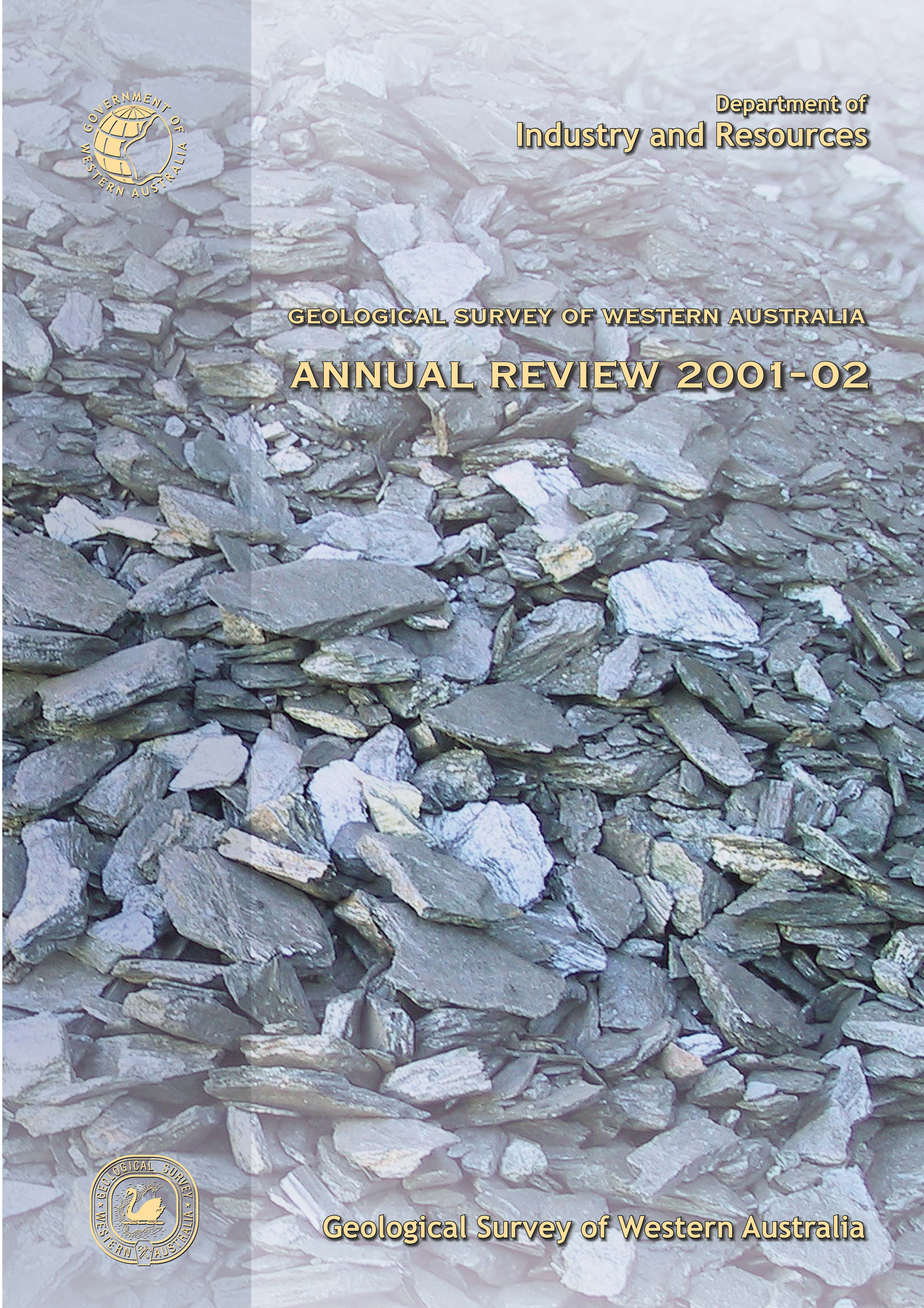

Department of
Industry and Resources

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 2001-02

Geological Survey of Western Australia

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Perth 2003

MINISTER FOR STATE DEVELOPMENT
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Cover:
Micaceous iron ore product from the Mount Gould deposit, chiefly used as an anti-corrosive in high-quality industrial paint pigment (photograph courtesy of Imdex Ltd)

Frontispiece:
Limestone karst towers (7–8 m high) in the Lower Permian Calytharra Formation, near Coronation Bore on Bidgemia Station, Southern Carnarvon Basin

Contents

GSWA mission statement 1

The year in review
by Tim Griffin 3

Overview of the mineral sector in Western Australia in 2001–02
by D. J. Flint and S. M. Searston 7

Declining greenfields exploration in Western Australia, 1996–2001
by D. J. Flint and R. Rogerson 27

Inside the GSWA 41

- Staff profiles 41
- Obituary: David Bruce Townsend, 1956–2002 44
- Staff list (30 June 2002) 45
- Staff movements (1 July 2001 to 30 June 2002) 47
- Organizational chart and key contacts 49

Technical papers 51

- **Stratigraphic revision of the Warrawoona and Gorge Creek Groups in the Kelly greenstone belt, Pilbara Craton, Western Australia**
  by L. Bagas 53
- **Geochemistry of the Corunna Downs Granitoid Complex, East Pilbara Granite–Greenstone Terrane, Western Australia**
  by L. Bagas, R. H. Smithies, and D. C. Champion 61
- **Stratigraphic and tectonic significance of eight local unconformities in the Fortescue Group, Pear Creek Centrocline, Pilbara Craton, Western Australia**
  by M. J. Van Kranendonk 70
- **Seismic stratigraphic framework of the Neoproterozoic successions, Officer Basin, Western Australia**
  by S. N. Apak and G. M. Carlsen 80

Program review 89

Appendices 121

List of acronyms and abbreviations 123

Planned achievements and publications released 124

External papers published by GSWA staff in 2001–02 129

Geological Survey Liaison Committee 132

GSWA mission statement

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

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

The 2001–02 year saw the formation of the Department of Mineral and Petroleum Resources from the merger of the former Department of Minerals and Energy and the Department of Resource Development. The Geological Survey of Western Australia (GSWA) has remained essentially unchanged in this merger, and continues to focus on the provision of high-quality pre-competitive geoscientific data and analysis for the mineral and petroleum resources industries.

The Western Australian resources industry remained buoyant in 2001–02 with minerals and petroleum sales totalling $26 billion, although this is down 5% from the previous year. Contributing 23% of the State's Gross State Product, the resources sector remains critical to the State's high living standards.

Mineral exploration expenditure, however, continued to decline, and at $376 million it is down 47% from the peak of $705 million reached during 1996–97. This is regarded by most analysts as too low to sustain the State's current high levels of mineral production, and State and Federal Governments are seeking ways to redress this situation. Of particular concern, is the marked decline in exploration activity in the so-called 'greenfields' areas of the State, as it is these areas that have the highest potential to provide important new discoveries that will develop into the major mining projects of future decades.

The Western Australian Government undertook to identify the drivers necessary to reinvigorate the sector, with the setting up in April 2002 of the Ministerial Inquiry into Greenfields Exploration in Western Australia chaired by John Bowler MLA, Member for Eyre. This followed the release of the Fardon Report in February 2002 that was primarily focused on an appropriate level of funding for the Geological Survey.

The extent of the downturn in exploration, and the long-term impact on the Australian economy, was also recognized by the Federal Government when it commissioned the Prosser Inquiry in May 2002 to look into impediments to increasing investment in mineral and petroleum exploration in Australia.

There is typically a ten-year lead time between an initial discovery and subsequent production. Without continued high levels of investment in mineral and petroleum exploration, existing deposits of many commodities will be seriously depleted over time, drastically reducing the State's income stream and employment opportunities.

GSWA plays an important role in providing essential geoscientific background information for explorers to help in area selection for detailed exploration. The availability of such data dramatically reduces risk, thereby making exploration investment more attractive. Continued and improved provision of this pre-competitive geoscience data at minimal cost is essential if we are to see high levels of exploration return to greenfields areas of Western Australia.

Highlights

GSWA's production targets were again successfully achieved. In 2001–02 we released 33 maps (geological, geophysical, geochemical, and regolith), and 48 publications, including 27 Records, 9 Explanatory Notes, and 3 Reports. In addition, internet delivery of products increased with major upgrades to GeoVIEW.WA, our interactive geoscience mapping facility accessible through the MPR website. This includes the addition of a State regolith map to compliment the 1:500 000 State geology; the area south of 26° is now on-line, with coverage for the northern half of the State to follow in 2002–03.

GSWA made major contributions to the 4th International Archaean Symposium in Perth, particularly in the organization of field trips in the shadow of the Ansett collapse and the events of 11 September. GSWA also published detailed field guides for this major symposium, including the north Pilbara, west Pilbara, east Pilbara, northeast Yilgarn – Gascoyne, southwest Yilgarn – Leeuwin, central Yilgarn, and Eastern Goldfields guides, and a specific guide to gold camps focused on the Yilgarn.

Record 2001/1 (*Geological Survey work program for 2001–02 and beyond*) provided a summary of activities and planned work areas for all aspects of our work. It also highlighted the importance of the regolith as a major source of the State's mineral wealth, with metals (excluding gold) and industrial minerals won from the regolith contributing over 30% of total mineral-production value in 2000. A Mineral Resources Bulletin on clays was published to add to the list of commodity publications, along with a GSWA Record updating the state of play on industrial minerals in Western Australia.

With the opening of the J. H. (Joe) Lord Core Library in Kalgoorlie last year and its successful operation since, contracts have now been let for the construction of a similar but larger facility at Carlisle, a suburb just 7 km from the Perth CBD. This facility is scheduled for completion and commissioning in early 2003, and will enable far easier access to mineral and petroleum cores by exploration companies and research organizations, and GSWA staff. A major program to collect selected mineral exploration core of significant geological interest has begun, and the selection criteria have been documented in a GSWA Record.

GSWA continued to maintain its statutory obligation to manage the collection, storage, and dissemination of mineral- and petroleum-exploration company statutory reports on tenements in Western Australia, and to ensure the efficient dissemination to industry of the information in these reports after the prescribed confidentiality period. The archive of statutory data relating to exploration is a valuable resource, providing a means whereby companies can assess the potential of an area and thus develop exploration strategies without the duplication of previous activities. The reports and data are also a valuable input into a number of GSWA mapping and assessment projects.

In 2001–02, almost 2100 mineral exploration reports were received and captured for indexing in the WAMEX database. The archive now holds approximately 65 000 reports, with about 36 000 open to public access. Comprehensive abstracts and keywords for all reports facilitate on-line user searches through the 'WAMEX-via-the-WEB' facility that was introduced in 2000–01. More than 6000 reports are now available for viewing on-line as scanned electronic files, complementing the availability of reports that are increasingly being submitted directly in digital format.

On the petroleum side, the new integrated petroleum information-management system and database was implemented, allowing on-line access to a wide range of petroleum exploration reports and data. By year-end, the system contained 11 gigabytes of database information and 9.4 gigabytes of electronic documents that can be accessed through a comprehensive spatial (geographic) search facility. With around 16 web 'hits' per day, the system has already proved to be very popular with domestic and international petroleum explorers seeking information from offshore and onshore reports on Western Australian petroleum exploration programs.

GSWA has introduced a new mapping process that takes full advantage of improvements in digital technology. This process revolutionizes the way maps are made and published by utilizing orthorectified aerial photographs, accurate GPS locations, and electronic recording of field observation and sample points. All data recorded — including site photographs, petrographic, geochemical, and geochronological information — are incorporated into GSWA's corporate databases. Apart from more accurate maps and more efficient fieldwork, the digital databases enable maps to be plotted as required from the regularly updated information, rather than relying on quickly outdated large print runs using the previous lithographic production techniques. Increasingly, geological databases are being made available on-line via the internet, where customers, whether corporations or individuals, can interrogate the data and create their own customized map product.

The remapping of the Pilbara Craton, based on extensive fieldwork, high-quality satellite imagery, and detailed SHRIMP geochronology, is nearing completion, with the release of a further seven geological maps in 2001–02. This work was complemented by the release of the data package on mineral occurrences and exploration potential of the east Pilbara, to match the west Pilbara data package released last year.

Mineral occurrence updates were provided for the Bangemall Basin and the southwest Western Australia datasets, and a Record on the geology and mineral resources of the Southern Cross – Esperance region was also released.

The program of 1:50 000 regolith–landform resources mapping that began with the Margaret River area (COWARAMUP – MENTELLE) was further expanded by release of adjacent maps, reports, and datasets for KARRIDALE–TOOKER and LEEUWIN.

Major meteorite impacts are recognized as playing a significant role in the geological history of the Earth, and may also be linked to mineral and petroleum concentrations. GSWA geoscientists studied several such impact structures during the year, and reports were released documenting the Woodleigh (Shark Bay area) and Shoemaker (Earaheedy Basin) impact structures.

Several well completion reports were published in 2001–02, including Vines 1, the stratigraphic well drilled by GSWA in the Waigen area of the Officer Basin, and three wells from the Gascoyne Platform of the Southern Carnarvon Basin. A discussion on basin development and petroleum exploration potential for the Gibson area in the western Officer Basin was also published, along with work from the northern Perth Basin.

Many GSWA publications are now accompanied by digital data, commonly with included free software to view the data on CD. Indeed, an increasing number of our products are being made available in digital form either via the internet or on CD, in response to customer demands. The release of products in this form is not only more effective for the end-user, but it also allows more frequent updates, and eliminates the costly large print runs associated with conventional printed versions. Digital products can also contain many more colour photographs than the printed copy.

Standard series GSWA publications such as maps and Records are often supported by detailed papers that highlight aspects of particular importance or interest. These include technical papers such as those in this volume, extended abstracts for the GSWA or MPR petroleum open days, and external journal articles that are listed in this volume. Well-researched and refereed scientific papers add considerably to the body of knowledge on Western Australian geology, and many papers by GSWA geoscientists are widely circulated in international journals.

GSWA is also continuing to develop stronger relationships with other agencies to encourage geological investigations beyond the scope of GSWA alone, and of great benefit to the understanding of Western Australian geology. Of particular significance in this regard was the release of data from a seismic reflection traverse across the granite–greenstone terrane in the northeastern Goldfields and onto the western margin of the Officer Basin. This work was carried out as a joint program with Geoscience Australia and pmd*CRC.

Work on the Eastern Goldfields seamless digital database reached a major milestone with the release of the central (Leonora–Laverton) section to complete the coverage of sixty 1:100 000 map sheets as a consistent digital dataset covering the Norseman–Wiluna region

The issue of sampling and exporting geoscience specimens, particularly fossils, has been addressed in a publication that explains the limitations and approvals necessary for geoscientists undertaking research in Western Australia.

Ongoing work program

The regional geological field-mapping program continues to be a major focus of GSWA activity. The program concentrates on areas regarded as highly prospective for mineral discovery, but which remain poorly understood geologically. These areas are consequently underexplored.

The Pilbara remains an important program, with fieldwork for the 1:100 000 map coverage to be completed next year. Related publications and regional syntheses will continue for at least another two years. Active mapping programs will continue in the Yilgarn Craton, both to the southeast of Kalgoorlie and north of Sandstone. The Eastern Goldfields seamless digital database will be further upgraded in 2003, with new regolith coverage of the entire sixty 1:100 000 sheet areas, and the addition of new mapping data currently being acquired to the south and southeast of the area, and the incorporation of geological mapping data from the areas north of Southern Cross.

Mapping also continued to elucidate the Capricorn Orogen in the Gascoyne Complex and adjoining Edmund and Collier Basins, and the Earaheedy Basin further east. The Earaheedy Basin project fieldwork will be completed next year, and this new data will be incorporated into a seamless digital geoscience database including the Bryah, Yerrida, and Padbury Basins to the west.

The focus for future petroleum studies will be reviewed through an industry workshop, as it is five years since the previous such review. GSWA will continue to provide better access to digital data and, where feasible, this will be on-line.

Links with the geological research groups of The University of Western Australia and Curtin University are continuing to develop, particularly with the Centre for Global Metallogeny, the Tectonic Special Research Centre, and the John deLaeter Centre for Mass Spectrometry.

Collaborative research programs with the Co-operative Research Centres pmd*CRC and CRC LEME, together with a close association with Geoscience Australia, are also helping to cover aspects of the geology of Western Australia that GSWA alone could not investigate. With reducing budgets at all levels, such collaborative research between State and Federal Government agencies and academic institutions will undoubtedly become more important in the future to ensure the community is getting the maximum benefit from research funding.

GSWA has incorporated the important roles of land assessment and community liaison that rely very heavily on up-to-date geological and mineral occurrence databases. Providing expert advice to counter pressures that place limits on access to land for exploration and mining is a rapidly growing role. Consequently, GSWA must continue to work closely with other sections of the Department of Mineral and Petroleum Resources and other Government agencies to ensure an optimum outcome for all its activities that addresses both the needs of the resources sector and provides maximum benefit to the wider community.

Overview of the mineral sector in Western Australia in 2001–02

by D. J. Flint and S. M. Searston[1]

Abstract

Consistent with worldwide trends and Australia as a whole, mineral-exploration expenditure figures (excluding petroleum) for Western Australia fell for the fifth successive year, dropping to $376 million in 2001–02, down by 46% since the peak activity in 1996–97. Trends and issues affecting exploration include merger and acquisition activity, a swing away from greenfields exploration, difficulties in obtaining seed and venture capital for junior explorers, declining mining-company market capitalization, taxation, land access, Aboriginal heritage issues, and perceived investment risk.

Drilling activity (RAB, RC, and diamond) in Western Australia is down by about 65% since the peak of 1996–97 and such a decline, together with access difficulties to land, greatly diminishes the number of opportunities for significant discoveries. These are necessary to boost mineral resource inventories, sustain the current level of mining development, and provide opportunities for growth in the industry. Both the Federal and State Governments have initiated parliamentary inquiries to identify impediments to exploration and ways to boost exploration, particularly greenfields exploration.

However, despite the downturn in exploration activities since 1996–97, important discoveries are still being made. These include the emergence of the Ashburton Basin and northeastern part of the Kimberley Basin as gold provinces, the huge resource upgrade at Telfer, further base metal discoveries at and around Golden Grove and Teutonic Bore (Jaguar), and discovery of high-grade nickel sulfides at Waterloo.

Mine development highlights include opening of the Thunderbox and Waugh gold mines, Ellendale diamond mine, West Angelas iron ore mine, and Dardanup heavy-mineral sands mine. The West Angelas operation represents a new phase in Western Australian iron ore mining as the first to market Marra Mamba iron ore as a stand-alone product. Advanced projects are numerous and include the direct smelting of iron ore (HIsmelt), the go-ahead for an iron ore mine at Eastern Ranges (near Paraburdoo), and the State's most advanced platinum–palladium project (Panton Sill) at the feasibility stage.

Mineral exploration trends

The State of Western Australia continues to attract the major proportion of mineral exploration expenditure in Australia (59%), a reflection of the State's real and perceived prospectivity (Fig. 1). However, mineral exploration expenditure figures (excluding petroleum) for Western Australia fell for the fifth successive year, from $424 million* in 2000–01 to $376 million in 2001–02, down by about 11%. This trend is also clearly illustrated by the quarterly data, which shows that the downturn is continuing (Fig. 2).

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[1] Post Office Box 489, West Perth, W.A. 6872.

* All $ figures in Australian dollars unless otherwise specified.

