of the Yilgarn Craton (the Yilgarn Geochemical Map project), based on laterite chemistry of samples at a nominal spacing of 9 km, was completed for the southwest part of the Yilgarn Craton, bordered in the north and east by 30°S and 120°E. The first data release of 2200 samples was completed in early March, as a CRC LEME open-file report. Sampling continued in the northwest Yilgarn Craton quadrant.

Lithogeochemical analysis by Geoscience Australia under the National Geoscience Agreement continued, with more than 400 samples prepared and analysed in 2005–06.

Future work

Following on from the delineation of the 1070 Ma Warakurna Large Igneous Province using a combination of precise dating and geochemistry, data capture commenced on a 500 Ma large igneous province represented by the Antrim Plateau Volcanics (and correlative units in the Northern Territory and western Queensland) and the Table Hill Volcanics of the Capricorn Orogen.

Continued acquisition of lithogeochemical and regolith geochemical data will continue, as part of GSWA's regional mapping activities, with storage of these data in the corporate database. As part of this program, acquisition and characterization of a komatiite reference material will be carried out, in conjunction with CSIRO and Geoscience Australia.

2005–06 publications and products

Laterite geochemical database for the southwestern Yilgarn Craton, Western Australia by M. Cornelius, P. A. Morris, and A. J. Cornelius: CRC LEME Open File Report 201/ CSIRO Report P2006/75, 2006, 27p.

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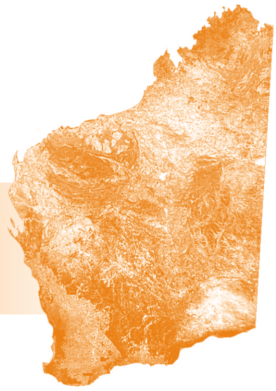
Biostratigraphy and paleontological services



Objective: *To provide information that allows precise interpretation of correlations, age, environment, and processes in the evaluation of the State's hydrocarbon and mineral potential.*

Highlights and activities 2005–06

The monograph on the palynology of the Ediacaran System was released in July 2006 and provides a detailed study of the biostratigraphy of the late Neoproterozoic across Australia. An updated version of GSWA paleontology reports from 1962 to 1996 was released on CD. Studies continued on stromatolites and palynology of the older Cryogenian rocks, including further work on Lancer 1 and Vines 1 from the Officer Basin. The handbook on microbialite and stromatolite methodology and terminology is nearing completion, as is a field guide to the stromatolites of Lake Thetis, near Cervantes, and work continues on a description of Archean stromatolites from the Strelley Pool Chert. Results from all of these studies will be published as GSWA publications.

Several external publications were published on various aspects of Precambrian paleobiology and correlation, including one on issues of biogenicity in Archean rocks, one on additional Ediacaran palynology, and one on sterane distribution in relation to acritarch diversity in the Ediacaran. Presentations were made at several national and international meetings during the course of the year.

Four external publications are under review: a book on Ediacaran animals, a correlation of the Ediacaran across Australia, a paper on Neoproterozoic glaciations, and a paper on Archean microfossils. A further four papers are in advanced stages of preparation.

A trip to Europe (as part of long service leave) allowed presentations of results to be made to various audiences, including a palynological meeting at the University of Liège in Belgium, the Natural History Museum and Leiden University in Holland, a field meeting on impact structures in Sweden, and the opportunity to continue work with colleagues at Uppsala University in Sweden. Presentations were also made to local societies and university departments, mainly in connection with either early life in the Pilbara or the Acraman impact event and its role in biotic changes in the Ediacaran.

Work of the section was disrupted for several weeks by renovations at Carlisle, which meant that the office and fossil store at Carlisle were unavailable. As usual, the section received numerous requests ranging from specific scientific enquiries to tourists seeking advice about visiting fossil sites and collecting constraints. Work continues on updating the fossil collection, and the capture of digital locational data for the general fossil collection is nearing completion. The next challenge is to attempt to capture digital location data for the type collection.