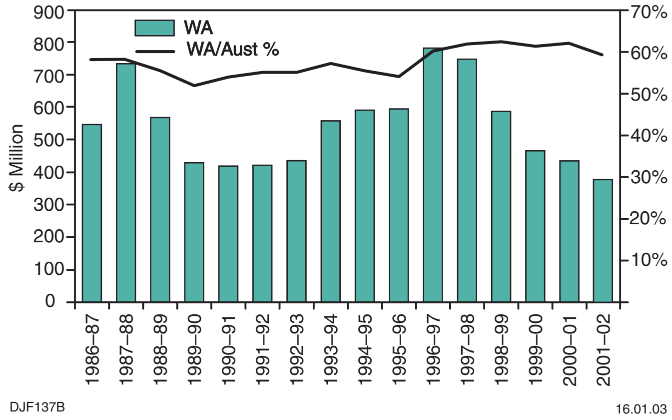

Figure 1. Mineral exploration expenditure in Western Australia, by year (June 2002 dollars)

The Western Australian figures are consistent with worldwide trends and Australia as a whole. The current level of mineral exploration expenditure within Australia is $636 million, which is 45% ($513 million) lower than the peak year of 1996–97 when expenditure reached $1149 million. The worldwide decline in exploration expenditure can be attributed to a number of factors, including continued low commodity prices, the ongoing perception of mining as a low-profit activity, lack of venture capital, slowing world growth, and the events of 11 September 2001. However, Australia and Western Australia continue to maintain their share of global exploration expenditure at about 17.5 and 10% respectively. This may be regarded as a positive reflection of the State's prospectivity as perceived by companies when they decide where to expend their reduced global exploration funds.

Exploration expenditure in Western Australia for gold and base metals (including nickel–cobalt) is now close to the lowest levels for a decade, with exploration expenditure activity similar to the recession years of the early 1990s. Despite this, Western Australia still accounts for the major proportion of the exploration dollars expended in Australia on exploration for iron ore (100%), gold (72%), diamond (82%), base metals including nickel–cobalt (47%), and heavy mineral sands (28%).

A number of trends and issues affecting exploration are now clear. They include merger and acquisition activity, a swing away from greenfields exploration, difficulties in obtaining seed and venture capital for

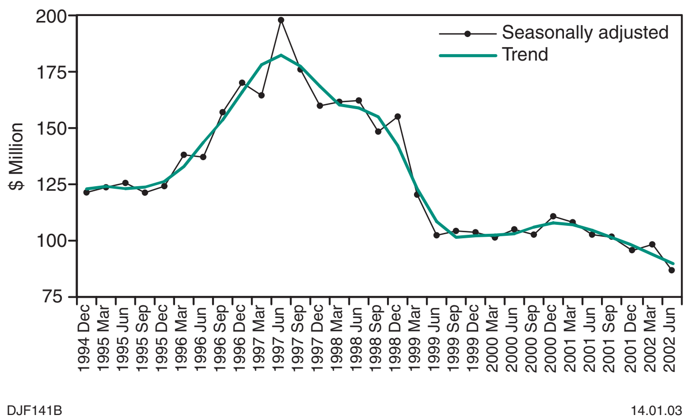

Figure 2. Mineral exploration expenditure in Western Australia, by quarter, on seasonally adjusted and trend terms (dollars of the day)

junior explorers, declining mining-company market capitalization, taxation, land access, Aboriginal heritage issues, and perceived investment risk.

Corporate rationalization, acquisitions, and mergers continued to dominate the mining industry, both nationally and internationally, but were down on the record levels of 2000–01 when more than $US60 billion of merger and acquisition activity occurred. Examples in 2001–02 include the acquisition of Normandy Ltd by Newmont Mining Corporation of America, Hill 50 Gold Mines by Harmony Gold Ltd of South Africa, AurionGold Ltd by Placer Dome Inc of Canada, and the in-progress acquisition of Lionore (Australia) Pty Ltd by Lionore International. WMC Ltd went against the current trend and plans to demerge its aluminium assets from the remainder of its core businesses.

Rather than targeting one sector of the minerals market, larger global companies are spreading asset acquisition across a number of metals, allowing diversification in the spread and depth of the mineral portfolio held by the individual companies. This spreading of risk has also been marketed as an attractive feature for investors. For example, in early 2002 Barrick advertized 'the lowest political risk profile of any major', whereas Newmont is understood to have 31% of its revenue obtained from 'politically sensitive areas' following the Normandy takeover; this is down from 42% pre-merger (Resource Stocks, 2002).

The result for the gold industry is a radical change in ownership — overseas control of Australia's gold production was 20% in 1995–96, 30% in 1999–2000, but rose to 60% in 2000–01 (Close, 2002). In contrast, the degree of ownership concentration within the copper and alumina sectors in 2002 is less than in the 1960s and 1970s.

A second trend in exploration expenditure is the steady fall in greenfields exploration. This is an important issue and is discussed in detail elsewhere in this volume in 'Declining greenfields exploration in Western Australia, 1996–2001'.

The number of junior exploration companies listed on the Australian Stock Exchange (ASX) has declined by 70% between 1997 and 2000 (from 270 companies to 80). This is a direct result of the lack of working capital, which remains a significant hurdle for juniors; the average cash reserve among explorers at the end of March 2002 was $2.1 million. A total of 95 listed mining-board companies held less than $1 million. Of these, 57 held less than $0.441 million, which was equivalent to the average cash requirements of a mining company to operate for a quarter. Amongst the 82 capital raisings in the March 2002 quarter, 39 brought in less than $0.5 million (Gonnella, 2002).

Market perceptions relating to mineral stocks also changed, and were well documented during 2001–02. For example, where the gold sector had comprised 7% of the ASX All Ordinaries Index in 1994, it was only 1% in 2001. Large investment-fund managers have used market index criteria (e.g. Dow Jones Index or TSE 300) as guides to investment in the mineral sector, and this has led to a decrease in the proportion of the metals, minerals, and gold sectors being represented in fund portfolios; from 20% in 1996 to only 5.5% in 2000 (Bogden, 2001; Brook and Alexander, 2001).

Another factor that leads to the exclusion of mining stocks from investment portfolios is the fact that the aggregate capitalization of all of the world's non-ferrous mining industry is still less than that of individual stocks such as General Electric or Microsoft. Therefore, most investment funds now require very little, if any, in the way of new mining equity to maintain their benchmark positions in mining stocks, leading to a dwindling of new capital that is available for mineral exploration.

Another issue contributing to the declining exploration expenditure in Australia is the continued perception of non-competitive taxation policies, compounded by the effect of Native Title issues on access to land.

Government inquiries into reduced mineral exploration

Both the Western Australian and Federal Governments recognize that the declining level of mineral expenditure is a major issue, and two parliamentary inquiries were commissioned during 2001–02.

In Western Australia, the State Government instigated a Ministerial Inquiry into greenfields exploration in Western Australia, chaired by Mr John Bowler MLA, Member for Eyre. The Bowler Inquiry is investigating numerous avenues that could be used to promote and increase levels of private investment in mineral exploration in Western Australia, particularly in greenfield or frontier areas. It will recommend actions that could be taken, particularly by the State and Federal Governments, to achieve a level of exploration that will sustain the resource sector's pre-eminent role in the Western Australian economy.

The Federal Government instigated a House of Representatives Inquiry, chaired by the Hon. Geoffrey Prosser MP, Federal Member for Forrest (WA). The Prosser Inquiry aims to identify impediments to increasing investment in mineral and petroleum exploration in Australia, including:

- An assessment of Australia's endowments of mineral and petroleum resources and the rates at which these are being drawn down;
- The structure of the resources industry and the role of small companies in resource exploration in Australia;
- Impediments to accessing capital, particularly by small companies;
- Access to land, including Native Title and cultural heritage issues;
- Environmental and other approval processes, including across jurisdictions;
- Public provision of geoscientific data by government agencies;
- Relationships with indigenous communities; and
- Contributions to regional development.

Mineral exploration expenditure by commodity and industry highlights

Within Western Australia, gold remains the main focus of mineral exploration (Fig. 3), accounting for about 63% of all exploration expenditure. Other commodities, in their order of importance as exploration targets in Western Australia, are base metals and nickel–cobalt (17%), diamond (8%), iron ore (5%), heavy mineral sands (2.5%), and others (4.5%).

Gold

Gold continues to be the main focus of mineral exploration expenditure in Western Australia, with $238 million expended during 2001–02. The slight recovery seen previously in 2000–01 was not sustained (Fig. 4), with expenditure declining in 2001–02 by 17% ($46 million). The level is now down 55% ($294 million) from the 1996–97 peak, and at a level equivalent to the base of the 1991–93 slump in exploration. Western Australia attracts 72% of the

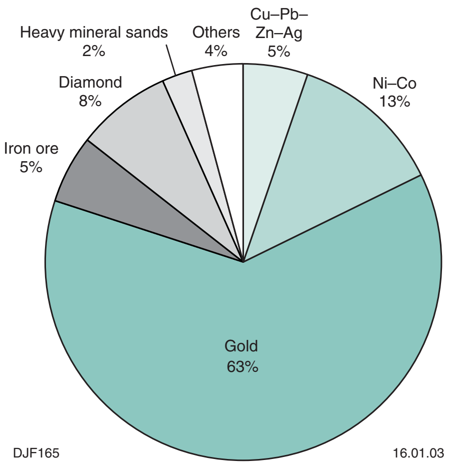

Figure 3. Mineral exploration expenditure in Western Australia, by commodity (2001–02 dollars).

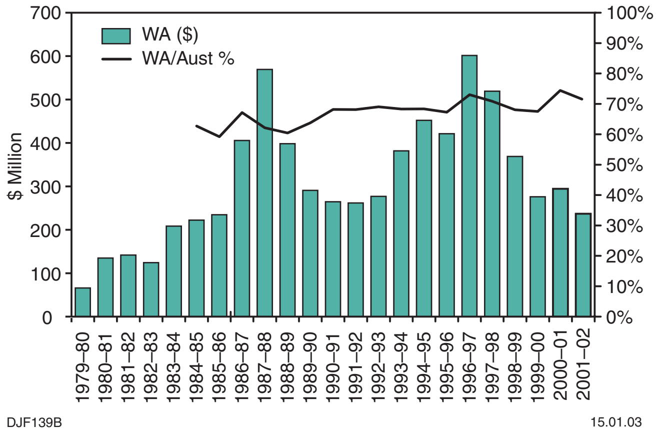

Figure 4. ***Gold exploration expenditure in Western Australia, by year (2001–02 dollars)***

total Australian gold exploration budget (down slightly from 74% in 2000–01), with these proportions (72–74%) being the highest since 1984–85, indicating a positive perception of the State's prospectivity.

Exploration highlights for the gold sector in 2001–02 show that despite the downturn in exploration activities since 1996–97, important discoveries are still being made. Selected highlights include:

- Recovery of alluvial gold at Striker Resource's 88 Creek prospect in the north Kimberley, within a larger area containing evidence of epithermal activity. This Oombulgurri area represents a new district of gold mineralization and has caused a major re-evaluation of the gold potential of the Kimberley Basin.
- Encouraging exploration results returned from the Ashburton joint venture, near Paraburdoo, of Newcrest Ltd and Sipa Resources International NL. Results include 14 m at 5.5 g/t Au from the Ibex prospect near Cairn Hill, 17 m at 3.5 g/t Au from 16 m at the Electric Dingo prospect, and 36 m at 2.2 g/t Au from 84 m at Cheela West. These promising discoveries have led to a minirenaissance of exploration within the underexplored Proterozoic Ashburton Basin.
- Multiple high-grade mineralized zones intersected at Newmont's Jundee mine during drilling of the Westside Lode structure. Reported intercepts included 4.4 m at 148 g/t Au and 5 m at 3288 g/t Au. The Jundee Westside discovery may be similar in tonnage and tenor to the major Barton Deeps orebody.
- An electromagnetic anomaly was identified at the Winston Churchill prospect (23 km west of Kalgoorlie), which is part of the Mungari East joint venture between Dioro Exploration NL and Mines and Resources Australia. A first-pass diamond drilling program intersected thick laminated quartz veins containing visible gold. Exploration is continuing to determine whether the mineralization represents a strike extension of the Raleigh trend being mined by AurionGold Ltd to the north.
- Reporting of previously unknown mineralization from the Westonia deposit in rock types not previously thought to be gold mineralized. Westonia Mines Ltd, part of the Lion Selection Group, is currently completing a feasibility study on Westonia.
- Depth extensions to the known Sandpiper resource in the Tanami area, owned by Tanami Gold NL and Barrick Gold. Drilling encountered mineralization that is interpreted to be a down-plunge extension of the known Sandpiper lenses, showing increases in both grade and width over the shallow Sandpiper intercepts.
- Continued reports from AngloGold Ltd of anomalous gold intercepts in the vicinity of the Coyote prospect (250 km southeast of Halls Creek).

AngloGold has defined 11 prospects within 20 km of Coyote and has a further 20 exploration targets within 20–50 km of the project.

- A similar geological setting to the 750 000 oz Goldrush deposit in the Northern Territory has been found by Barrick at the Finch prospect (270 km southeast of Halls Creek) in the Tanami area.
- Placer Dome Inc., the Binduli joint venture operator, reported discovery of a new mineralized corridor at Nefertiti, 400 m west of the existing Binduli line of openpits.
- Exploration drilling by AurionGold at the White Feather Reward prospect east of Kanowna Belle (20 km northeast of Kalgoorlie) returned 3 m at 70 g/t Au in the initial drillhole.

Development highlights for the gold sector during 2001–02 include increases in the resource inventories of a number of projects, rapid development from exploration target to operating mine, and the continued re-evaluation of previously subeconomic mineralization using alternative mining or extraction methods. Selected highlights include:

- A massive upgrade in resources at the Newcrest-owned Telfer mine to 26 Moz (808 t) of gold. The Telfer project now contains one of the largest gold endowments in Western Australia. Newcrest is continuing with a feasibility study into an expanded Telfer project whereby the company plans a 25-year mine life commencing operations in 2004, with a planned production rate of about 750 000 oz of gold per annum.
- Successful mining by Placer/Aurion of Wallaby (first ore production was in late 2001). Wallaby is now the cornerstone of the Granny Smith project, and production of around 400 000 oz is expected for 2002. A further expansion is planned for 2003.
- Commencement of mining operations in mid-2002 at the Thunderbox deposit (54 km southeast of Leinster), a joint venture between Dalrymple Resources NL (40%) and Lionore Mining International Ltd (60%). Total reserves are 10.89 Mt at 2.4 g/t Au.
- Mining commenced at Raleigh, part of the Kundana East joint venture, and a feasibility study continued on the possibility of underground mining as well.
- Mining of the White Foil deposit, 23 km southwest of Kalgoorlie, commenced in mid-2002.
- Mining of the Waugh deposit (36 km southeast of Paraburdoo) started in mid-2002, marking one of the most rapid transitions from exploration discovery to mine — the deposit was discovered in November 2001.
- Commencement of mining at Minjar (50 km southeast of Yalgoo) in December 2001. Gindalbie Gold NL has produced over 1 t of gold from the project by late 2002, and further pits are under development.
- The private company Whinnen Gold Pty Ltd commenced mining of the Whinnen Shoot, part of the Hamill Resources-owned Mount Ida project (80 km northwest of Menzies) in mid-2002.
- In November 2001, Barra Resources Ltd commissioned the First Hit mine (145 km northwest of Kalgoorlie). However, the high-grade Kylies lode performed under expectations, and total production was 0.11 Mt at 7.47 g/t Au.
- The Boddington gold mine (12 km north of Boddington) was placed on indefinite care-and-maintenance in December 2001, but the joint venture partners (Newcrest Mining Ltd 22%, AngloGold Ltd 33%, and Newmont Mining Corporation 44%) obtained regulatory approvals for the $500 million Boddington Expansion (Wandoo) project.
- Plans by the Coolgardie joint venture (Mining Project Investors, Pittson Mineral Ventures of Australia Pty Ltd, and Herald Resources Ltd) to recommence underground mining of the Empress deposit and opencut mining of Lindsays pit.
- Completion of a feasibility study by Equigold NL into the development of the Kirkalocka deposits (100 km southeast of Mount Magnet). First production is expected in late 2002.

- Detailed project design and tendering activities by St Barbara Mines Ltd are in progress for the Paulsen project (180 km west of Paraburdoo). The total resources at Paulsen are 3.97 Mt at 4.5 g/t Au, and would support a five-year mine life.
- A feasibility study has been commissioned into openpit and underground mining of the Frogs Legs deposit, 22 km east of Kalgoorlie. Resources total about 3.2 Mt averaging 5.8 g/t Au.
- Pit optimization studies leading to a bankable feasibility study are underway at Mount Gibson (280 km north of Perth); Oroya Mining Ltd expects to recommence production in mid-2003.

During 2001–02, Western Australia produced 184.9 t of gold, valued at $3.279 billion. This represented a decrease in quantity of production of 16.3 t from 201.2 t in 2000–01, but a slight increase in value (by $34 million) from $3.245 billion in 2000–01. A list of the top-ten gold producers (by production) in Western Australia is presented in Table 1. The largest producers include KCGM Ltd at Golden Mile – Kalgoorlie; Gold Fields Ltd at St Ives – Kambalda; Placer Dome Inc/AurionGold Ltd at Granny Smith, Kanowna Belle, and Paddington; Newmont Mining Corporation at Jundee–Nimary; AngloGold Ltd at Sunrise Dam; and Sons of Gwalia Ltd at Marvel Loch – Southern Cross. Collectively, these produced 108.98 t of gold during 2001–02, representing 59% of the State's gold output.

Base metals and nickel–cobalt

Exploration expenditure for base metals (including nickel and cobalt) fell by 25% ($20.4 million), from $82.5 million in 2000–01 to $62 million in 2001–02. This is the fourth consecutive year of decline in base metal exploration, with expenditure down by about 52% ($55 million) since the 1996–97 peak. Nickel–cobalt exploration expenditure fell by 26% ($19.1 million) from $72.8 million in 2000–01 to $53.7 million in 2001–02. Exploration for the base metals copper, lead, and zinc fell by 19.6% ($32.5 million), from $165.4 million in 2000–01 to $132.9 million in 2001–02.

During 2001–02, Western Australia received 47% of the Australian base metal exploration budget, up slightly from 44% in 2000–01. This increase can be attributed to higher expenditures on the new discoveries of nickel sulfide and volcanic-hosted massive sulfide mineralization reported during the year.

These exploration successes include:

- The brownfields success of Pilbara Mines Ltd and Inmet Mining Corporation at the Jaguar deposit, 4 km south of the historic Teutonic Bore base metal mine (operational during 1980–85). Jaguar is a previously unknown volcanogenic massive-sulfide (VMS) system, and the discovery drillhole intersected a thickness of 7.7 m of massive sulfide mineralization assaying 4.3% Cu, 16.1% Zn, and 173 g/t Ag at 450 m drilled depth.

Table 1. Top-ten gold mining operations in Western Australia by production (2001–02)

Ranking	*Mine*	*Owner*	*Production 2001–02 (t Au)*	*Ranking 2000–01*	*Production 2000–01 (t Au)*	*% Change in production*
1	Golden Mile – Kalgoorlie	KCGM Ltd	21.79	1	25.77	-15
2	Kambalda – St Ives	Gold Fields Ltd	16.01	2	13.60	+18
3	Granny Smith	Placer Dome Inc/AurionGold Ltd	13.01	4	9.81	+33
4	Jundee–Nimary	Newmont Mining Corp	11.07	3	12.79	-13
5	Sunrise Dam	AngloGold Ltd	10.11	6	8.45	+20
6	Plutonic	Barrick Gold Corp	8.74	5	8.84	-1
7	Bronzewing – Mount McClure	Newmont Mining Corp	8.50	8	8.10	+5
8	Kanowna Belle	AurionGold Ltd	7.10	7	8.40	-15
9	Paddington	AurionGold Ltd	6.57	16	4.45	+48
10	Marvel Loch – Southern Cross	Sons of Gwalia Ltd	6.08	17	4.41	+38

- Further exploration successes reported by Newmont Mining Corporation at Golden Grove (230 km east of Geraldton), with the discovery of base metal, gold, and silver sulfides in a number of stacked, high-grade lenses at the Ethel, Zeewijk, and Hougoumont zones.
- Discovery of disseminated and fault-hosted massive nickel-sulfide mineralization by Dalrymple Resources NL at the Waterloo prospect, 48 km southeast of Leinster. The discovery drillhole returned an intercept of 10.68 m at 4.83% Ni.
- An upward revision of resources at the Fossil Downs Zn–Pb deposits following recent diamond drilling. The Fossil Downs project, about 20 km north of the Pillara minesite and within the Lennard Shelf, is owned by Western Metals Ltd.
- Outokumpu Zinc Australia Pty Ltd completed a feasibility study on the Sulphur Springs (Panorama project) VMS zinc–copper deposit (52 km west of Marble Bar).
- Significantly enhanced tonnages of nickel and cobalt resources reported from Acclaim Exploration NL's large lateritic deposit at Wingellina in the Musgrave Complex (240 km east of Warburton).
- Identification by Jubilee Mines NL of nickel sulfide mineralization at the Babylon prospect (65 km northwest of Leonora). The discovery drillhole intersected 0.9 m at 2.6% Ni from 118.8 – 119.7 m located within an identified komatiite lava channel.
- At the Bow River prospect (140 km southwest of Kununurra) in the Kimberley, Valdera Resources Ltd reported low-grade Ni–Cu intercepts, up to 20 m thick, of disseminated, stringer, and massive nickel sulfides.
- WMC Ltd reported further disseminated nickel-sulfide mineralization within the Babel–Nebo zone at the Gerar prospect (760 km northeast of Kalgoorlie) in the Musgrave Complex.
- Western Areas NL identified a new zone of nickel sulfide mineralization in the footwall zone at New Morning, in the Forrestania greenstone belt (114 km southeast of Marvel Loch). Assay results from the discovery intersection included 1.7 m at 4.1% Ni from 299.6 m.

The development highlights of the year 2001–02 included:

- Production of nickel ore recommenced at the Long–Victor complex, near Kambalda. Independence Gold NL purchased the operations from WMC Ltd in 2002.
- Lionore Australia NL decided to develop the Maggie Hays nickel deposit (110 km west of Norseman) within the Forrestania greenstone belt. The existing plant at the Emily Ann mine will be expanded to 500 000 tpa capacity.
- Underground development commenced at Western Metal Ltd's Zn–Pb deposit at Kapok West on the Lennard Shelf (76 km southeast of Fitzroy Crossing).
- The solvent extraction plant at the Nifty copper mine (located 350 km east of Port Hedland, and operated by Straits Resources) was upgraded to a nameplate capacity of 25 000 tpa. Other metallurgical modifications to the Nifty process resulted in increased recoveries and additional ore sources identified.
- A feasibility study on mining sulfide ore from the Nifty deposit was commissioned. The study is also to include an evaluation of mining of the Maroochydore copper deposit, 60 km southeast of Nifty.
- An updated feasibility study was completed by Straits Resources on the Whim Creek and Mons Cupri copper deposits (90 km east of Roebourne), with plans to utilize plant and equipment from the company's Nifty and Girilambone operations.
- Completion of a feasibility study into mining the Panorama – Sulphur Springs polymetallic VMS deposits (59 km west of Marble Bar). The Panorama project is a joint venture between Outokumpu Zinc Australia Pty Ltd and Sipa Resources International NL.

- The Magellan lead mine (30 km west of Wiluna) is under construction. The project is a joint venture between Ivernia West Inc of Ireland and the unlisted Australian company Magellan Metals Pty Ltd. Capital costs of development are estimated at $44 million.
- Tectonic Resources NL plans to mine the Trilogy shale-hosted, copper–gold–silver–lead–zinc deposit (18 km southeast of Ravensthorpe).
- BHP Billiton completed a feasibility study on the Ravensthorpe nickel laterite project (16 km east of Ravensthorpe). The company was awaiting confirmation that new low-pressure leach technology could work effectively in economically extracting nickel and cobalt.
- The feasibility study on the Sally Malay nickel sulfide deposit (105 km northeast of Halls Creek) was completed by Sally Malay Mining. The project will commence as an opencut operation, and proceed later to underground mining. Ore is to be treated using conventional technology to produce a bulk Ni–Cu–Co concentrate to be exported from Wyndham and be treated at Jinchuan Group Ltd smelter–refinery complex in China.
- Titan Resources NL purchased nickel sulfide deposits in the North Widgiemooltha block (47 km south of Kambalda) from WMC. The company also acquired nickel sulfide deposits at the Carr Boyd Rocks property (71 km southeast of Menzies) from Defiance Mining NL.
- A consortium of Mining Project Investors Pty Ltd (80%) and the OM Group (20%) acquired the Black Swan (45 km northeast of Kalgoorlie) and Honeymoon Well (37 km southeast of Wiluna) nickel sulfide projects in mid-2002;
- Fox Resources Ltd acquired nickel sulfides at the Radio Hill mine (closed) and the nearby Mount Sholl deposit (30 km southeast of Karratha) from Titan Resources.
- Mincor Resources NL purchased the closed Wannaway nickel mine (47 km southeast of Kambalda) from WMC.
- Anaconda Nickel NL completed metallurgical testwork on nickel laterite and preliminary designs for a 30 000 t trial pit at Heron Resources Ltd's Goongarrie South project.
- WMC Ltd announced long-term development of the Yakabindie nickel sulfide deposit to supplement ore from the Mount Keith operations.

During 2001–02, Western Australian mines produced about 195 000 t of nickel (as refined nickel, or as contained nickel in nickel matte and concentrate), with sales valued at $2.0 billion. About 20% of the nickel was obtained from lateritic nickel deposits, and WMC accounted for about 103 500 t (53%) of mine production. The State's top-ten nickel operations and their operators are shown in Table 2. Sales of byproduct cobalt during 2001–02 were 4 500 t valued at $133 million.

Table 2. Top-ten nickel operations in Western Australia by mine production (2001–02)

Ranking	*Mine*	*Owner*	*Production (t)*
1	Mount Keith	WMC Ltd	45 850
2	Leinster	WMC Ltd	38 405
3	Murrin Murrin	Anaconda Nickel Ltd	28 651
4	Silver Swan	Outokumpu Oyj	(a) 21 828
5	Kambalda	WMC Ltd	19 337
6	Cosmos	Jubilee Mines NL	10 809
7	Miitel	Mincor Operations Ltd	7 759
8	Bulong	Preston Resources NL	6 409
9	Radio Hill	Titan Resources NL	5 168
10	RAV8	Tectonic Resources NL	3 260

NOTE: Production data sourced from company quarterly reports to Australian Stock Exchange
(a) Silver Swan figures reported on a calendar year, not financial year. Figures are production for 2001

Table 3. Top-three base metal operations in Western Australia by mine production (2001–02)

Ranking	*Mine*	*Owner*	*Production*		
			Cu (t)	*Pb (t)*	*Zn (t)*
1	Lennard Shelf	Western Metals Ltd	–	69 833	182 237
2	Golden Grove	Newmont Mining Corporation	26 069	[a]2 455	57 329
3	Nifty	Straits Resources Ltd	22 338	–	–

NOTE: Production data sourced from company quarterly reports to the Australian Stock Exchange
(a) Lead production reported for first half of 2001–02 only

The total value of copper, lead, and zinc production for Western Australia during 2001–02 was $337 million. Zinc dominated production, representing 51% of the total value. Zinc production dropped in quantity from 236 089 t (2000–01) to 223 669 t (2001–02), with a commensurate fall in the value of production from $280 million to $173 million respectively. Table 3 summarizes the mine production details for the top-three base metal producers in Western Australia — Western Metals (Lennard Shelf), Newmont Mining Corporation (Golden Grove), and Straits Resources (Nifty).

Diamond

Diamond exploration in Western Australia increased by $4 million (15%) to $30 million in 2001–02. About 82% of Australia's diamond exploration budget was expended in the State, mainly in the Kimberley region. The increase is due in part to:

- Commissioning by Kimberley Diamond Company NL of the State's second diamond mine at Ellendale (90 km northwest of Fitzroy Crossing). An 11.47 carat yellow octahedral diamond was recovered in 2002, and represents the largest diamond ever recorded from the Ellendale field. Mining is forecast to continue at 657 000 tpa for 2–3 years from the near-surface zones of the Ellendale 4 and 9 pipes. The first 15 months of production was expected to return about $56 million;
- Increased exploration expenditure by companies utilizing BHP Billiton's patented Falcon airborne gravity system.

Mine production of diamond in Western Australia for 2001–02 was 30.5 million carats, with Rio Tinto Ltd the only producer (Table 4). Diamond sales were valued at $489 million. Kimberley Diamond Company NL commenced production at Ellendale in mid-2002, with mine production of 4320 carats in July–August 2002.

Iron ore

During 2001–02, iron ore exploration within the State fell by 11% ($3 million), from $23 million in 2000–01 to $20 million in 2001–02. A combination of factors was responsible, including the collapse of the Kingstream Steel consortium, apparent lack of significant progress by the Austeel consortium

Table 4. Western Australia diamond production (2001–02)

Ranking	*Mine*	*Owner*	*Production (carats)*
1	Argyle	Rio Tinto Ltd	[a]30 563 000
2	Ellendale	Kimberley Diamond Co NL	[b]4 320

NOTE: Production data sourced from company quarterly reports to the Australian Stock Exchange
(a) Production includes both AK1 and alluvial diamond sources
(b) Production for first 5.5 weeks of opearation in 2002, equates to August 2002 production

that is developing the Fortescue deposits, and the uncertainty over the development of the Hope Downs deposits, where access to railway infrastructure remains contentious. However, there were some very significant positive developments during 2001–02.

Development highlights of the year included:

- Opening of the West Angelas mine (110 km west of Newman) in mid-2002. The West Angelas operation, owned by Robe River Iron Associates, comprises an openpit mine, an ore processing plant producing lump and fine ores, stockpiles, reclaimers, and train-loading facilities. Ore production commenced in April 2002. The mine is producing at an initial 7 Mtpa, which is expected to rise to approximately 20 Mtpa by 2005. The West Angelas operation represents a new phase in Western Australian iron ore mining as the first to market Marra Mamba iron ore as a stand-alone product.
- Signing of a joint-venture agreement between Hamersley Iron (Rio Tinto) and China's largest steel maker, Shanghai Baosteel Group Corporation (Baosteel), to form an unincorporated iron ore joint-venture operation in which Hamersley Iron will supply Baosteel with a total of 200 Mt of iron ore products, averaging 10 Mtpa over the joint venture's 20-year life. The arrangement includes the development of a new mine (Eastern Ranges), 10 km east of Hamersley's established Paraburdoo mine, with an initial capital outlay of $124 million (US$64 million).
- Agreement by Rio Tinto to continue development of the HIsmelt direct smelting project at Kwinana.
- $100 million expansion plans announced by Portman Ltd. These included upgrading of the Esperance harbour facilities and commissioning of a feasibility study to develop the Windarling and Mount Jackson deposits about 130 km north of Southern Cross.
- Agreement by Portman Ltd to extract a further 4 Mt of ore from below sea level at Cockatoo Island in the west Kimberley.
- Aztec Resources is evaluating the feasibility of recommencing iron-ore mining operations at Koolan Island in the west Kimberley.
- A study by Mount Gibson Iron Ltd into the feasibility of mining Tallering Peak (following its purchase from Kingstream Steel Ltd) and exporting shipping-grade hematite from Geraldton.

During 2001–02, Western Australia produced 159.79 Mt of iron ore, valued at $5.098 billion, of which 94% was exported. This represented a slight decrease in quantity of production (1.98 Mt), but a slight increase in value of production ($0.19 billion), from 2000–01. The major producers and their approximate share of production are BHP Billiton (42%), Rio Tinto Ltd (37%), Rober River Iron Associates (17%), and Portman Ltd (3%).

Heavy mineral sands

Mineral sand exploration in Western Australia had declined in the period 1997–2001 in response to the change in focus by explorers to the Murray Basin in Australia's eastern states. During that time, Western Australia was regarded as a mature exploration area for heavy mineral sands, hence Western Australia's share of the Australian exploration expenditure for heavy minerals fell steadily — from 69% in 1994–95 to only 28% in 2001–02. However, exploration expenditure on mineral sands in Western Australia during 2001–02 increased by 17% ($1 million) from $8 million to $9 million.

Nissho Iwai Corporation of Japan advised during 2001–02 that it was considering divestment of its Australian subsidiary, RZM Cable Sands (WA) Pty Ltd, which has operations at Sandalwood, Jangardup, and Yarloop and a dry-separation plant at Bunbury.

Activity highlights for the year included:

- Opening of the $30 million Dardanup mine (17 km east of Bunbury) owned by Doral Mineral Industries. The mine is expected to produce about 110 000 tpa of ilmenite and 10 000 tpa each of leucoxene and zircon over a planned nine-year mine life.

- Completion of a prefeasibility study on the Dongara project (26 km southeast of Dongara) owned by Magnetic Minerals NL. Ticor were undertaking due diligence on the deposit in late 2002.
- Plans by Cable Sands to develop the Jangardup South mineral sands deposit (45 km east of Augusta) were given a boost when a Native Title agreement was signed, following two years of negotiation, with the Boojarah people.

During 2001–02, Western Australia produced 1.87 Mt of heavy mineral sands (ilmenite, upgraded ilmenite or synthetic rutile, rutile, staurolite, leucoxene, and zircon, but excluding garnet) valued at $848 million. Lower pigment prices, together with excess inventory, maintenance shutdowns, and commissioning problems, led producers to be below 2000–01 production figures, when a total of 2.24 Mt of heavy mineral sands valued at $904 million were produced.

Tantalum

The fall in the tantalum price during 2001–02, due to disputes between end-purchasers of tantalum product, has affected exploration expenditure and caused several planned mining operations to be shelved.

Sons of Gwalia Ltd, which had committed to a $70 million expansion of the Greenbushes project (15 km northwest of Bridgetown) in 2000, saw the mine expansion opened by the Minister for State Development, Clive Brown, in 2002. Production capacity is now a nameplate 1.25 million pounds of Ta_2O_5 per annum. A similar upgrade in plant capacity, from 0.8 to 1.1 million pounds per annum, at a cost of $35 million, was made for Sons of Gwalia's Wodgina operation (110 km south of Port Hedland). Haddington International Resources Ltd commenced production from its Bald Hill mine (60 km southeast of Kambalda) in 2001, with all of the concentrate from a 200 000 tpa throughput being sold to Sons of Gwalia.

Two producers, Sons of Gwalia (at Greenbushes and Wodgina) and Haddington International Resources Ltd (at Cattlin Creek and Bald Hill) were responsible for the State's 905 t of tantalite output.

Platinum–palladium

Western Australia produces small quantities of platinum and palladium as byproducts from nickel-sulfide mining operations in the Eastern Goldfields. During 2001–02, two independent platinum–palladium projects advanced to feasibility status.

- Platinum Australia Ltd finished its prefeasibility study on the Panton project (52 km north of Halls Creek), which indicated robust project economics. The company is undertaking pilot plant testing on, and metallurgical evaluation of, ore sourced from an exploration decline.
- Helix Resources Ltd completed a scoping study on its Munni Munni project (40 km south of Karratha) and is currently drilling to evaluate additional resource potential along strike of the Ferguson Reef within the Munni Munni layered mafic intrusion. A decision on proceeding to a full feasibility study will be made in late 2002 or early 2003.
- Surface assays up to 108 g/t platinum, 70.2 g/t palladium, 119 g/t gold, 2700 g/t silver, and 8% copper were reported by Western Areas NL and Wedgeside Pty Ltd at the Copper Hills project (350 km east of Newman).

In 2001–02, production of platinum and palladium as byproducts from nickel–cobalt mining operations was 828 kg and 144 kg respectively, valued at $24 million.

Mineral tenement activity

In general, the trends in mineral exploration expenditure were also reflected in the 2001–02 mineral tenement statistics. For all tenement types under the Mining Acts of 1904 and 1978, the area under tenure has increased slightly (1%) from 23.8 million hectares in 2000–01 to about 24 million hectares in 2001–02. However, the number of tenements in force decreased by 5% (839 tenements) to 16 487 tenements, reversing the moderate increase of 2000–01 (Fig. 5).

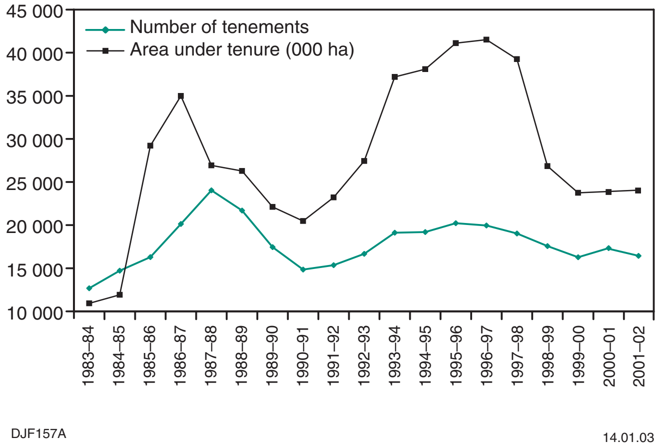

Figure 5. Tenements in force (1904 and 1978 Mining Acts)

The tenement data indicate declining numbers of large greenfields exploration licences. Although the decline partially stabilized in 2000–01, it appears to have restarted.

Figure 5 illustrates that the area held under tenure in Western Australia is currently at a level similar to the previous recession in mineral exploration of the early 1990s. This is interpreted to be largely the result of two factors. Firstly, there have been lengthy delays in progressing many tenement applications through the Native Title process, with a total of 11 802 tenement applications (including 5152 mining leases, 3703 exploration licences, and 2489 prospecting licences) outstanding and yet to be granted as at 30 June 2002. This is an increase of 80% over the last five years, corresponding to an average increase of 12.5% per year. Secondly, there have been large reductions in greenfields exploration; this aspect is discussed in detail elsewhere in this volume in 'Declining greenfields exploration in Western Australia, 1996–2001'.