2005–06 publications and products

- *Ediacaran Palynology of Australia*: Memoir of the Association of Australasian Palaeontologists;
- *GSWA Palaeontology Reports 1962–96* (CD).

Future work

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

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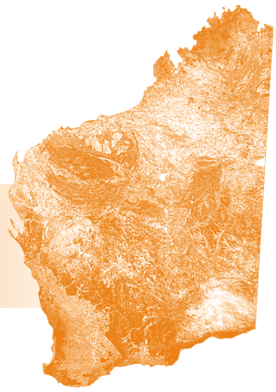
Geophysics and remote sensing



Objective: *To provide geophysical and remote sensing data, maps, and interpretation products to support GSWA programs of regional and detailed geological mapping and analysis.*

Regional airborne geophysics

In this second year of the Government's four-year, $12 million initiative to increase airborne magnetic and radiometric coverage of Western Australia, three new National Geoscience Agreement airborne geophysical-survey projects were initiated and, towards the end of the period, contracts were let for surveys programmed for the third year (2006–07) of the program.

All new surveys are flown at a line spacing of 400 m and at a mean altitude of 60 m above ground level. Where appropriate, the Department attempts to acquire intellectual property rights to existing data from private companies to complement the new survey flying. In the 2005–06 financial year, a total of almost 750 000 km of data were purchased from the private sector.

The current status of all surveys over the program life to date is summarized in Table 2; the survey locations are shown in Figure 11.

Regional gravity surveys

During 2005–06, a regional gravity survey was conducted in the Paterson area, where 4273 stations were surveyed on a 2.5-km grid.

Contracts were approved for two surveys in the WEBB and Murchison areas to take place in 2006–07 and, if land access negotiations are successful, a survey in the Tanami area may also occur. Approximately 4100 stations will be acquired in the WEBB area and 3600 in the Murchison, both on a 2.5-km square grid pattern.

Airborne geophysical survey register and data repository

During 2005–06, 90 new airborne-survey datasets, containing approximately 432 000 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 4.1 million line-km of private data from 828 surveys were held in the repository.

The location and basic specifications of surveys are available through the GeoVIEW.WA system on the Department's website (www.doir.wa.gov.au).

Remote sensing

During 2005–06, there was continued high internal demand from project teams for satellite and other multi-spectral remote-sensing image

Table 2. Regional airborne magnetic and radiometric survey program

Year/survey name	*Contractor*	*Coverage (line-km)*	*Release date (*provisional)*
2004–05			
South Yilgarn	Fugro/UTS	306 000	May–July 2005
Data purchases		139 000	
Total 2004–05		**445 000**	
2005–06			
Paterson North	Fugro	69 000	7 Oct 2005
Paterson South	UTS	128 000	Aug 2006
East Yilgarn	Fugro	164 000	7 Jun 2006
Gascoyne	UTS	106 000	7 Jun 2006
Data purchases		773 000	various
Total 2005–06		**1 240 000**	
2006–07			
Musgrave Extension	Fugro	82 000	*Jan 2007
Ashburton	UTS	98 000	*Feb 2007
Officer (Trainor) Basin	GPX	105 000	*Feb 2007
Total 2006–07		**285 000**	