Drilling activity

Drilling activity has declined markedly since the peak of exploration in 1996–97, demonstrating that cutbacks in exploration budgets have adversely impacted on all types of drilling (Fig. 6). Rotary air blast (RAB), reverse circulation (RC), and diamond drilling have now declined by about 80, 65, and 65% respectively since their peaks in 1996–97 or 1997–98. RAB drilling was the first to be affected when companies began cutbacks to expenditure

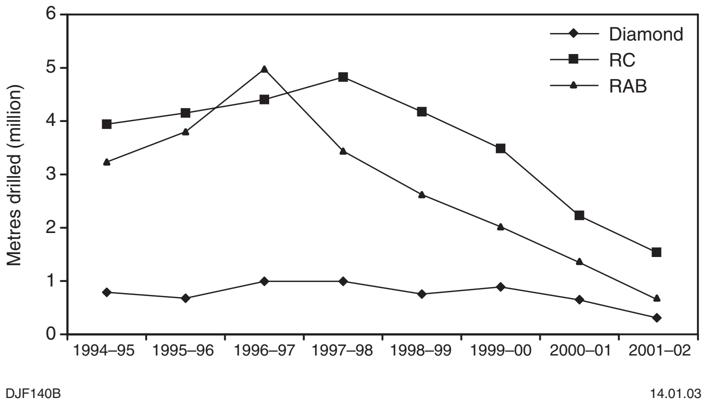

Figure 6. Mineral exploration drilling in Western Australia, by drilling type and year

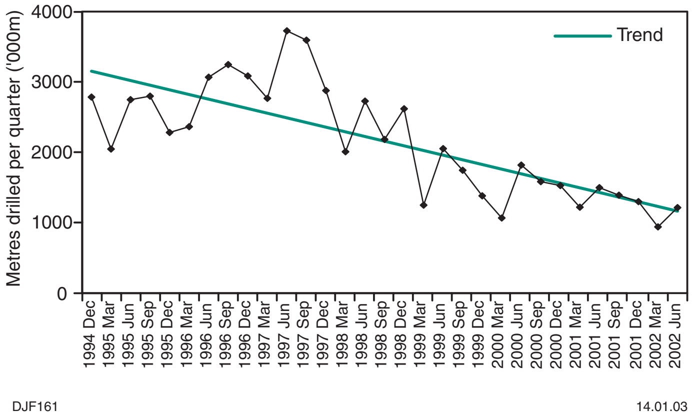

Figure 7. Australian mineral exploration drilling, by quarter

and moved away from grassroots greenfields exploration. This reduction in RAB drilling was followed one year later by declining RC drilling, as expenditure cuts deepened. RAB and RC drilling continued their decline during 2001–02, and have now been joined by a decrease in diamond drilling during 2001–02.

The falls in 'metres drilled' from earlier peak levels in 1996–97 show a more dramatic trend in reduced exploration activity than the more general fall shown in the overall trend for exploration expenditure. The decline of up to 80% in metres drilled since the peak of the boom should be compared with the corresponding drop of 'only' 45% in total exploration expenditure.

Recent quarterly data from the Australian Bureau of Statistics show that the downward trend in drilling activity is still firmly in place and does not show any sign of levelling off (Fig. 7). That data, which includes mineral exploration drilling of all types, both on production and non-production leases, shows that mineral exploration drilling in Australia has declined by 75% (2.79 million metres) since mid-1997.

Such declines in drilling activity greatly reduce the opportunities for significant discoveries that are necessary to boost mineral resource inventories, sustain the current level of mining development, and provide opportunities for growth in the industry.

Mineral resources

The substantial resources of major mineral commodities produced in Western Australia are listed in Table 5.

The State's inventory of measured and indicated gold resources increased by 552 t (13.8%) to 4551 t during 2001 (Fig. 8). The increase is primarily due to one resource upgrade — that by Newcrest for Telfer. Other increases in the measured and indicated resources are from resource upgrades at some of the existing operating mines, and from the conversion of some inferred resources to the measured and/or indicated category for a number of companies. The latter is evident in some company floats during 2001 and early 2002, where older resource estimates have been 'reworked' as part of the company float. When the Telfer resource increase is excluded from the data, there is no net increase of gold contained within measured and indicated resources for Western Australia during 2001; contained gold would have declined by about 10 t.

Gold contained within the inferred resource category decreased by 96 t (5.0%) to 1834 t during 2001, primarily due to resource upgrades at some of the existing operating mines and deposits (especially Telfer), as discussed above. The decrease in inferred resources of contained gold would have been substantial (more than 400 t) without the large boost from the revised resource estimate for Telfer.

Table 5. Estimates of mineral resources for major commodities in Western Australia

Commodity	*Units*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*
Measured and indicated resources							
Iron ore (high grade)	Mt	21 960	22 539	22 407	22 282	22 316	14 892
Gold	t	3 009	3 376	3 496	3 752	3 999	4 551
Bauxite ore	Mt	3 359	3 386	3 387	3 387	3 194	3 194
Mineral sands	Mt	128.9	163.4	208.7	208.7	215	216
Nickel	Mt	10.73	13.41	16.77	20.23	17.44	17.90
Diamond (industrial + gem)	Mct	140	177	534	534	646	614
Inferred resources							
Iron ore (high grade)	Mt	10 466	10 382	10 525	10 587	12 796	16 288
Gold	t	1 295	1 549	1 750	1 807	1 930	1 834
Bauxite ore	Mt	1 326	1 314	1 314	1 314	1 314	1 314
Mineral sands	Mt	52	53	73	73	68	70
Nickel	Mt	6.96	10.58	10.15	11.68	15.94	14.96
Diamond (industrial + gem)	Mct	86	59	59	59	34	33

NOTE: Data sourced from the MINEDEX database. Information nominally as at 31 December for year shown, but data extracted from the MINEDEX database on 30 June in following year
For iron ore and bauxite, it is the quantity of resources that is shown. Only high-grade iron ore resources are included. High-grade iron ore is based on iron content only, but cut-off grade (55% or 60% Fe) depends on mineralization type
For heavy minerals, the total of all heavy minerals is shown
For all other commodities, it is the contained element/mineral in the resources that is shown
t Tonnes
Mt Million tonnes
Mct Million carats

The net increase in gold contained within measured and indicated resources and reserves corresponds to an average discovery cost for 2001 of $A12 per ounce (Table 6). If inferred resources are also included, then the average discovery cost rises to about $A13 per ounce as there was a net decrease in gold contained within inferred resources.

During the last decade, gold production in Western Australia has ranged between 182 t and 238 t per year, with peak production in 1997. Since then, gold production has declined steadily, with only 191.7 t produced during 2001. Annual gold production in Western Australia has declined by 46 t (almost 20%) since 1997.

Re-estimation of mineral resources at some of the major nickel mines and deposits has led to an increase of nickel contained within measured and indicated resources of 459 kt, but with a decrease of 977 kt of nickel contained within inferred resources. Figure 9 clearly illustrates that nickel sulfide

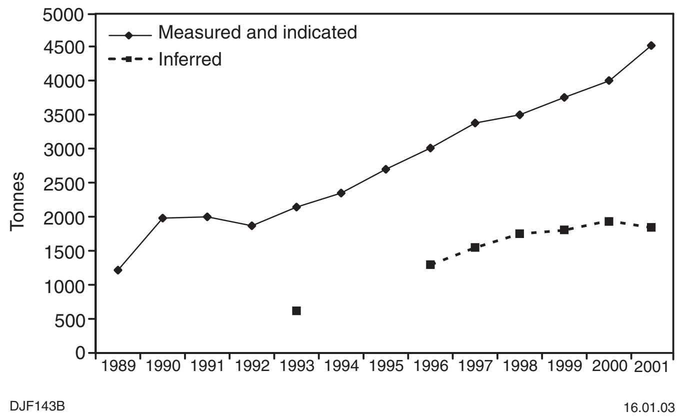

Figure 8. Estimates of gold resources in Western Australia, by year

Table 6. Gold discovery costs per ounce of measured and indicated resources, Western Australia [(a)]

Year	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*
Cost ($A) per ounce discovered	21	28	22	26	26	30	17	20	12

NOTE: (a) This includes any resources converted to reserves, but does not include inferred resources. Discovery costs are in dollars of the day

resources in Western Australia have remained essentially static for the period 1996–2000, and that the increase has been for nickel contained in laterite deposits.

Much of the State's nickel resources are within projects that are not currently economic and many of these are nickel laterite deposits. Consequently, it is difficult to assess what the future production might be in the medium term. The unresolved issue is obviously the technical and financial viability of mining lateritic nickel deposits, which contain 58% of the State's nickel in measured–indicated resources and reserves and 71% of the nickel contained within inferred resources.

Current reserves for lateritic nickel projects total 446 kt of contained nickel, sufficient for an industry 'mine life' of about 12 years at current production rates for the laterite sector. However, the low average grades of the resources (measured, indicated, and inferred), at only 0.76 – 0.93% Ni, suggest that many deposits may not be economic without further technological advances or sustained higher prices for nickel, although small selected (high-grade) portions of the deposits may be economically extracted.

The situation for nickel sulfide resources in Western Australia is similar, with an average grade that is very low — in the range of 0.63 to 0.90% Ni, and where the total of measured and indicated resources is smaller than the total reserves. Although the total proven and probable reserves are high, the figures are dominated by the reserves at WMC's opencut mines at Mount Keith, which contain 70–75% of the proven and probable reserves. The reserves at Mount Keith have marginal grades of only 0.53 – 0.58% Ni, whereas remaining reserves at underground nickel mines elsewhere in Western Australia typically have grades of over 3% Ni.

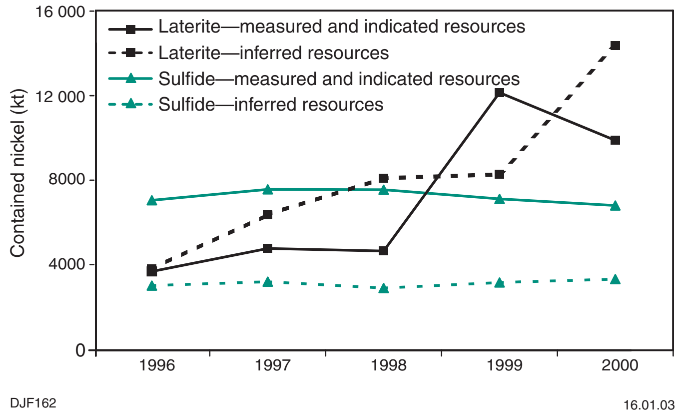

Figure 9. Total contained nickel in resources, Western Australia, by mineralization style and resource type

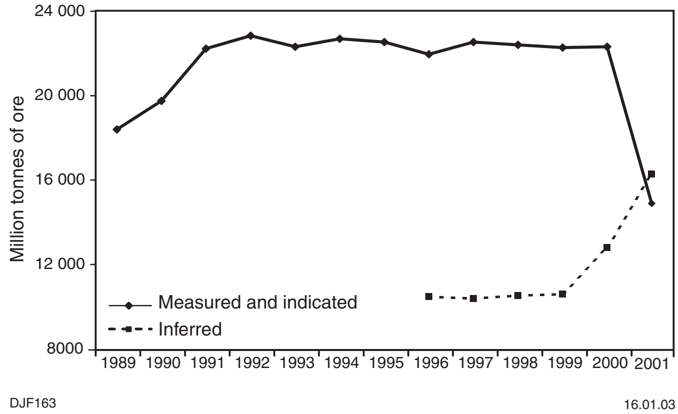

Figure 10. Total iron ore resources in Western Australia, by year

Western Australia's high-grade iron ore resources in the measured and indicated category plunged by 7424 Mt (33%) during 2001, falling to 14 892 Mt (Fig. 10). Conversely, inferred resources of iron ore increased, but by a smaller amount of 3492 Mt to 16 288 Mt, an increase of 27%. Several factors combined to produce this result. These include:

- Companies now use the current JORC code for reporting resources.
- Elimination of 20 to 30 year-old resources that companies no longer regard as part of the official resource base.
- MPR obtaining extensive new JORC-compliant estimates from the major producers Rio Tinto Ltd and BHP Billiton.
- MPR conducting a thorough update and audit of the resources in MINEDEX, including MPR eliminating double counting of some of the resource estimates in MINEDEX.

For other commodities (diamond, bauxite, and heavy mineral sands) resources have remained essentially unchanged during 2001–02 (Table 5).

Mineral production

Following the record values for mineral and petroleum production in Western Australia during 2000–01, production values contracted by 5% to $26 billion during 2001–02. Given the poor global commodity prices, slow world growth, and the extraordinarily high production values recorded in the period 1999–2001, the State's achievement is still remarkable. Between 1990–91 and 2001–02, there has been an average annual growth rate of 8.1% per annum in the value of mineral and petroleum production. This represents a doubling of the value of production every ten years, which far outstrips the general growth of the economy. The overall rise in production values since 1993–94 (assisted by the fall in the Australian dollar) is illustrated in Figure 11.

The gold sector experienced more buoyant prices that translated to a small sales-value increase, despite an 8% drop in sales volumes to 5.9 million ounces. Similarly, iron ore sales increased in value, thanks to higher prices from an earlier round of negotiations between producers and consumers. Lower international prices for nickel, diamond, alumina, and base metals translated to these commodities showing decreased, or at best static, sales values for 2001–02, despite increases for the quantity of sales.

Western Australia continues to be a very significant producer of the following minerals and mineral products (an estimate of the proportion of world production is shown in brackets) — diamond, including industrial diamond (38%), zircon (32%), tantalite (25%), rutile (24%), ilmenite (20%), alumina (20%), iron ore (14%; also has 34% of the world seaborne trade), nickel (14%), gold (8%), and vanadium (7%).

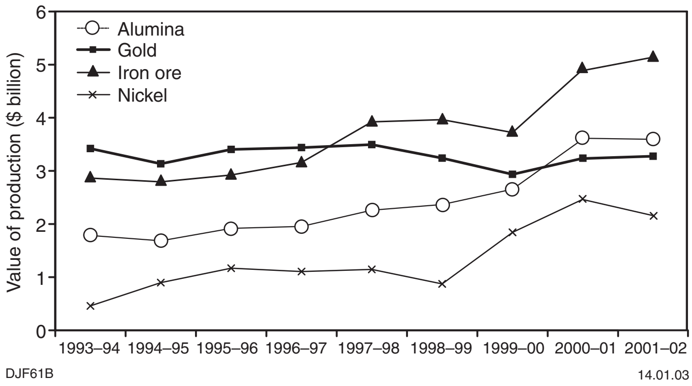

Figure 11. Comparative value of mineral production for major commodities in Western Australia, by year (dollars of the day)

Exploration expenditure versus the value of production

Each of the main commodities produced in Western Australia shows a characterisitic profile when the proportion of production value is compared to exploration expenditure. This relationship is sufficiently consistent in many cases to be a good predictive tool. Figure 12 illustrates the relationship for gold, base metals (including nickel–cobalt), heavy mineral sands, iron ore, and diamond. All of these commodities, except diamond, are exhibiting low points in the period 1999–2000 to 2001–02.

The gold sector stands out as being the most active in funding ongoing exploration, with about 7–8% of production value returned to exploration even in recessionary times, and up to 16% during boom times (Fig. 12). However, the level of exploration expenditure necessary to sustain the gold industry in Western Australia may be about 10% of the value of gold production (for further details see the Western Australian Government's submission to the 2002 Prosser Inquiry).

Expenditure on base metal (including nickel–cobalt) exploration, relative to the value of production, is now only 2.5% — by far the lowest level since 1991–92 (Fig. 12). Much of the fall in exploration over the last few years reflects lower expenditures that followed after the completion of feasibility studies and the commissioning of various nickel-laterite projects, some of which have experienced technical and financial problems.

Expenditure on diamond exploration, relative to the value of production, has fluctuated between 3.5 and 10% during the last decade (Fig. 12). The

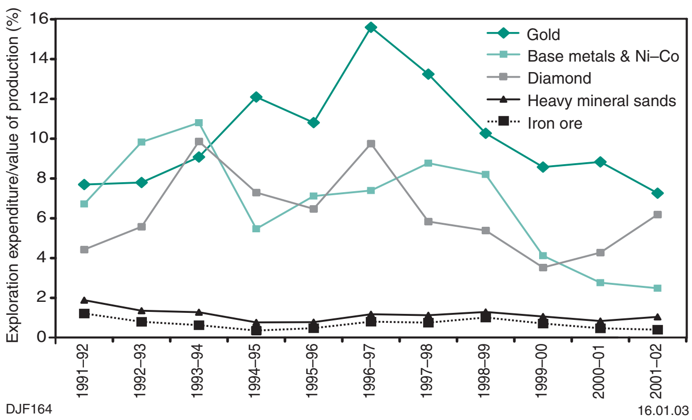

Figure 12. Exploration expenditure relative to the value of mineral production for major commodities in Western Australia, by year

expenditure has been primarily at Argyle where increased exploration was carried out to delineate further resources needed to extend the life of the mine. Following this phase of exploration at Argyle, which was successful, the proportion of exploration expenditure had eased back to around 4%, but over the last two years the proportion has risen to around 6%, due primarily to increased exploration as a prelude to mining at Ellendale.

Exploration expenditure for iron ore and heavy mineral sands, relative to the value of production, reflects the very mature stage of these industry sectors. Both have consistently returned less than 2% of the value of mineral production back in to exploration (Fig. 12). Although the proportion of expenditure did rise very slightly during the minerals boom of the late 1990s, exploration expenditure relative to the value of production has declined since then, and both are now at or near historic low points of 1% or less.

As a comparison with the mineral sector, exploration expenditure for petroleum (relative to the value of production) has typically ranged between 8 and 10% during the last decade.

Acknowledgments

Mineral exploration expenditure data were compiled by the Australian Bureau of Statistics.

Information on the State's inventory of mineral resources is contained within the Department's MINEDEX (mines and mineral deposits information) database, a compilation of resource estimates that have been reported by a large number of companies. Drilling statistics for mineral exploration were extracted from the Department's WAMEX (Western Australian mineral exploration) database, and were compiled from statutory mineral-exploration reports received by the Department during the period (hence there are some data in them that relate to the previous period). The Royalties Branch of the Department supplied information on the quantity and value of mineral production from Western Australia for 2001–02. Information on mining tenements in Western Australia was supplied by the Mineral Titles Division of the Department.

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Declining greenfields exploration in Western Australia, 1996–2001

by D. J. Flint and R. Rogerson

[Modified extract from: Bowler, J, 2002. Ministerial Inquiry into greenfields exploration in Western Australia: Western Australia Department of Mineral and Petroleum Resources, 146p.]

Abstract

This paper presents results of innovative research undertaken by the Geological Survey of Western Australia. It looks at the significant fall in mineral exploration expenditure in Western Australia since the peak activity in 1996–97, with emphasis on analysing and demonstrating how much of that decline has been specifically related to greenfields exploration. Mineral exploration expenditure in the State is down 47% from 1996–97 to 2001–02, with gold down 55%. Exploration activities in greenfield areas, particularly RAB and RC drilling, have borne the brunt of the decline. Detailed analysis suggests that an average distance of 5 km from mine sites is a reasonable measure of the transition from brownfields to greenfields exploration. Regardless of what distance measure is used as a proxy for greenfields exploration (from 5 km to 40 km), the relative proportion of expenditure incurred from 1997 to 2001 fell in all cases. However, exploration expenditure more than 5 km from mine sites (nominally greenfields) has declined from 40% of the total in 1997 to only 28% of the total in 2001. The gap between brownfields and greenfields exploration is continuing to widen.

These results are not in agreement with the currently available Australian measure of exploration activity compiled by the Australian Bureau of Statistics (ABS) that is widely used as a proxy for greenfields exploration. That measure is exploration expenditure for both production leases and off production leases. The ABS data indicates that exploration expenditure off production leases has remained almost unchanged since 1997 at 75–80% of the total (for Australia as a whole).

Introduction

Mineral exploration expenditure in Western Australia has declined markedly since 1996–97 and is now, in real terms, at levels lower than the recession of the early 1990s (Fig. 1). In 2001–02, mineral exploration in the State was down 47% from the peak reached during 1996–97 (in dollars of the day terms), whereas gold-sector exploration expenditure was down 55.2% for the same period. Unfortunately, quarterly data indicate that the bottom of the downturn had not been reached in mid-2002 (Fig. 2).

The task was to prove the anecdotal belief of recent years that exploration in greenfields areas had suffered the greatest declines and is now at seriously depressed levels. Brownfields exploration may be proving successful in the short term, and win immediate support from shareholders, but it is discoveries in greenfields areas that are required for the long-term sustainability of the mining industry in Western Australia.

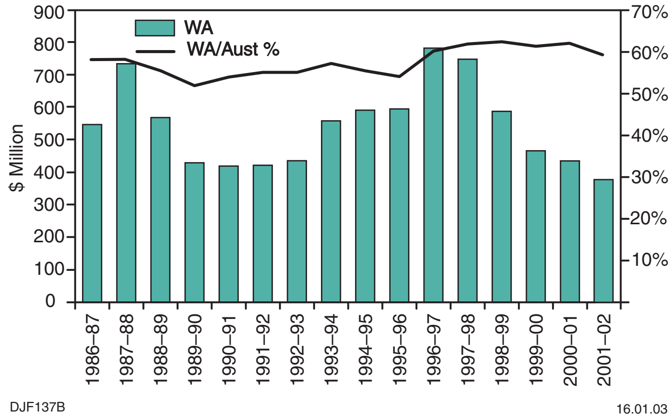


Figure 1. Mineral exploration expenditure in Western Australia, by year (June 2002 dollars)

What is 'greenfields' exploration?

This section examines the meaning of the terms 'greenfields' and 'brownfields' within the context of minerals exploration.

These terms, and their synonyms 'frontier' and 'mature' respectively, are also used for basins within the context of petroleum exploration. An understanding of these terms, and their definitions is critical to the probity of the public policy recommendations arising out of the Ministerial Inquiry (Bowler, 2002).

The importance of clearly defining greenfields exploration is underlined by a statement released by Western Mining Corporation (WMC) on 27 November 2001 to the Australian Stock Exchange (http://www.wmc.com.au).

> *'WMC, Australia's third-largest mining company, plans to halve spending on greenfields exploration and slash staff at its Perth offices as it tries to attract a buyer.*
>
> *Expenditure on greenfields exploration will be cut to $25 million from $50 million, and 60% of exploration staff at the Melbourne-based miner's Perth offices will lose their jobs. Exploration staff will also be cut in Denver (USA), Chile and Brazil.*
>
> *Spending on brownfields exploration will remain unchanged, apart from the natural reduction caused by the sale of WMC's gold division.*

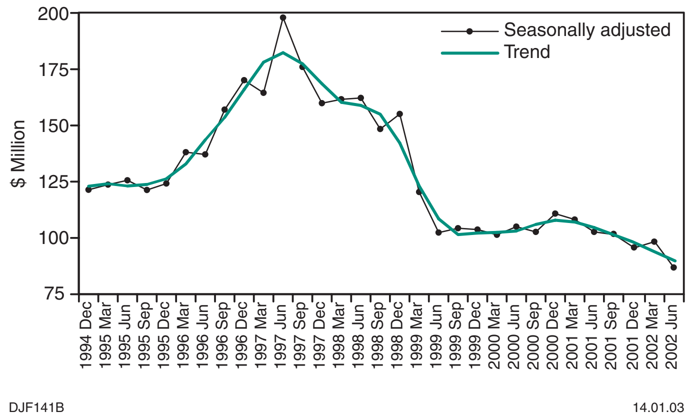


Figure 2. Mineral exploration expenditure in Western Australia, by quarter, on seasonally adjusted and trend terms (dollars of the day)

> *Exploration now comes under the business strategy and development department headed by Andrew Michelmore, placing it alongside development of technology and other 'value-added' growth areas of the company.*
>
> *Effectively, it will have to compete with those areas for funds.'*

Description of greenfields

A survey of the literature relating to exploration failed to unearth a definition of greenfields and the following statements will serve to establish a number of characteristics of greenfields or brownfields exploration.

- Greenfields exploration is described as work undertaken in search of new orebodies that can be mined economically;
- 'Brownfields' exploration (proving-up known resources on granted leases) rather than 'greenfields' exploration (exploring for new deposits);
- Near-mine or brownfields exploration and away from greenfields exploration;
- The more expensive and time-consuming 'greenfields exploration'… 'greenfields' (grass-roots) and they are not 'brownfields' (next to existing mines);
- Brownfields exploration focusing on the environs of existing mining operations;
- Greenfields exploration to find new deposits;
- Expenditure on greenfields exploration (exploring in new regions).

The prevalence of parentheses in these quotations indicates that the authors have not been sure of how their readers would interpret the terms greenfields and brownfields. Nevertheless, the quotations highlight a number of characteristics of these terms.

Greenfields exploration	*Brownfields exploration*
Exploring in new regions	Proving-up known deposits on granted leases
Searching for new mineral deposits	Near existing mining operations
Use of 'grassroots'* techniques	

An important characteristic of brownfields exploration is that it is more spatially confined than greenfields exploration. Brownfields exploration appears to be carried out near existing mining operations or deposits, and perhaps on a granted mining lease, where work is focused on the discovery close to an existing orebody or discrete mineral deposits containing resources that could be converted easily to ore. Alternatively, brownfields exploration could involve conversion of *mineral resources* in an existing orebody to *ore reserve* status.

In a sense, greenfields seems best defined as those areas that are not tacitly considered to be brownfields.

The greenfields–brownfields continuum

The distribution of existing orebodies within a region would suggest that there should be a continuum between bull's eye-like areas surrounding known mining operations marked by intense brownfields exploration, and areas that gradually pass outwards into those with less intensive exploration where grassroots exploration techniques are employed. Clearly, large areas exist where there is no exploration. A hypothetical case is illustrated in Figure 3.

The shape of the curve in Figure 3 is a reflection of the distribution of perceived prospectivity or mineral potential of the area, which is ultimately a function of geology. Areas with a sharp boundary between prospective rock and non-prospective rock will have steep expenditure–distance curves, perhaps passing from brownfields exploration directly into 'no exploration'.

* Grassroots exploration techniques are usually taken to be those used early in an exploration program, such as wide-spaced sampling and geological mapping.

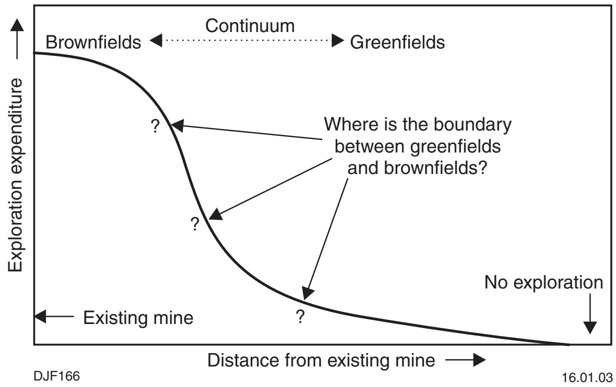


Figure 3. The greenfields–brownfields continuum expressed as exploration expenditure

Approaches used to distinguish greenfields and brownfields exploration

Four broad approaches have been used by different jurisdictions to distinguish between greenfields and brownfields exploration expenditure. The approaches include those based on the following:

- *Tenement type.* Productive mining is usually carried out on mining leases, and exploration on exploration or prospecting licences. Some Australian states use this approach.
- *Exploration technique.* In this case, advanced exploration techniques or studies such as close-spaced diamond or reverse-circulation drilling, metallurgical studies, bulk sampling, and trial mining are taken to indicate an exploration project is at an advanced stage. Papua New Guinea uses this approach.
- *Production.* In this case, brownfields could be limited to the area of a tenement that has existing production. This approach is used by the Australian Bureau of Statistics.
- *Historic production.* In this case, an area would be considered brownfields because it has been defined as a goldfield or mineral field.

Table 1 outlines the advantages and disadvantages of these approaches in different circumstances.

The Australian Bureau of Statistics has traditionally collected quarterly data from companies relating to exploration expenditure on both 'on' and 'off' production leases — as a quasi measure for brownfields and greenfields exploration respectively. Figure 4 shows that despite a known massive drop in total exploration expenditure and area under tenement in Western Australia, ABS data suggest that expenditure 'off' production leases for Australia remains relatively unchanged at around 75–80% of the total! If any pattern is evident from the ABS data, it tends to suggest the real situation is the reverse of that universally accepted to be the case. That is, the ABS data are indicating the lowest level of exploration expenditure 'off' production leases was during the boom of 1996–97 rather than during 2001–02. This is certainly against the commonly held belief in industry.

Unfortunately, there has been a tendency for many commentators to use the expenditure 'off' production leases as a proxy for greenfields exploration expenditure. This is very misleading, as most industry practitioners would regard brownfields exploration expenditure extending well beyond their immediate production lease. The ABS data also suggest that 70–80% of exploration expenditure is 'off production leases', that is, nominally greenfields, but no one really believes that greenfields exploration in recent years is anywhere near that level.

The reason for the ratio between 'on' and 'off' production lease expenditure remaining approximately constant, despite strong anecdotal evidence that greenfields exploration activity has declined, probably goes to the heart of the definitional problems associated with greenfields exploration.

Table 1. Approaches to defining greenfields and brownfields exploration expenditure

Approach	*Advantages*	*Disadvantages*
Tenement type	Clear-cut. Works well where production leases are only granted for production purposes and leases are reasonably small	In WA, most mining leases are only used for exploration purposes. In many cases in WA, greenfields exploration techniques are applied on mining leases
Exploration technique	Theoretically clear-cut if information on exploration techniques being used is easily obtained. Would work well where only a small number of brownfields areas are involved	Where a large number of brownfields areas exist, or where information is not easy to obtain, this approach could be difficult to use
Production	Clear-cut	Brownfields techniques are applied in areas outside leases on which production occurs
Historic production	Clear-cut	Ignores the fact that the mineral field may be greenfields for the particular commodity being explored for. Brownfields techniques may be applied in areas outside mineral fields

One probable explanation is that the outer boundary of greenfields exploration against areas with no exploration has probably moved inwards towards production leases (Fig. 5). While there has been a similar percentage reduction in exploration expenditure 'on' and 'off' production leases, vast areas that were once the object of greenfields exploration now see no exploration.

The brief analysis in Table 1 shows that there is no easy or natural method of distinguishing brownfields and greenfields exploration. A method of calculating brownfields exploration expenditure is therefore required that is easy to understand by industry and policy makers, and that is amenable to rapid database analysis when the number of tenements is high.

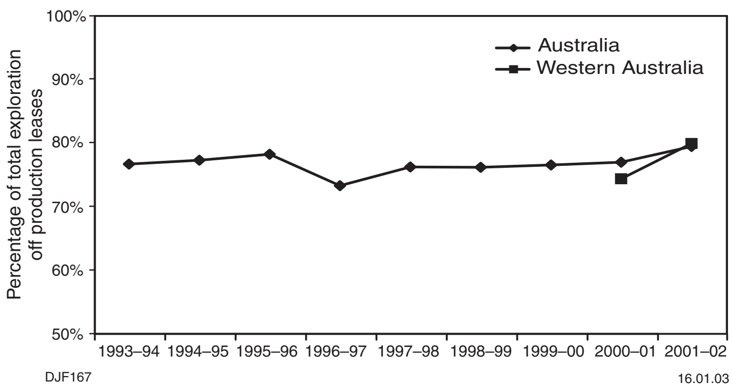


Figure 4. Australian mineral exploration expenditure off production leases (ABS estimates)

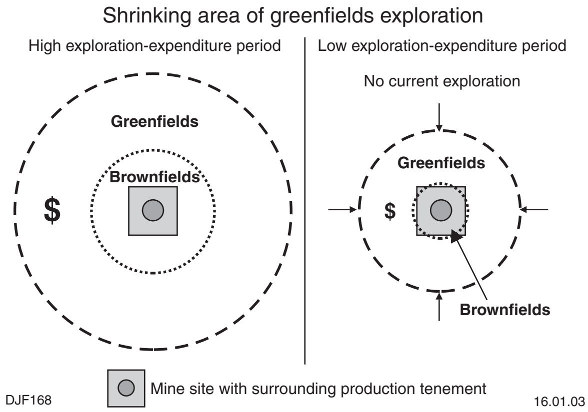


Figure 5. The shrinking area of greenfields exploration may be a major consequence of declines in exploration expenditure generally

Given the large number of mineral tenements in Western Australia, and the fact that greenfields exploration techniques are used on mining leases not used for productive mining, any technique used would need to be independent of the underlying tenement type. An effective approach would also need to possess the following characteristics:

- Produce unambiguous, unbiased results meeting the requirements of the Australian Bureau of Statistics;
- Produce results useful for formulating public policy in the mineral sector;
- If possible, be applicable Australia-wide;
- If possible, be simple to apply on a quarterly basis.

The MPR approach

The Department of Mineral and Petroleum Resources (MPR) has three datasets that are amenable to analysis using geographic information system (GIS) software in order to produce exploration expenditure within a user-defined brownfields area surrounding a site that is producing, or has recently produced minerals.

The three datasets are:

- TENGRAPH — a database of all mineral tenements (includes attributes such as the type of tenement and the geographical coordinates of their boundaries);
- MINEDEX — a database of all mineral deposits and mine sites (includes attributes such as operating status and the geographical coordinates of their location);
- Exploration expenditure — a database containing the statistics of exploration, and production expenditure on mineral tenements submitted by tenement holders (Form 5 of the Western Australian Mining Act, 1978).

Thus MPR has a technique that allows the calculation of the greenfields or brownfields exploration expenditure total for any desired radius from a mine site. Importantly, this calculation can be made independently of the underlying tenement type (Fig. 6).

Notes on the analysis technique

Form 5

Before presenting the results, a comment is required on the use of the Form 5 data as a measure of exploration expenditure. An amended Form 5 was introduced in Western Australia in July 1999, and only since then is there sufficient detail to accurately distinguish exploration expenditure from production expenditure, even when both occur on the same tenement. Data capture for Form 5 submitted to MPR since July 1999 is in progress.

However, a detailed analysis is required for the period from the peak of the boom in 1997 to the current serious recession in exploration activity (2001 and 2002).

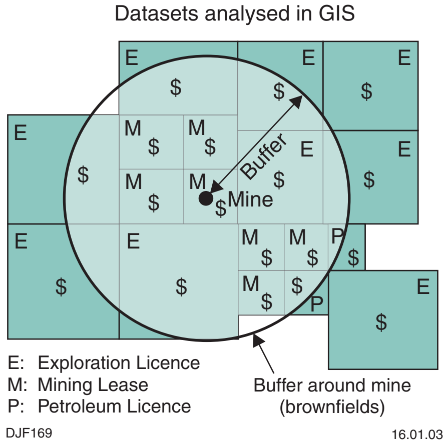


Figure 6. A buffer of flexible radius surrounding a mine location can be used to calculate brownfields exploration expenditure

As detailed Form 5 data are not yet available, the total expenditure for each and every tenement (as sourced from the pre- and post-1999 Form 5) was used. This includes exploration and mining costs as an undistinguished total. As an estimate of the exploration expenditure, an arbitrary $2 million expenditure was used. That is, any expenditure greater than $2 million for any one tenement in one year was regarded as production expenditure and excluded from the results.

Such an approach facilitates rapid evaluation of the data, but Table 2 indicates that this is no substitute for full detailed data from the newer Form 5, which is now considered to have high strategic value.

The method using the $2 million cut-off per tenement produces both overestimates and underestimates of the exploration expenditure, depending on the stage of the boom–bust cycle.

It was found that the method using the $2 million cut-off produces a reasonable estimate of the ABS estimate of mineral exploration in the recession years of 1999–2001, but significantly underestimated mineral exploration expenditure in the boom times of 1996 and 1997. Further refinement of the technique is required for historical information, but in future the new Form 5 data will be used.

However, for the purposes of this study, the technique using an arbitrary $2 million cut-off was considered suitable to give indicative trends in mineral exploration.

Table 2. Comparison of estimated exploration expenditure in Western Australia

Year	*ABS*	*Form 5 ($2 million cut-off)*
	$ million	
1996	601.5	499
1997	700.8	552
1998	626.7	495
1999	427.3	417
2000	420.7	425
2001	408.5	442

Mine sites

Mine sites were selected from MPR's MINEDEX database, with snapshots taken of the database as it existed in each of the years 1996 to 2001. All mines were included, regardless of whether their stage of operation was operating, under development, care and maintenance, or shut.

Excluded from the dataset were low-impact mines, that is, prospecting sites. Also excluded were mines where the target commodity is construction materials or dimension stone, as there is, in essence, minimal or no exploration for these commodities in surrounding tenements.

Also excluded were the very large number of historic mine sites; basically those worked prior to about 1980. If these were also included, the results would mean that the amount of brownfields exploration would be even higher.

This produces a coherent dataset that consists predominantly of mines worked since about 1980 — a dataset that easily fits most definitions of brownfields exploration.

The brownfields–greenfields continuum in a Western Australian context

Rather than predetermine the distance from a mine site that corresponds to the transition from brownfields to greenfields exploration, the analysis was repeated at a range of distances — 1.75 km (corresponding to the nominal radius of a single mining lease), 5 km, 10 km, 20 km, and 40 km.

The smaller distance of only 1.75 km from mine sites was taken as an unambiguous measure of certain brownfields exploration, thus providing a minimum measure.

The distance of 40 km was chosen as representing the interpreted maximum distance for trucking ore to a nearby plant, and is thus a reasonable measure of the outer limit and maximum amount of brownfields exploration.

The results are equally valid if one of the intermediate values is taken to represent the transition point from brownfields to greenfields exploration.

Although the results are preliminary, clear trends are evident in the data for Western Australia.

Trends in greenfields exploration for 1996 to 2001

These trends are examined in three areas — exploration expenditure and tenement distribution as a function of distance from mine sites, and drilling activity (as another measure of greenfields–brownfields exploration).

Exploration expenditure

Amidst the large falls in exploration expenditure in Western Australia that have occurred since 1997, it is possible to discern the trend towards near-mine exploration. This is best illustrated by using the estimated exploration expenditure data at ± 5 km from mine sites (Figs 7 and 8), which dramatically show the trend towards near-mine exploration in both actual expenditure data and in 'percentage of the total' terms. In addition, the data are revealing that the gap between brownfields and greenfields exploration is widening with time.

Figure 7, dealing with dollars spent, illustrates the trend to brownfields exploration, as well as the widening gap between brownfields and greenfields exploration — the gap widened in 1998 (as exploration expenditure fell generally) and the trend has continued at a more rapid pace since then. Although near-mine (<5 km) exploration expenditure has shown signs of recovering in 2000 and 2001, the greenfields (>5 km) exploration expenditure has continued to deteriorate.

Figure 8, dealing with the same data but expressed as a percentage of the total, illustrates a similar pattern, with the widening gap between brownfields and greenfields exploration. Exploration expenditure more than 5 km from mine sites (nominally greenfields) has declined from 40% of the total in 1997 to only 28% of the total in 2001.

This is not in agreement with ABS data (Fig. 4) that indicate that exploration expenditure off production leases, which is often used as an indicator of

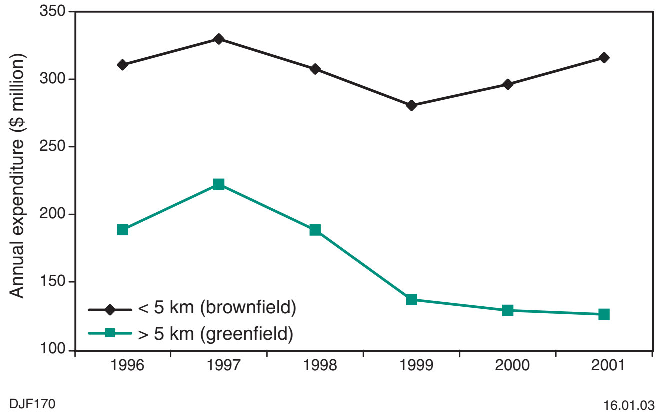


Figure 7. ***Greenfields–brownfields trends in annual exploration expenditure (actual dollars), Western Australia, 1996–2001 (based on ±5 km from mine sites)***

greenfields exploration, has remained almost unchanged at 75–80% of the total (for Australia as a whole). Comparable, specific ABS data for Western Australia are available only for the last two years (2000–01 and 2001–02), but are similar to the national ABS data.