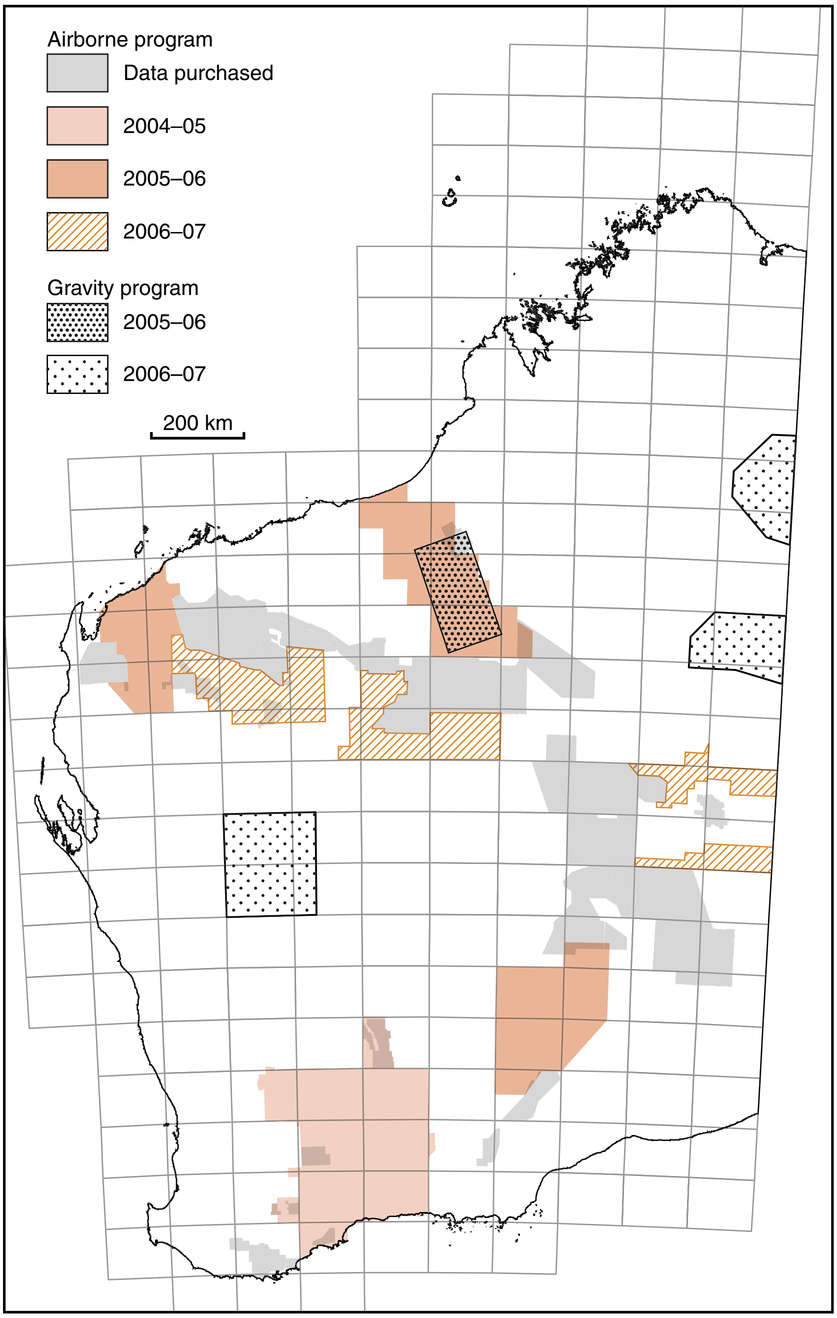


Figure 11. Location of regional geophysical surveys

processing. The GSWA internal inventory of remote sensing imagery continued to grow with the inclusion of digital elevation data from the NASA Shuttle Radar Topography Mission (SRTM). Where publication of these data is permitted by the owners of the intellectual property rights, they are also included as digital layers in the various digital packages published.

Regional geological interpretations

Geological interpretations are being made from the new regional airborne-survey data — integrated with remote sensing data and legacy and new field data — in order to update GSWA's 1:500 000-scale geological maps and to provide context for the 1:100 000-scale regional geological mapping and regolith–landform mapping programs (refer to individual project reports for details of these programs).

In 2005–06, an interpretation of the northern Murchison area was completed and released as part of the digital Murchison exploration data package (Record 2006/2).