Results also indicate that it matters little what distance measure is used as a proxy for greenfields exploration, the proportion of exploration expenditure incurred from 1997 to 2001 fell in all of them — at distances more than 40 km from mine sites, at 20–40 km from mine sites, at 10–20 km from mine sites, and even a slight fall at distances of 5–10 km from mine sites (Fig. 9). Expenditure in the distance range of 1.75 – 5 km from mine sites is almost unchanged since 1997, and the proportion of exploration expenditure at mine sites (within 1.75 km) has clearly increased since 1997.

Figure 10 provides a view of the profile of exploration expenditure with distance from a mine site, and how that has changed from 1997 to 2001. Most of the difference between the curves results from lower exploration generally from 1997 to 2001, with the exploration expenditure profile from mine sites usually lower with each successive year (note that the intervening years are not shown on Figure 10). However, the data for 2001 highlight the real trend to brownfields exploration, with the highest recorded near-mine exploration (within 1.75 km) and with low or the lowest recorded exploration expenditure at all other distances.

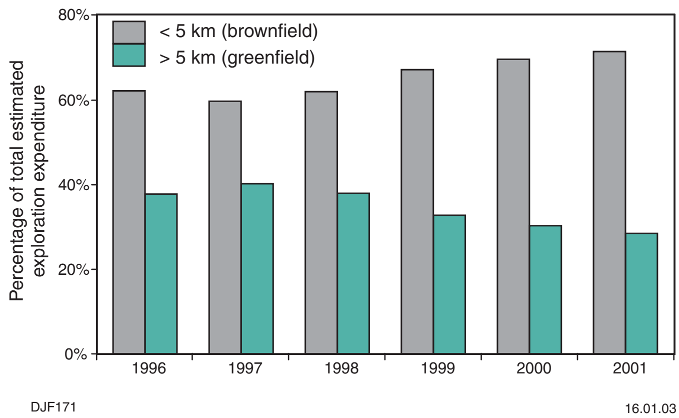


Figure 8. ***Greenfields–brownfields trends in annual exploration expenditure (percentage of total exploration expenditure), Western Australia, 1996–2001 (based on ±5 km from mine sites)***

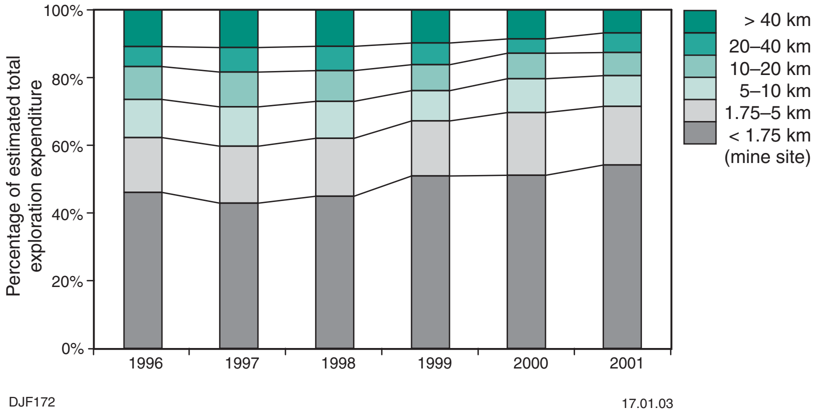


Figure 9. Estimated exploration expenditure by distance from mine sites, percentage of total, Western Australia, 1996–2001

Figure 11 highlights how greenfields exploration (regardless of how it is defined) has borne the brunt of the general decline in mineral exploration from 1997 to 2001. Note that Figure 11 is based on estimated mineral exploration expenditure using Form 5 data and with an arbitrary $2 million cut-off, but this method does understate the general decline in mineral exploration expenditure since 1997. By this method, the decline in total expenditure to 2001 is only 20%, whereas the ABS data reveal a 47% decline. Despite this, the trend revealed in Figure 11 is considered real.

Furthermore, Figure 11 also depicts the percentage falls in mineral exploration with distance away from mine sites, with the fall generally increasing with distance from the mine sites. The decline in greenfields exploration is greater than the overall decline in expenditure, with mineral exploration at mine sites staying static or even increasing slightly. Brownfields exploration at 1.75 – 5 km from mine sites has declined, but the fall is nowhere near the magnitude of the falls in greenfields exploration. These data are entirely consistent with and strongly support the hypothesis of increasing brownfields exploration (at least relatively speaking, and perhaps even absolutely at mine sites) and that greenfields exploration has borne the brunt of the general decline in exploration expenditure since 1997.

Drilling activity

Drilling data compiled by MPR indicate that cutbacks in drilling are more severe than the general decline in exploration expenditure.

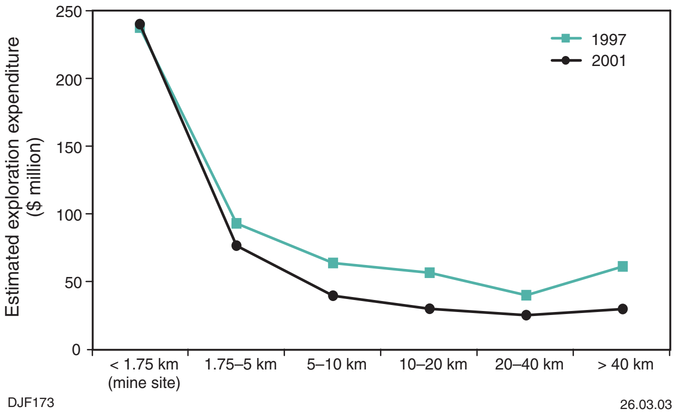


Figure 10. The yearly shift in exploration expenditure profile towards brownfields mineral exploration, 1997 to 2001, Western Australia

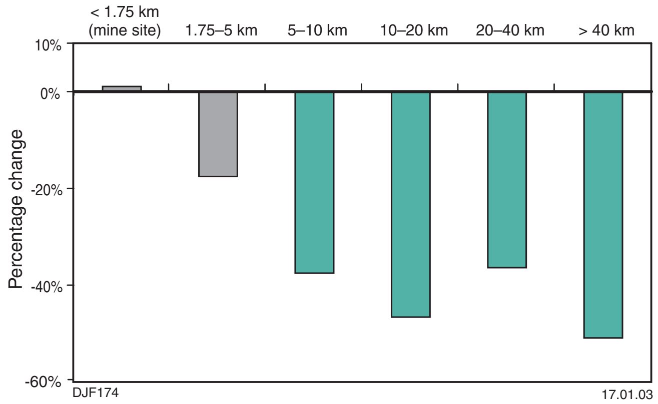


Figure 11. The percentage change in greenfields and brownfields exploration expenditure from 1997 to 2001, by distance from mine sites

Drilling activity* since the peak of exploration in 1996–97 clearly shows that cutbacks in exploration budgets have had a severe impact on all types of drilling (Fig. 12). Rotary air blast (RAB), reverse-circulation (RC), and diamond drilling have now declined by about 80%, 65%, and 65% respectively since their peaks in 1996–97 or 1997–98. RAB drilling was the first to be adversely affected as companies reduced expenditure and moved away from grassroots greenfields exploration, and this was followed one year later by declining RC drilling, as expenditure cuts deepened. RAB and RC drilling continued their decline during 2001–02, and have now been joined by falling diamond drilling during 2001–02.

The falls in 'metres drilled' from their earlier peak levels are more severe than the general fall in overall exploration expenditure. The decline of about 80% in RAB, 65% in RC, and 65% in diamond drilling since the peak of the boom should be compared with the corresponding drop of 'only' 47% in total exploration expenditure.

Recent quarterly data from the Australian Bureau of Statistics show that the downward trend is still firmly in place and has not shown any sign of levelling off. That data, which includes all mineral exploration drilling of all

* Drilling statistics extracted from MPR's Western Australian mineral exploration (WAMEX) database, as supplied by the mining industry and best regarded as a trailing indicator.

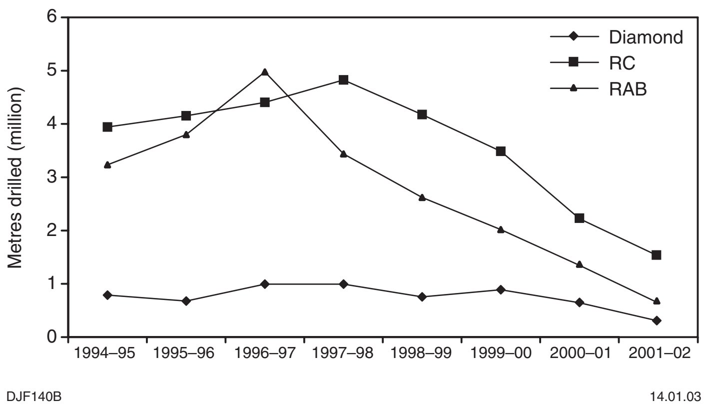


Figure 12. Mineral exploration drilling in Western Australia, by drilling type and year

types, both on and off production leases, shows that mineral exploration drilling in Australia has declined by 75% (2.79 million metres) since mid-1997.

Such declines in drilling activity greatly diminish the opportunity for significant discoveries that are so necessary to change perceptions and boost exploration.

Tenement distribution

Tenement activity can also be used as a measure of exploration activity; hence, the analytical method was also used to examine the number of granted tenements as a function of the distance from mine sites, and how this has changed with time since 1997 (Fig. 13). Figure 13 shows that the number of granted tenements in Western Australia within 5 km of mine sites has increased since 1999, whereas the number of granted tenements in all zones more than 5 km from mine sites has been declining since 1997.

Other points to note from the analysis include the following:

- The number of granted tenements greater than 40 km from mine sites (i.e. unquestionably greenfields tenements) has dropped from 1407 in 1997 to 802 in 2001, a decline of 43% over four years. Such greenfields tenements represent only 7% of the granted tenements. This supports the concept (see Fig. 5) of the shrinking area of greenfields exploration.
- The exploration expenditure on those tenements has dropped from $76 million (1997) to $45 million (2001), a decline of 41% over the four years.
- That exploration expenditure in undisputed greenfields areas (>40 km from mine sites) has dropped from 2.0% (1997) to 1.2% (2001) of reported expenditure on granted tenements (i.e. including mining and all other costs). This highlights how little of industry's total costs are directed to undisputed high-risk greenfields exploration (i.e. more than 40 km from mine sites).

Trends in greenfields exploration in the backlog of pending tenements

A total of 11 768 tenements were at the application stage in June 2002. The expenditure commitment associated with these tenements (and assuming no overlap) would total $458 million. This compares with a total of only $408 million of exploration expenditure spent on all the granted tenements in Western Australia during 2001, and only $376 million spent in 2001–02.

The potential exploration expenditure as a function from existing mine sites is shown in Figure 14. This indicates that most of the potential exploration commitment is near mines (within 10 km) and that there is much less interest in areas more distant from mine sites.

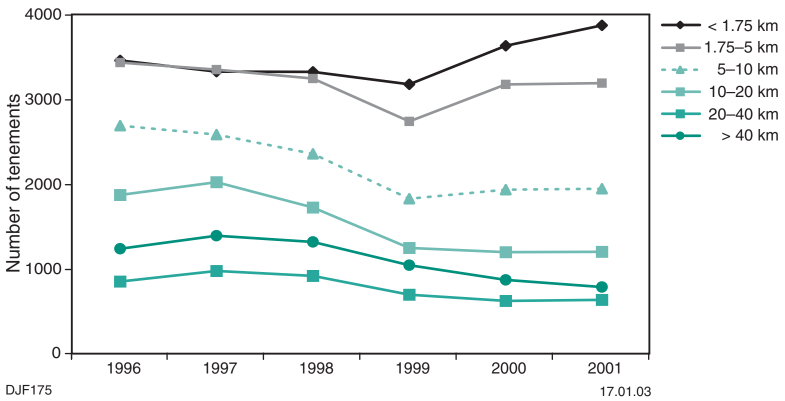


Figure 13. Granted tenements in Western Australia, by distance from mine site and year

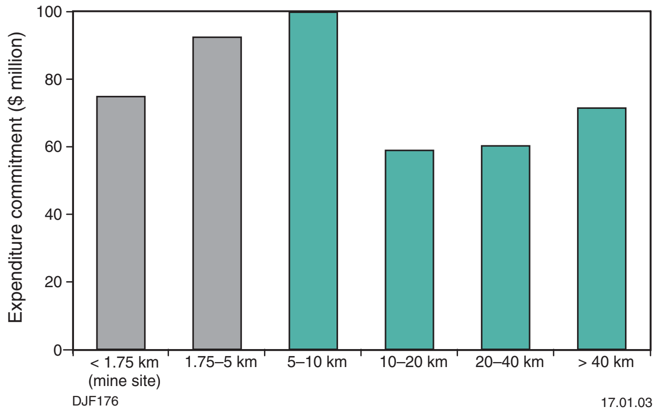


Figure 14. Expenditure commitment if pending tenements granted, by distance from mine sites

Summary

- In 2001–02, mineral exploration in the State was down 47% from the peak reached during 1996–97 (in dollars of the day), and with gold down 55% for the same period;
- Discoveries in greenfields areas are required for the long-term sustainability of the mining industry in Western Australia, but the decline in greenfields exploration since 1996–97 has been more severe than the general decline;
- These developments coincide with a long-term decline in the rate of discovery of new major mineral deposits;
- Detailed analysis by MPR suggests that an average distance of 5 km from mine sites is a reasonable measure of the transition from brownfields to greenfields exploration;
- Results also indicate that it matters little what distance measure is used as a proxy for greenfields exploration (that is, from 5 km to 40 km) — the proportion of exploration expenditure incurred from 1997 to 2001 fell in all of them;
- Exploration expenditure more than 5 km from mine sites (nominally greenfields) has declined from 40% of the total in 1997 to 28% of the total in 2001;
- The gap between brownfields and greenfields exploration is continuing to widen;
- These results are in stark contrast to the ABS data that indicate that exploration expenditure off production leases has remained almost unchanged since 1997 at 75–80% of the total (for Australia as a whole);
- The number of granted tenements in Western Australia within 5 km of mine sites has increased since 1999, whereas the number of granted tenements in all zones more than 5 km from mine sites has been declining since 1997;
- Despite a total of 11 768 tenements at the application stage in June 2002, with a corresponding potential exploration-expenditure commitment of $458 million, it is unlikely that the total potential expenditure commitment associated with these would be realized if granted immediately. Reasons for this include the depressed state of the minerals sector (low metal prices and returns on investment) and the difficulty of raising investment capital for minerals exploration;
- The location of applications for tenements reinforces the notion that there is still greater interest near mines, rather than in remote greenfields areas.

Inside the GSWA

Mike Donaldson

Towering above most of the staff, with a stride as wide as his smile, is the very noticeable Mike Donaldson. A recent employee of GSWA, Mike has brought to the Survey 30 years of diverse experience in the minerals industry, as well as a love of natural history shared by many of his coworkers.

Mike graduated from Macquarie University in 1972 with an honours degree in geology. For the next 16 years he worked for Western Mining Corporation (WMC), mostly on nickel projects in the Western Australian goldfields. It was during this time that he undertook a PhD project to study Archaean ultramafic rocks (komatiites). Based at Kambalda Nickel Operations, he became WMC's Senior Research Geologist between 1979 and 1983.

Moving his interest to northwest Queensland, Mike then managed WMC's base-metal exploration program between 1984 and 1986, before returning to Kalgoorlie and becoming involved in gold exploration. With the gold boom in full swing, Mike decided to make a break from WMC and join a junior exploration company, Coolgardie Gold NL, as Exploration Manger, where he was involved in the development and mining of several significant gold deposits around the historic Coolgardie area. Leaving in 1991 to join Sons of Gwalia as General Manager Exploration, he expanded their exploration team, becoming active in north Queensland and the Tanami area of the Northern Territory, and around Leonora, Laverton, and the Southern Cross region.

Diamonds lured Mike to Ashton Mining Ltd in 1996 as General Manager Exploration. Here he had a chance to diversify into the world of international diamond exploration in places such as Indonesia, Russia, Finland, Canada, and several African countries.

In 2001, Mike was appointed General Manager Regional Mapping for GSWA, which although it is mostly an office-based job, still lets him out into the field to visit the various mapping projects. From his long association with the bush has developed a passion for natural history, pursued through interests in Aboriginal rock art, early explorers, and remote Kimberley bushwalking. Such enthusiasm led him to delve into the history of Frank Hann, the famous Australian pastoralist, prospector, and bushman, which ultimately saw Mike transcribe several diaries into publications.

Too tall for the camp beds, Mike prefers to sleep on the ground in the field, where perhaps he ponders the hardships of those early explorers that walked the country long before him.

Marian McCabe

Marian is not a geologist. She wants this made clear. She may think that she is avoiding some obscure social stigma attached to such a label, but it has been learned that she has studied some geology in her murky past. Regardless, she has used her atrophied geological powers in conjunction with her considerable computing powers for the forces of good as the Survey's only regionally based geoscience information officer. Marian joined the Kalgoorlie regional office of GSWA in 1997 and during the past five years has been invaluable in establishing the East Yilgarn geoscience database, a geological GIS (geographic information system) package that will be of use to explorationists and prospectors alike. Marian brought to the project ten years of experience working with and developing GIS packages for Government departments in the Northern Territory and Canberra that focused on mapping and analysis of land and natural resource information.

Marian was born in Cottesloe, but lived in the Northern Territory for many, many, many years. After completing year 12, she undertook a traineeship as a cartographer with the Northern Territory Department of Lands and Housing. Following her training, Marian quickly moved into the then new field of land and geographic information systems, and has returned to the land of her birth with this knowledge gained in the mystical east.

There can be no doubt that one of the highlights of a visit to the Joe Lord Core Library is to experience the seismic tones of Marian's laughter (although some would argue that a trip to Kalgoorlie is unnecessary because her laugh can be heard in Perth). Marian can always be relied upon to lighten the atmosphere, although her rapier wit and sense of the ludicrous have been known to whoosh loudly over the heads of the less perceptive. She has requested that it be known that she can be bought off — a most reasonable bribe of a bottle of fine merlot, preferably Victorian, can achieve expeditious and expertly manicured results in all things relating to GIS.

Marian has boldly gone with the East Yilgarn geoscience database where no GIS officer has gone before. She has utilized her expertise to establish the framework for this very detailed, regionally extensive geological database over the Eastern Goldfields, from Norseman in the south to Wiluna in the north, taking in major gold and nickel mining centres such as Kalgoorlie, Kambalda, Leonora, and Laverton. What set this project apart from others is the magnitude of the data incorporated into the GIS, including 1:100 000-scale geology outcrop data from 56 map sheets, structural points, mine sites, aeromagnetic data, and solid geological interpretations to name a few, over an area larger than many European countries. Marian's work has allowed comprehensive and rigorous accumulation of this data into the GIS while simultaneously allowing users straightforward access to, and interrogation of, the data for extraction of information. This framework is still being utilized for the most recent additions to the database, and will form the basis for the evolving departmental GIS that will ultimately incorporate Western Australian geology at 1:100 000 scale Statewide.