A similar interpretation is presently in progress in the south Yilgarn area, encompassing the Bremer Bay, Newdegate and Ravensthorpe areas, for release in 2006–07.

2005–06 publications and products

Regional survey datasets

- South Yilgarn 2004 airborne magnetic and radiometric survey, Block C: NEWDEGATE, RAVENSTHORPE, BREMER BAY 1:250 000 map sheet areas;
- Paterson 2005 airborne magnetic and radiometric survey, North block;
- Paterson 2005 ground gravity survey;
- East Yilgarn 2005 airborne magnetic and radiometric survey;
- Gascoyne 2005 airborne magnetic and radiometric survey.

Hardcopy images and maps

- 1:250 000 Ternary Radiometric and Total Magnetic Intensity images: NEWDEGATE, RAVENSTHORPE, BREMER BAY;
- 1: 500 000 Total Magnetic Intensity images: East Yilgarn, North Gascoyne;
- 1: 2 500 000 Magnetic Anomaly Map of Western Australia.

Digital data layers

- Regional interpreted bedrock geology map of the northern Murchison Domain (in the Murchison geological exploration package, February 2006 update).

Books

- Record 2006/9: *Image processing of ASTER multispectral data*;
- Record 2006/10: *Interpreted bedrock geology of the northern Murchison Domain, Youanmi Terrane, Yilgarn Craton*;
- Presentation: *Interpretation of multiple datasets in revising the geology of the Archean Murchison Domain, W.A.* Extended abstract in AIG Bulletin 44, 2006 (presented at Outcrop to Orebody combined AIG and AMEC meeting, May 2006).

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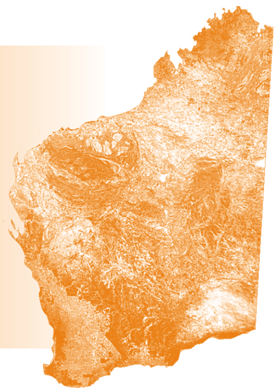
Logistics support and core libraries

Objectives:
- *To manage core library facilities in Perth and Kalgoorlie to service the needs of industry, researchers, and GSWA*
- *To manage field support services, including transport and other equipment, and to 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

Robust activity in offshore petroleum exploration continues to set a high demand on services at the Perth core library. Client use of facilities for viewing of core and cuttings has run at full capacity for most of the year. There is also a growing trend for petroleum, mineral, and research groups to use the Perth and Kalgoorlie core library facilities for core-related workshops.

Amendments to the Mining Act were proclaimed in February 2006, providing the Department increased powers to ensure valuable mineral-exploration core is made available to the Department. Procedures are in place to administer this process and a program to collect valuable historical mineral core is ongoing.

The second phase of scanning core using the newly developed CSIRO thermal infrared Hylogger was carried out at the Kalgoorlie core library in November–December 2005. A total of 9000 m of core was scanned for the project, which is funded by Placer Dome, Goldfields Australia, and GSWA. MERIWA have also contributed funds to assist in the development of the infrared Hylogger, which has provided additional information including silicate analysis of selected cores.

During the year, a total of 716 clients viewed and/or sampled core or cuttings at the Perth and Kalgoorlie facilities. Clients spent a total of 3041 hours viewing core and cuttings and took 1515 samples for further analysis. A total of 10 195 m of core, 2405 boxes of cuttings, and 990 sidewall cores were accessioned into the collection.

Field logistics

The 40-year-old building housing the Field Logistics team, vehicles, and equipment at Carlisle has been given a major facelift. Work was completed in June to remove all asbestos-bearing building materials and replace them with colourbond and polycarbonate sheets. The new façade complements the recently completed core library building, providing excellent accommodation for staff and equipment for decades to come.

The specialized and diversified 4WD fleet continues to satisfy all divisional field requirements. Fly-in, fly-out arrangements incorporated with carefully programmed field schedules ensured efficient use of the fleet.

Additional field assistants required for field mapping programmes continue to be sourced from an employment agency, allowing flexibility in meeting short-term needs for field staff at short notice.

Safe working practices in the field and the provision for suitable training for all staff using 4WD vehicles and associated equipment remains a high priority. Twenty-two persons were trained in the in-house Safety Training course. Although most field staff are issued with satellite phones, the high-frequency radio communication base at the Carlisle depot continues to be the focus point for monitoring safe operations in the field. The Safety Officer is on roster to cover weekends.

The Geological Survey's publication store at Carlisle maintained the issue of Reports, Bulletins and maps to the point of sale at the Information Centre in Mineral House.

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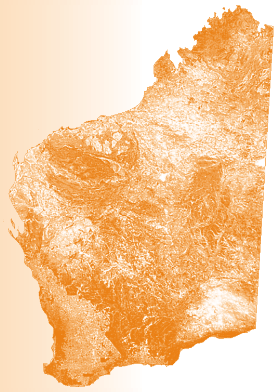
Geoscience information products

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.*



2005–06 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

Twenty-six maps and images at various scales were published (see Appendix: Planned achievements and publications released, p. 129), including:

- seven 1:100 000 geological series maps
- two 1:250 000 geological series maps
- eight project maps at various scales
- nine geophysical images at various scales

Geoscientific digital data packages

Eighteen geoscientific digital data packages were released in 2005–06 (Appendix, p. 129), including:

- four 1:100 000 geological information packages
- two geological exploration packages
- three mineral occurrences and exploration potential data packages
- two acreage release data packages
- three geoscience of WA promotional CDs
- one geochronology package
- three miscellaneous data packages.

Geoscientific reports

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

- Explanatory Notes for two series maps
- 14 Records and Reports
- eight miscellaneous publications including the GSWA Annual Review 2004–05.

Other activities

Promotional activities

Publication of Fieldnotes (the GSWA quarterly newsletter) continued during 2005–06 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, and ad hoc email newsletters were used to inform interested customers of recent and imminent releases and GSWA events.

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

- Diggers & Dealers (Kalgoorlie, August 2005)
- IGES (Perth, September 2005)
- Good Oil (Perth, September 2005)
- AAPG (Paris, September 2005)
- Offshore Europe (Aberdeen, September 2005)
- Mining 2005 (Brisbane, October 2005)
- Mines & Money (London, November 2005)
- China Mining (Beijing, November 2005)
- NAPE (Houston, Texas, February 2006)
- Explorers Conference (Perth, February 2006)
- PDAC (Toronto, Canada, March 2006)
- APPEA (Gold Coast, April 2006)
- Kal 2006 (Kalgoorlie, May 2006)
- AMEC (Perth, June 2006)

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)
- GSWA 2006, which was again held in February to hook up with the RIU Explorers Conference conducted at the same venue in Fremantle (Perth, February)
- Company visits — a number of companies in Perth and Kalgoorlie were visited to promote our latest products and services and to provide an opportunity for feedback
- GSWA Information and Training Sessions were held in March and May 2006 to provide hands-on training for our customers on how to use our online systems and to increase awareness about available GSWA products and services.

Online services

In 2005–06, GSWA continued to improve its provision of data online by introducing a new series-map data download service on the Internet, where customers can download free 1:100 000- and 1:250 000-scale map sheet data. In addition, we have continued to add new datasets to the GSWA Data and Software Centre, including the latest version of GSWA's free PC-based interactive map-viewing software, GeoVIEWER.WA.

GSWA publications and WAMEX reports continued to be scanned and uploaded to GSWA's new online document-delivery system. At 30 June 2006, the system contained 19 500 WAMEX items and 870 GSWA publications, for a total of over 260 Gb of online data. This system allows users to view and print the documents without having to download them first, and also contains a download facility.