Marian is quite proud of the fact that, despite her enjoyment and flair for her job, work is not her life. She is an avid (though not uniform-wearing) Trekker and sci-fi buff, is mad about her horses (particularly her standardbred, Jock), is a great patchwork quilter, and supplies select friends with the best tie-dye gear in the west. Most important of all, she has a very close relationship with her teenage daughter Heather, and they share their hobbies and clothes. Dark clouds may be gathering, however, because there is presently a dispute about who is the tallest, and escalating extravagant use of platform shoes by both parties is sure to lead to misery, either in the form of broken ankles or through public ridicule as the stilt-freaks of Kalgoorlie.

Sarah Jones

Dr Sarah Jones is originally from Auckland, New Zealand and has two sisters, one of whom is an identical twin. The resemblance between Sarah and her twin sister Rachael is so close that in early childhood photographs Sarah is unable to distinguish herself from her sister. On one occasion, when Sarah was unable to attend an educational ceremony to collect a prize, Rachael collected the prize instead, and nobody in the audience recognized the switch.

After leaving school, Sarah completed a three-year apprenticeship in typography in Auckland and as soon as that finished she went to Whakapapa skifield, on Mount Ruapehu in the North Island, to work as a ski-lift operator so that she could ski every day. She then spent the next three years working winters in the snow, summers working back in Auckland as a typographer, and also managed to fit in a nine-month trip to Norway, where she lived in a remote valley planting trees and trying unsuccessfully to learn a bit of Norwegian.

Sarah started university in her mid-twenties and as she had always had an interest in rocks she decided to try geology, and she has been looking at rocks ever since. As a child she spent all of her summers on the Coromandel Peninsular and would walk up and down the creeks looking for quartz and amethyst crystals, jasper, and chalcedony.

Sarah moved to Australia in 1996 after completing a BSc and MSc at Otago University in Dunedin, South Island, New Zealand. She considers herself lucky to be given a Masters project in Antarctica entitled 'Structural evolution of Northern Walcott Bay, South Victoria Land, Antarctica'.

In Australia, Sarah worked for two and a half years as an exploration geologist at the Darlot gold mine in the Eastern Goldfields for Plutonic Resources and Homestake Gold of Australia Ltd. Most of her geological work was on the Centenary gold deposit.

Wanting to pursue her professional career, Sarah left her job at Darlot to enrol as a Doctor of Philosophy (PhD) student at the Centre for Ore Deposit Research (CODES), University of Tasmania. Sarah's doctoral thesis examined the origin and evolution of siliceous caprocks above Cu–Pb–Zn (VHMS) deposits at Myra Falls, Vancouver Island, British Columbia, Canada. According to her PhD supervisor, Sarah produced an excellent thesis that satisfied all its aims and was completed in near record time.

In January 2002, Sarah commenced work for the Geological Survey of Western Australia as a field geologist in the Kalgoorlie regional office. Sarah has settled into Kalgoorlie–Boulder with her partner Mike, a surveyor, whom she met during her stint at the Darlot gold mine. As downhill skiing is a bit difficult in Kalgoorlie, Sarah spends most of her time gardening, drawing, reading, walking, and collecting 'treasures' for the garden. Sarah tries to get back to New Zealand every year.

Obituary

David Bruce Townsend 1956–2002

David Townsend died on 23rd June 2002 following a protracted battle with cancer. David had worked for the Geological Survey for about 14 years, having joined in 1988. A wealth of knowledge regarding the changes within the mining industry over that period of time went with David, and he is greatly missed by all those who worked with him.

David Bruce Townsend was born in Williamstown, Victoria, on 30 November 1956, the middle child of three. David grew up on a Victorian farm, and his love of the outdoors was developed early, along with a fascination for the sciences. He was a true rebel, said his family.

David attended Latrobe University in Melbourne, graduating with a geology degree. The mid-70s were not good times for geologists, so his first job was with ICI Australia, in Deer Park in Melbourne, working with the explosives section. There he gained his shot-firer's licence.

Following a 12-month stint as an offshore well jockey in Western Australia, David was employed by CRA Exploration. He was involved with the company's diamond exploration program, based at Camp Bow. David was in his element, with the combination of working in the outdoors and scientific discovery. The Kimberley remained a fascination long after he left CRA, and David returned many times.

In 1988, he joined the Geological Survey. A recently married man, David had decided that a settled job was important for his burgeoning family, and he established a base in Perth. At the Survey, David initially worked on a data back-capture project, abstracting and annotating company statutory-exploration reports for release to open file. He then commenced work on the raw materials evaluation of the Coral Bay – Shark Bay area, which has been included in the World Heritage Register. Reports on the mineral potential and mineral deposits of the Albany 1:1 000 000 map sheet and the Nullabor Plain regions followed. In addition, David produced a Record on the nickel resources of Western Australia in 1990.

In 1990–91, David began work on the project that became synonymous with his name within the Survey. He was a key player in developing and maintaining the MINEDEX database on mines and mineral deposits, and through such work became one of the Department's primary sources of information on projects, mining companies, and mineral deposits, and a first port of call for industry customers of the Department. David's work on MINEDEX led to his co-authoring six publications using the data as part of the Regional Minerals Program supported by the Federal Government, and two Records outlining the uses of and the background to the MINEDEX system. However, his interest in the field, and fieldwork remained. David was always one of the first to volunteer for a field visit to an operation or site.

David was diagnosed with coeliac disease in the late 1990s. As he became more ill, he remained true to his rebel younger days. He would always enliven a morning tea break with wry opinions, which were often at odds with accepted views on the topic under discussion. He retained a devotion to chocolate that was legendary, adapting his tastes to Cherry Ripe bars to suit the coeliac requirements. David endured much in the last years, and it is a mark of his character, and his true love of his job, that he worked for as long as he was physically and mentally able.

He is survived by his mother Aileen, siblings John and Jeanette, wife Maryanne, and the joys of his life, his children Zoe and Matthew.

Staff list (30 June 2002)

GRIFFIN, Tim (Director)

Regional Geoscience Mapping Branch

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

Terrane Custodians

MORRIS, Paul (Archaean and Regolith — Chief Geochemist)
SHEPPARD, Steve (Proterozoic Orogens)
HOCKING, Roger (Basins)

Edmund and Collier Basins
MARTIN, David
THORNE, Alan

Earaheedy Basin
JONES, Amanda
PIRAJNO, Franco

East Yilgarn (Kalgoorlie Office)
GROENEWALD, Bruce
JONES, Sarah
RIGANTI, Angela
ROBERTS, Ivor
ROSS, Adrienne

Central Yilgarn
CHEN, She Fa
WYCHE, Stephen

Pilbara Craton
BAGAS, Leon
FARRELL, Terry
HICKMAN, Arthur
SMITHIES, Hugh
VAN KRANENDONK, Martin
WILLIAMS, Ian

Lennard Shelf
PLAYFORD, Phillip

Geochronology
BRZUSEK, Marianna
CLANCY, Lisa
NELSON, David
WILLIAMS, John

Geophysics, Remote Sensing and Regolith
HOWARD, David
MARNHAM, Jodie
SHEVCHENKO, Sergey
WATT, John

Publications and CAD
COSGROVE, Lisa
DAY, Lyn
DOWSETT, Suzanne
EDDISON, Fiona
GOZZARD, Margie
HALL, Glennis
HARTLEY, Gary
HOFFMAN, Arthur
JOHNSTON, Jean
JONES, Murray
KUMAR, Manjeet
LENANE, Tom
MIKUCKI, Jennifer
MULLIGAN, Sue
NOONAN, Kath
PRAUSE, Michael

REDDY, Devika
STRONG, Caroline
SUTTON, Dellys
WILLIAMS, Geoff

Map Production and GIS
BANDY, Stephen
BRIEN, Cameron
COLDICUTT, Shaun
COLLOPY, Sean
D'ANTOINE, Neville
DAWSON, Brian
FRANCOIS, Annick
GREEN, Ellis[1]
GREENBURG, Kay
HAMILL, Sammy
KIRK, John
KUKULS, Liesma (Les)
LADBROOK, David
LOAN, Geoff
McCABE, Marian
TAYLOR, Peter
THEEDOM, Erica
VICENTIC, Milan
WALLACE, Darren
WARD, Brendon
WILLIAMS, Brian
WRIGHT, Gareth

Data Integration
GOZZARD, Bob

Mineral and Petroleum Resources Branch

ROGERSON, Rick (General Manager)[1]

Petroleum Systems Studies
APAK, Sukru (Neil)
CARLSEN, Greg
DE LEUW, Lorraine
D'ERCOLE, Cecilia
GHORI, Ameed
IASKY, Robert
IRIMIES, Felicia
LOCKWOOD, Andrew
MORY, Arthur
SIMEONOVA, Anelia
STEVENS, Mark

Mineralization and Exploration Assessment
ABEYSINGHE, Pathmasekara (Abey)
FERGUSON, Ken
HASSAN, Lee
PEIRIS, Elias
RUDDOCK, Ian

Industrial Minerals
FETHERSTON, Mike

Mining Legislation Advice
PAGEL, Jutta

Inventory of Abandoned Mine Sites
ORMSBY, Warren

Resource Access Planning
ANDERSON, Bill
KOJAN, Chris
TRENCH, Gao Mai

Urban and Development Areas Geology
LANGFORD, Richard

Palaeontology
GREY, Kath

Executive Support
CRESSWELL, Brian
SLATER, Elizabeth
STOYANOFF, Nell

Special Projects
GOSS, Andrew

Carlisle Operations
BONER, Peter
CAREW, Eugene[1]
CLARK, Dean
ELLIOTT, Ian
GREEN, Robert
HOLMES, Mario
LOCKYER, Stuart
MOORE, Brian

Core Libraries
HITCHCOCK, Wayne
BROOKS, Chris
WILLIAMS, Gary

Mineral and Petroleum Exploration Information
BELL, Ann
DALY, Matthew
DODD, Fiona
ELLIS, Margaret
EMMS, Rosie
FITTON, Ann
HAWORTH, Jeffrey
HUGHES, Bernard
KARNIEWICZ, George
LESIAK, Irena
MASON, Jan Sandra
MacCORQUODALE, Fiona
McKEATING, Joan
NAGY, Pearl
O'BRIEN, Richard
STAPLETON, Gladys[1]
THOMSON, Amanda
WALKER, Robert
WONG, Henrietta[1]

[1] on secondment to another Division

Staff movements (1 July 2001 to 30 June 2002)

Internal reclassifications
ABEYSINGHE, Pathmasekara — to Level 6
BRIEN, Cameron — to Level 3
CHEN, She Fa — to Level 6
NELSON, David — to Level 7

Commencements
CLANCY, Lisa
D'ANTOINE, Neville
D'ERCOLE, Cecilia
EATON, Nathan
GREEN, Robert
JONES, Sarah
LOCKWOOD, Andrew
McKEATING, Joan
O'BRIEN, Richard
ORMSBY, Warren
ROSS, Adrienne
SIMEONOVA, Anelia
THOMSON, Amanda
WILLIAMS, Geoff
WRIGHT, Gareth

Graduate Geologist work experience program
WALKER, Robert

Resignations
ARATHOON, Claudette
BLUNDELL, Kelvin
BOVELL, Lisa
BURDEN, Philip
CARROLL, Peter,
DOWNING, John
EDWARDS, Tara
FERDINANDO, Darren
GREENFIELD, John
MARTIN, Anne-Louise
PAINTER, Matthew
SANDERS, Andrew
TETLAW, Nathan

Voluntary severance
BRADLEY, John
SMURTHWAITE, Tony

Secondments
CAREW, Eugene — to Office of Major Projects
GREEN, Ellis — to Corporate Services Division
ROGERSON, Rick — to Office of the Director General
STAPLETON, Gladys — to Mineral Titles Division
WONG, Henrietta — to Petroleum Division

Transfers in (MPR integration)
ANDERSON, Bill — from Land Access Branch
HARTLEY, Gary — from Land Access Branch
KOJAN, Chris — from Land Access Branch
KUMAR, Manjeet — from Land Access Branch
MULLIGAN, Sue — from Land Access Branch
SMURTHWAITE, Tony — from Land Access Branch
TRENCH, Gao Mai — from Land Access Branch

Transfers out (MPR integration)
BRADSHAW, Brian — to Finance and Administration Branch
EVANS, Elaine — to Finance and Administration Branch
CHEUNG, Eunice — to Library, Corporate Services Division
CROSS, Robert — to Library, Corporate Services Division
FLINT, Don — to Investment Attraction Division
FORBES, Alex — to Investment Attraction Division
KNYN, Brian — to Library, Corporate Services Division
TOWNSEND, David — to Investment Attraction Division

Casual, Short term, and Fee for service
CARPENTER, Nancy
COPP, Iain
CORBETT, Nicole
DAVIS, Angela
DOWLING, Sarah
DURMANICH, Marie
EVANS, Margaret
FERGUSON, Andrew
FRICK, Louise
HUMBLE, Nicole
JABLON, Marianne
LULICH, Luci
McCAUGHAN, Bethwyn
McILHARGEY, Barbara
MUKHERJI, Alexandria
NOWAK, Ian
O'CONNOR, Michael
SEARSTON, Stella
SIMONETTI, Joseph
SUCHODOLSKI, Christine

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DIRECTOR
Tim Griffin

GENERAL MANAGER
Mike Donaldson

REGIONAL GEOSCIENCE MAPPING BRANCH

- ***Geoscientist Specialist Support***
  - *Geochemistry*
    Paul Morris
  - *Geochronology*
    David Nelson
- ***Geophysics and Remote Sensing***
  David Howard
- ***Geoscience Information Products***
  Steve Bandy
  - *Map and Text Editing*
    Jenny Mikucki
  - *Publication Drafting and Design*
    Michael Prause
  - *Geographic Information System*
    Neville D'Antoine
  - *Computer Assisted Map Production*
    Brian Dawson
  - *Data Integration*
    Bob Gozzard
- ***Kalgoorlie Office***
  Ivor Roberts
  - *East Yilgarn Geoscience Database*
    Bruce Groenewald
  - *Core Library*
    Wayne Hitchcock
- ***Central Yilgarn***
  Steve Wyche
- ***Earaheedy Basin***
  Franco Pirajno
- ***Pilbara Craton***
  Arthur Hickman
- ***Edmund and Collier Basins***
  Alan Thorne
- ***Lennard Shelf***
  Phillip Playford

Terrane Custodians

- *Archaean and Regolith*
  Paul Morris
- *Basins*
  Roger Hocking
- *Proterozoic Orogens*
  Steve Sheppard

Chief Geoscientist
Ian Tyler

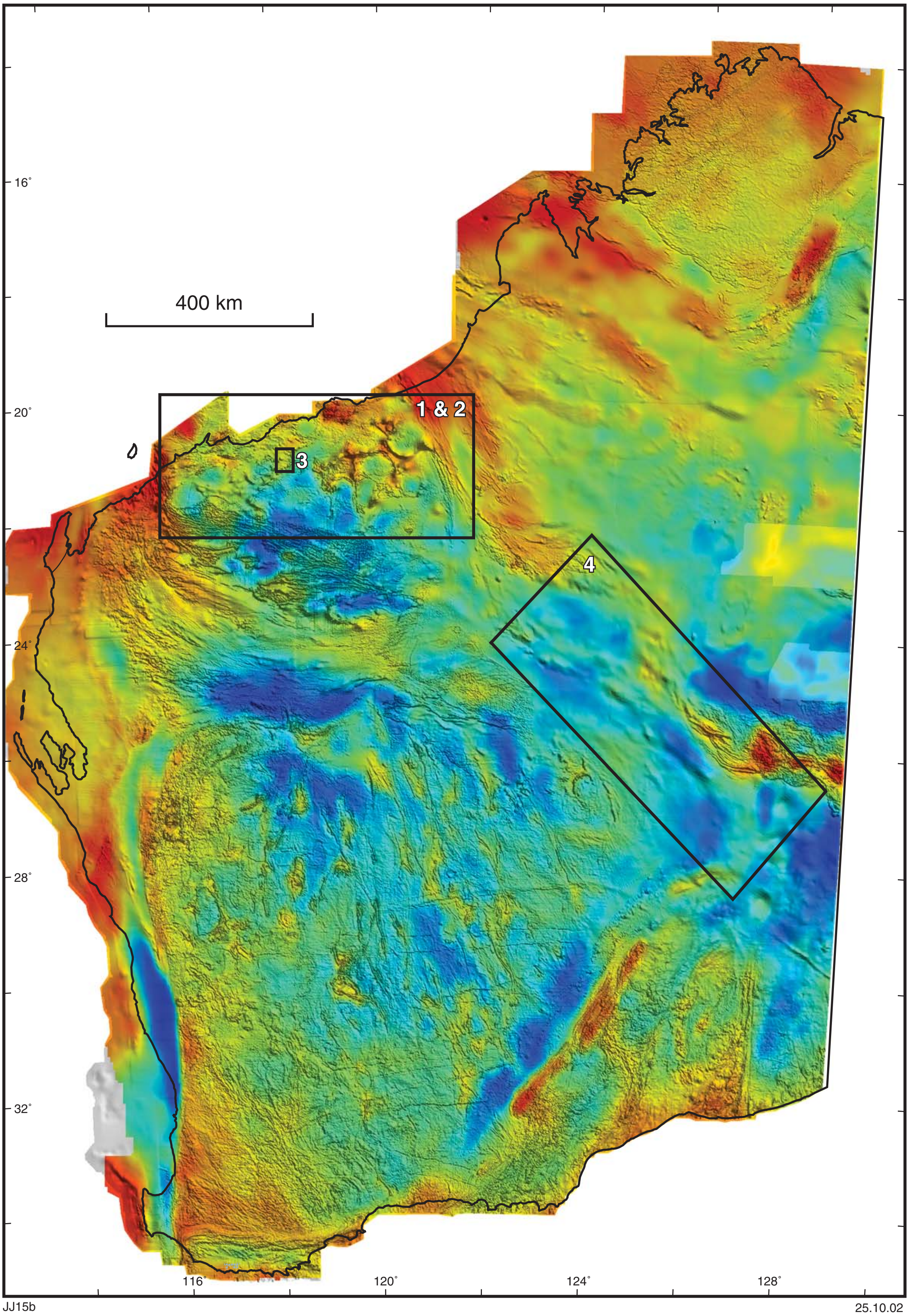
GENERAL MANAGER
Rick Rogerson

MINERAL AND PETROLEUM RESOURCES BRANCH

- ***Mining Legislation Advice***
  Jutta Pagel
- ***Industrial Minerals***
  Mike Fetherston
- ***Exploration Information Management and Support***
  David Howard
  - *Mineral Exploration Data*
    Margaret Ellis
  - *Petroleum Exploration Data*
    Jeff Haworth
  - *Carlisle Operations*
    (Transport and stores)
    Ian Elliott
  - *Core Library*
    Gary Williams
- ***Resource Assessment and Advice***
  INVESTMENT ATTRACTION DIVISION, MPR
  - *Principal Industry and Commodity Analyst*
    Don Flint
  - *MINEDEX Database*
    Roger Cooper
- ***Petroleum Systems Studies***
  Greg Carlsen
  - *Interior Basins*
  - *Western Margin*
    Arthur Mory
- ***Development Areas Resource Mapping***
  Resources Access Planning
  Inventory of Abandoned Mine Sites
  Richard Langford
- ***Mineralization and Exploration Assessment***
  Ian Ruddock
- ***Land Access***
  Tony Smurthwaite
- ***Palaeontology***
  Kath Grey

TJG74b

Revised structure effective 01/03/02
16.10.02



Map of Western Australia showing the locations discussed in the four technical papers on the following pages. Pseudo-colour Bouguer gravity image and grey-scale Total Magnetic Intensity. Blue = gravity low; TMI highlights structural information. Data courtesy of Geoscience Australia

Technical papers

1. **Stratigraphic revision of the Warrawoona and Gorge Creek Groups in the Kelly greenstone belt, Pilbara Craton, Western Australia**
   by L. Bagas 53

2. **Geochemistry of the Corunna Downs Granitoid Complex, East Pilbara Granite–Greenstone Terrane, Western Australia**
   by L. Bagas, R. H. Smithies, and D. C. Champion 61

3. **Stratigraphic and tectonic significance of eight local unconformities in the Fortescue Group, Pear Creek Centrocline, Pilbara Craton, Western Australia**
   by M. J. Van Kranendonk 70

4. **Seismic stratigraphic framework of the Neoproterozoic successions, Officer Basin, Western Australia**
   by S. N. Apak and G. M. Carlsen 80

Stratigraphic revision of the Warrawoona and Gorge Creek Groups in the Kelly greenstone belt, Pilbara Craton, Western Australia

by L. Bagas[1]

Abstract

Mapping in the Kelly greenstone belt in the eastern part of the East Pilbara Granite–Greenstone Terrane of the Pilbara Craton indicates that the stratigraphy of the Warrawoona Group requires significant revision. Four stratigraphic revisions are proposed. The Warrawoona Group now includes the redefined Salgash Subgroup and the newly defined Kelly Subgroup. The felsic volcanic rocks of the c. 3325–3320 Ma Wyman Formation conformably overlie the Euro Basalt and are now included in the Warrawoona Group. The 3324 ± 4 Ma Kelly porphyry, previously thought to be a felsic volcanic interbed in the Euro Basalt, is now recognized as intruding the Euro Basalt and is associated with the overlying Wyman Formation. The Charteris Basalt, previously included in the Gorge Creek Group, is now included with the Kelly Subgroup and it conformably overlies the Wyman Formation. The redefined Warrawoona Group is unconformably overlain by sedimentary rocks of the c. 3308 Ma Budjan Creek Formation and dominantly clastic sedimentary rocks of the 3240–2940 Ma Gorge Creek Group (locally redefined to exclude the Charteris Basalt).