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Appendices

Planned achievements and publications released

Major planned achievements for 2005–06

GSWA continued its ambitious project-based work program for 2005–06 focusing primarily on promoting Western Australia's exploration potential. The planned achievements for 2005–06 included the release of 44 geoscientific maps at various scales; publication of 37 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers; publication of 22 digital geoscience datasets; and the release of 560 000 line-km of airborne geophysical data. In addition, GSWA continued and enhanced the 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 continued. The surveys aim to increase mineral exploration expenditure in Western Australia.

In 2005–06 GSWA published:

- 26 geological maps, including seven 1:100 000 Geological Series maps;
- 24 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- 18 digital datasets.

The 2005–06 regional geophysical program involved new airborne surveys in the Paterson (197 000 km in two survey blocks), Gascoyne (106 000 km), and east Yilgarn (164 000 km) regions. A further 773 000 km of existing airborne data were purchased from private companies. In addition, a regional gravity survey was conducted in the Paterson area, where 4273 stations were surveyed.

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. GSWA publication milestones for 2005–06 were met, with a total of 68 published products being released.

Provision of open-file company exploration reports to industry via the WAMEX and WAPIMS database systems continued through the year. GSWA is in the middle of a three-year program to accelerate the public release of archival information contained in 21 000 non-confidential, tenement-holder exploration reports that are more than five years old, in order to encourage greenfields exploration activity. More than 7000 reports were scanned in 2005–06.

Maps, books, and datasets released in 2005–06

Geological maps

1:100 000 Geological Series

BATES by H. M. Howard, R. H. Smithies, F. Pirajno, and M. S. Skwarnecki
COLLURABBIE by J. A. Jones
EASTERN CREEK (v. 2) by T. R. Farrell
ERAYINIA by S. A. Jones
MOUNT MARSH by M. J. Van Kranendonk
YOUNO DOWNS by S. F. Chen, S. Wyche, and M. G. Doyle
YARDINA by C. E. Hall, S. A. Jones, and B. Goscombe

1:250 000 Geological Series

PORT HEDLAND – BEDOUT ISLAND by M. J. Van Kranendonk and R. H. Smithies
EDMUND by A. M. Thorne, S. Sheppard, D. McB. Martin, S. A. Occhipinti, and I. A. Copp

1:500 000 maps

Iron ore deposits of the Pilbara region, 2005 compiled by R. W. Cooper and D. J. Flint

Geological maps at other scales

Mineralization and geology of the Paterson area
by K. M. Ferguson and L. Bagas (Report 97)
Asteroid impact signatures of the Pilbara Craton (scale 1:1 000 000)
by A. Y. Glikson and A. H. Hickman
Western Australian mines — operating and under development, 2006
(scale 1:2 500 000) by R. W. Cooper and D. J. Flint
Major resource projects 2006 (scale 1:3 000 000)
by D. J. Flint and R. W. Cooper
Iron ore deposits of the Yilgarn Craton, 2006 (scale 1:1 500 000)
compiled by R. W. Cooper and D. J. Flint
Exploration licences — designated areas
by Geological Survey of Western Australia
Interpreted bedrock geology of the northwestern Pilbara Craton
(scale 1:250 000) by A. H. Hickman, R. H. Smithies, and C. A. Strong

Geophysical images

1:250 000 images

BREMER BAY Total Magnetic Intensity image
BREMER BAY Ternary Radiometric image
NEWDEGATE Total Magnetic Intensity image
NEWDEGATE Ternary Radiometric image
RAVENSTHORPE Total Magnetic Intensity image
RAVENSTHORPE Ternary Radiometric image

1:500 000 images

North Gascoyne Total Magnetic Intensity image
East Yilgarn Total Magnetic Intensity image

1:2 500 000 images

Magnetic Anomaly Map of Western Australia

Reports

97 **Mineral occurrences and exploration potential of the Paterson area**
by K. M. Ferguson, L. Bagas, and I. Ruddock

101 **Archean volcanic and sedimentary rocks of the Whim Creek greenstone belt, Pilbara Craton, Western Australia**
by G. Pike, R. A. F. Cas, and A. H. Hickman

Records

2005/1 **Geological Survey work program for 2005–06 and beyond**

2005/11 **Geology of the western Albany–Fraser Orogen, Western Australia — a field guide**

2006/3 **GSWA 2006 extended abstracts: promoting the prospectivity of Western Australia**

2006/6 **Nickel–cobalt in Western Australia: commodity review for 2004** by P. B. Abeysinghe and D. J. Flint

2006/7 **Petroleum geochemistry of the Canning Basin, Western Australia: basic analytical data 2004–05** by K. A. R. Ghori and P. Haines

2006/8 **A revised geological framework for the Yilgarn Craton, Western Australia** by K. F. Cassidy, D. C. Champion, B. Krapěz, M. E. Barley, S. J. A. Brown, R. S. Blewett, P. B. Groenewald, and I. M. Tyler

2006/9 **Image processing of ASTER multispectral data** by J. R. Gozzard

2006/10 **Interpreted bedrock geology of the northern Murchison Domain, Youanmi Terrane, Yilgarn Craton** by C. V. Spaggiari

2006/11 **Stratigraphy and physical volcanology of the Archean Kurnalpi Terrane, Yilgarn Craton — a field guide** by P. B. Groenewald, M. G. Doyle, S. J. A. Brown, and S. J. Barnes

2006/13 **Copper–lead–zinc in Western Australia: commodity review for 2003 and 2004** by P. B. Abeysinghe, S. Searston, and D. J. Flint

2006/14 **The Pilbara drilling project: c. 2.72 Ga Tumbiana Formation and c. 3.49 Ga Dresser Formation, Pilbara Craton, Western Australia** by M. J. Van Kranendonk, P. Philippot, and K. Lepot

2006/15 **Revised lithostratigraphy of Archean supracrustal and intrusive rocks in the northern Pilbara Craton, Western Australia** by M. J. Van Kranendonk, A. H. Hickman, R. H. Smithies, I. R. Williams, L. Bagas, and T. R. Farrell

Explanatory Notes

1:100 000 Geological Series

Geology of the Eastern Creek 1:100 000 sheet by T. R. Farrell
Geology of the Wodgina 1:100 000 sheet by R. S. Blewett and D. C. Champion

Miscellaneous books

Summary of petroleum prospectivity, onshore Western Australia and State waters 2006: Bonaparte, Canning, Officer, Perth, Southern Carnarvon, and Northern Carnarvon Basins
Geological Survey of Western Australia Annual Review 2004–05
Fieldnotes v. 36, 37, 38, 39
Overview of mineral exploration in Western Australia for 2004–05 by D. J. Flint
Catalogue of geoscience products 1980–2006 (March 2006)

Digital products

Central Yilgarn (1:100 000 Geological Information Series)

West Musgrave (1:100 000 Geological Information Series)

Pilbara (1:100 000 Geological Information Series)

Western Capricorn Orogen, June 2006 (1:100 000 Geological Information Series)

Murchison geological exploration package, February 2006 update (Record 2006/2)

Northeastern Yilgarn geological exploration package, April 2006 update (Record 2006/4)

Mineral occurrences and exploration activities of the Mid West coast area (Record 2006/5)

Mineral occurrences and exploration activities of the west Hamersley area (Record 2006/12)

Promotional CD 2006

Mineral occurrences and exploration potential of the Paterson area (Report 97)

Iron ore deposits of the Pilbara region, 2005 update

Inventory of abandoned mine sites: progress 1999–2005 (update)

Western Australia petroleum acreage release, September 2005

Western Australian petroleum acreage release, May 2006

Byro promotional CD

GSWA publications 2003–05 (CD)

GSWA Palaeontology Reports 1962–96 (CD)

Compilation of geochronology data, June 2006 update

Major planned achievements for 2006–07

GSWA will continue to pursue a project-based program of work and maintain a vigorous level of output to match funding received. The priority areas for high-tech aerial geophysical surveys in 2006–07 are the Musgrave, Ashburton, and Officer (Trainor) Basin regions, with expected coverage of a total of 526 000 line-km. Gravity surveys will be carried out in the WEBB area (prospective for base metals, nickel and gold), in the Murchison region (highly prospective for nickel and gold), and possibly in the Tanami region (prospective for gold). Expenditure on geophysical surveys planned for 2006–07 is A$3 million.

Planned achievements for 2006–07 include:

- release of 41 geological maps at various scales including 16 at 1:100 000 scale;
- publication of 31 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of 20 digital data packages;
- release of 526 000 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 will complete a three-year A$1.2 million commitment from the State Government to release more than 21 000 confidential geological reports submitted by mineral exploration companies over many years. Expenditure planned for this activity in 2006–07 is A$400 000, sufficient to release the final 7000 reports.

External publications by GSWA staff 2005–06

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

Note: GSWA authors in italics

AWRAMIK, S. M., and *GREY, K.*, 2005, Stromatolites: biogenicity, biosignatures, and bioconfusion, *in* Astrobiology and Planetary Missions *edited by* R. B. HOOVER, G. V. LEVIN, A. Y. ROZANOV, and G. R. GLADSTONE: SPIE — The International Society for Optical Engineering, Proceedings, v. 5906, paper 5906-24, 9p.

BAGAS, L., HUSTON, D., ANDERSON, J., and MERNAGH, T. P., 2006, Paleoproterozoic gold deposits in the Bald Hill and Coyote areas, western Tanami, Western Australia; Evolution and metallogenesis of the North Australian Craton Conference, Alice Springs, N.T., 2006, Conference Abstracts: Geoscience Australia, Record 2006/16, p. 32.

BAGAS, L., and *NELSON, D. R.*, 2005, Constraining the provenance of Neoproterozoic successions of the northwesternmost Centralian Superbasin, Western Australia; Centralian Australia Basins Symposium, Alice Springs, N.T., 2005, Abstracts: Northern Territory Geological Survey, Record 2005/5, p. 18–17.

BOLHAR, R., and *VAN KRANENDONK, M. J.*, 2005, Trace element geochemical evidence for a lacustrine environment of deposition of Late Archaean Fortescue Group stromatolitic carbonates, Western Australia: Geological Society of New Zealand, Annual Conference, Kaikoura, New Zealand, 2005, Annual conference programme and abstracts; Miscellaneous publication 119A, p. 9–10.

CHEN, S. F., *MORRIS, P. A.*, and *PIRAJNO, F.*, 2005, Occurrence of komatiites in the Sandstone greenstone belt, north-central Yilgarn Craton: Australian Journal of Earth Sciences, v. 52, p. 959–963.

CHEN, Y-J., and *PIRAJNO, F.*, 2005, Linking the CMF model to metallogenic zoning in the east Qinling Orogen, central China, *in* Mineral deposits research: meeting the global challenge, v. 1 *edited by* J-W. MAO and F. BIERLEIN: SGA, 8th Biennnial Meeting, Beijing, China, 2005, Proceedings, p. 905–908.

CHEN, Y-J., *PIRAJNO, F.*, QI, J-P., and WANG, H-H., 2006, Ore geology, fluid geochemistry and genesis of the Shanggong gold deposit, eastern Qinling Orogen, China: Resource Geology, v. 56, p. 99–116.

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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
ESRI	Environmental Systems Research Institute
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
IUGC	International Union of Geological Sciences
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
NCRIS	National Collaborative Research Infrastructure Strategy

NGA	National Geoscience Agreement
NTGS	Northern Territory Geological Survey
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, WAPEX, and TENGRAPH are registered Trademarks of DoIR

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