KEYWORDS: Archaean, Pilbara Craton, stratigraphy, East Pilbara Granite–Greenstone Terrane, Kelly greenstone belt.

Introduction

The Archaean Pilbara Craton in the northwest of Western Australia contains well-exposed granite–greenstones that are unconformably overlain by volcanic and sedimentary rocks of the c. 2770–2400 Ma Hamersley Basin, which around the Kelly greenstone belt are part of the 2770–2630 Ma Fortescue Group (Trendall, 1990; Thorne and Trendall, 2001). The granite–greenstones of the Kelly greenstone belt form part of the c. 3655–2830 Ma East Pilbara Granite–Greenstone Terrane (EPGGT) of the northern Pilbara Craton (Hickman, 2001; Fig. 1).

Hickman (1983, 1984) provided a regional lithostratigraphic interpretation of the EPGGT based on 1:250 000-scale reconnaissance geological mapping during the 1970s. Subsequent investigations broadly confirmed the continuity between greenstone belts of the EPGGT, but have also shown that the greenstones are more laterally variable than previously thought (Van Kranendonk et al., 2002). The following review and reinterpretation of the stratigraphy of the Kelly greenstone belt is based on mapping and geochronology resulting from the National Geoscience Mapping Accord (NGMA) projects on the SPLIT ROCK * (Bagas and Van Kranendonk, in prep.), MOUNT EDGAR (Williams and Bagas, in prep.), and NULLAGINE (Bagas, in prep.) 1:100 000 sheet areas.

East Pilbara Granite–Greenstone Terrane

The EPGGT is characterized by large ovoid granitoid complexes forming domes that are surrounded by synformal greenstone belts or unconformably overlain by volcanic and sedimentary rocks of the Fortescue Group (Fig. 2). The greenstone belts commonly dip at moderate to steep angles away from granitoid complexes, and are typically metamorphosed to greenschist facies, although higher grades are reached near the complexes.

Table 1 summarizes the former and current stratigraphic nomenclature of the EPGGT, and Table 2 shows the geochronological data for the Kelly greenstone belt.

Stratigraphy of the Kelly greenstone belt

The southern part of the Kelly greenstone belt outcrops between the Corunna Downs Granitoid Complex (CDGC) to the west and

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

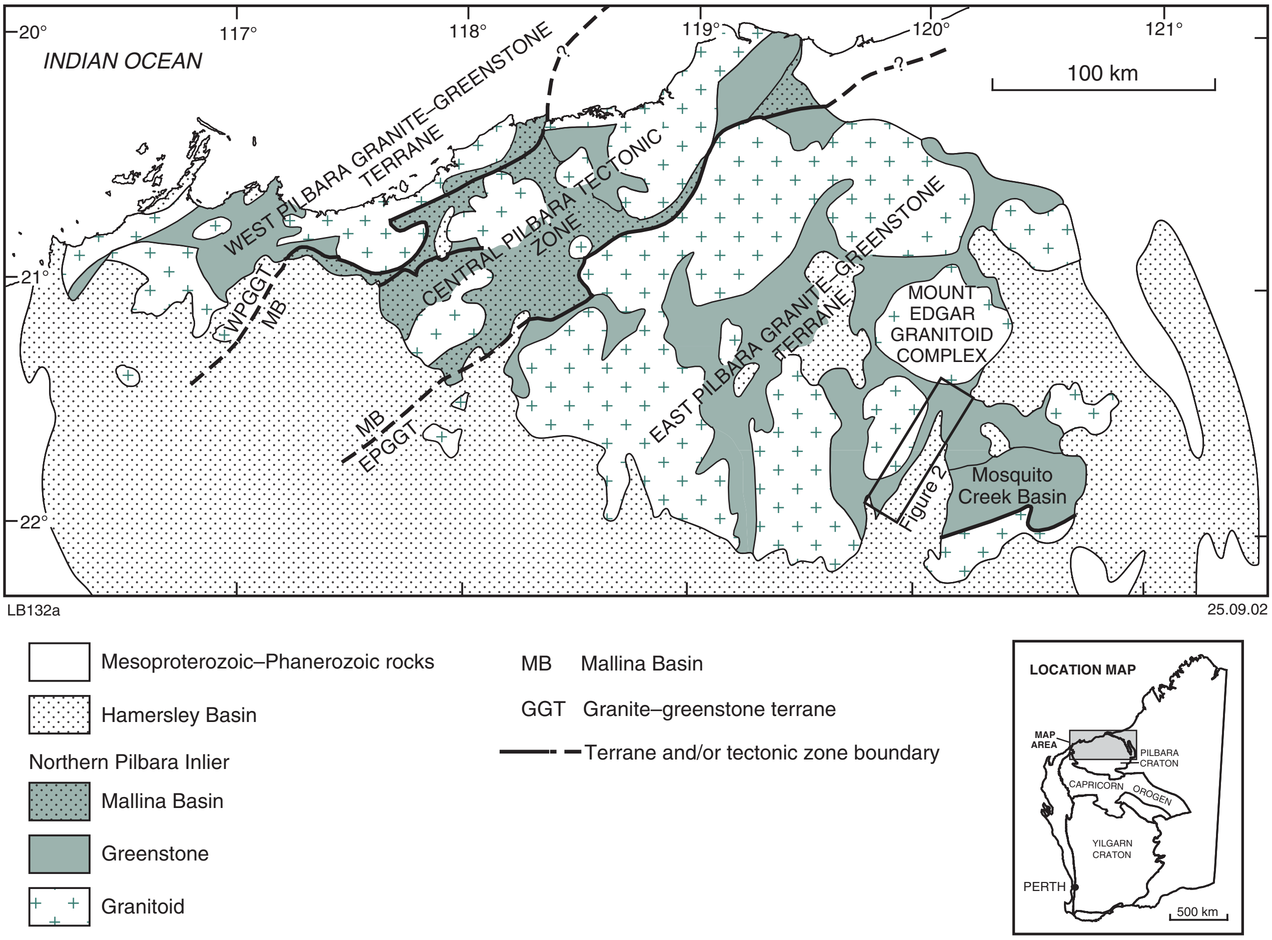

Figure 1. Regional geological setting of the East Pilbara Granite–Greenstone Terrane

the Fortescue Group to the east, and the northeastern part of the belt lies between the McPhee Dome and the Mount Edgar Granitoid Complex (Fig. 2). In both areas the belt comprises dominantly greenschist-facies volcanic rocks of the Salgash and Kelly Subgroups of the Warrawoona Group. The Warrawoona Group is unconformably overlain by the dominantly sedimentary sequences of the Budjan Creek Formation (Noldart and Wyatt, 1962; Lipple, 1975), which in turn is unconformably overlain by the dominantly clastic sedimentary rocks of the Gorge Creek Group (Noldart and Wyatt, 1962; Ryan and Kriewaldt, 1964; Hickman and Lipple, 1978; Hickman, 1983), and the Fortescue Group (Bagas and Van Kranendonk, in prep.; Table 2).

Granitoid rocks in the CDGC (Fig. 2) mostly range in age from about 3317 to 3307 Ma (Nelson, 2001, 2002), and were emplaced approximately contemporaneously with felsic volcanic rocks of the Wyman Formation and the Budjan Creek Formation (Bagas et al., 2002).

Warrawoona Group

Following detailed mapping and geochronological studies in the Kelly greenstone belt, three major stratigraphic revisions have been made for the Warrawoona Group (Tables 1 and 2):

- The Kelly greenstone belt is now subdivided into the redefined Salgash Subgroup and the newly defined Kelly Subgroup.
- The felsic volcanic rocks of the c. 3325–3320 Ma Wyman Formation conformably overlie the Euro Basalt and are now included in the Warrawoona Group.
- The Charteris Basalt, which was previously included in the Gorge Creek Group, is now included with the Euro Basalt and Wyman Formation in the Kelly Subgroup of the Warrawoona Group.

Another change not shown in Table 1 is that the 3324 ± 4 Ma Kelly porphyry, previously thought to be a correlative of the Panorama Formation (Hickman, 1983) or a felsic volcanic interbed in the Euro Basalt (McNaughton et al., 1993), is now recognized as intruding the Euro Basalt and associated with the overlying Wyman Formation.

Salgash Subgroup

The Salgash Subgroup, which formerly included the Towers Formation, Apex Basalt, Panorama Formation, and Euro Basalt (Hickman 1990), now comprises the Apex Basalt (not in the Kelly greenstone belt), Panorama Formation, and Strelley Pool Chert (Table 1).

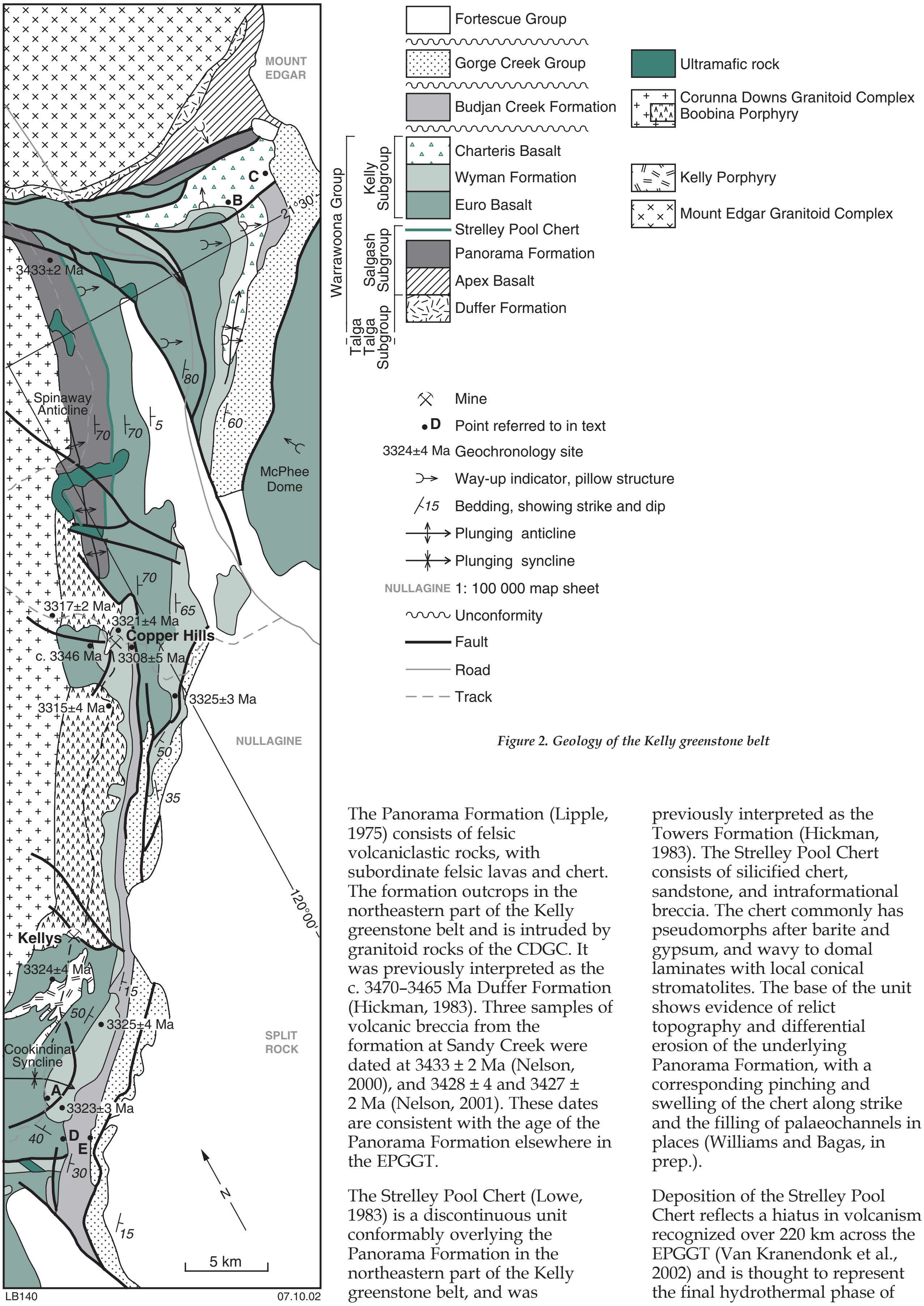

Figure 2. Geology of the Kelly greenstone belt

The Panorama Formation (Lipple, 1975) consists of felsic volcaniclastic rocks, with subordinate felsic lavas and chert. The formation outcrops in the northeastern part of the Kelly greenstone belt and is intruded by granitoid rocks of the CDGC. It was previously interpreted as the c. 3470–3465 Ma Duffer Formation (Hickman, 1983). Three samples of volcanic breccia from the formation at Sandy Creek were dated at 3433 ± 2 Ma (Nelson, 2000), and 3428 ± 4 and 3427 ± 2 Ma (Nelson, 2001). These dates are consistent with the age of the Panorama Formation elsewhere in the EPGGT.

The Strelley Pool Chert (Lowe, 1983) is a discontinuous unit conformably overlying the Panorama Formation in the northeastern part of the Kelly greenstone belt, and was previously interpreted as the Towers Formation (Hickman, 1983). The Strelley Pool Chert consists of silicified chert, sandstone, and intraformational breccia. The chert commonly has pseudomorphs after barite and gypsum, and wavy to domal laminates with local conical stromatolites. The base of the unit shows evidence of relict topography and differential erosion of the underlying Panorama Formation, with a corresponding pinching and swelling of the chert along strike and the filling of palaeochannels in places (Williams and Bagas, in prep.).

Deposition of the Strelley Pool Chert reflects a hiatus in volcanism recognized over 220 km across the EPGGT (Van Kranendonk et al., 2002) and is thought to represent the final hydrothermal phase of

Table 1. **Stratigraphy of the East Pilbara Granite–Greentone Terrane. Units in the Kelly greenstone belt are here shown in bold, and the stratigraphic nomenclature for units outside of the belt is taken from Van Kranendonk et al. (2002)**

Hickman (1990)

De Grey Group		Lalla Rookh Sandstone
De Grey Group		**Budjan Creek Formation**
unconformity		
Gorge Creek Group		Honeyeater Basalt
Gorge Creek Group		Cleaverville Formation
Gorge Creek Group	Soanesville Subgroup	**Corboy Formation**
Gorge Creek Group	Soanesville Subgroup	**Charteris Basalt**
local unconformity		
Wyman Formation		
unconformity		
Warrawoona Group	Salgash Subgroup	**Euro Basalt**
Warrawoona Group	Salgash Subgroup	**Panorama Formation**
Warrawoona Group	Salgash Subgroup	Apex Basalt
Warrawoona Group	Salgash Subgroup	Towers Formation
Warrawoona Group		Duffer Formation
Warrawoona Group	Talga Talga Subgroup	Mount Ada Basalt
Warrawoona Group	Talga Talga Subgroup	McPhee Formation
Warrawoona Group	Talga Talga Subgroup	North Star Basalt

This paper

De Grey Group		Lalla Rookh Sandstone (s)
unconformity		
Gorge Creek Group		Pyramid Hill Formation (sh)
Gorge Creek Group		Honeyeater Basalt
Gorge Creek Group	Soanesville Subgroup	**Paddy Market Formation** (sh, BIF)
Gorge Creek Group	Soanesville Subgroup	**Corboy Formation**
Gorge Creek Group	Soanesville Subgroup	Pincunah Hill Formation (sh, BIF)
local unconformity		
Sulphur Springs Group		Kangaroo Caves Formation (f, an, c)
Sulphur Springs Group		Kunagunarrina Formation (u, b)
Sulphur Springs Group		Leilira Formation (ss, f)
F—F fault / unconformity		
Golden Cockatoo Formation (ss, sh)		
Budjan Creek Formation (cong, ss, sh, f)		
unconformity		
Warrawoona Group	Kelly Subgroup	**Charteris Basalt** (b, f)
Warrawoona Group	Kelly Subgroup	**Wyman Formation** (f, ss)
Warrawoona Group	Kelly Subgroup	**Euro Basalt** (b, c)
Warrawoona Group	Salgash Subgroup	**Strelley Pool Chert** (c, ss, cong)
Warrawoona Group	Salgash Subgroup	**Panorama Formation** (f)
Warrawoona Group	Salgash Subgroup	Apex Basalt (b)
Warrawoona Group	Towers Formation (c, b)	
Warrawoona Group	Talga Talga Subgroup	Duffer Formation (f, an)
Warrawoona Group	Talga Talga Subgroup	Mount Ada Basalt (b)
Warrawoona Group	Talga Talga Subgroup	McPhee Formation (u, c, f)
Warrawoona Group	Talga Talga Subgroup	North Star Basalt (b, u)
Warrawoona Group	Talga Talga Subgroup	Dresser Formation (c, b)
Warrawoona Group	Talga Talga Subgroup	Double Bar Formation (b)
Coonterunah Group		Coucal Formation (f, c)
Coonterunah Group		Table Top Formation (b)

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∿∿∿	unconformity	cong	conglomerate
∿∿– -	local unconformity	ss	sandstone
F——F	fault	sh	shale
b	basalt	c	chert
u	ultramafic rock	BIF	banded iron-formation
an	andesite	f	felsic volcanic rocks

felsic volcanism associated with the deposition of the Panorama Formation. Both formations are interpreted to be genetically related (Van Kranendonk, 2000), whereas the overlying ultramafic and mafic rocks of the Euro Basalt mark the beginning of a new volcanic phase. Van Kranendonk et al. (2002) suggested that the Euro Basalt was related to a separate mantle plume than the one they interpreted to have produced the Salgash Subgroup. For this reason the Euro Basalt has been separated from the Salgash Subgroup and included in the overlying Kelly Subgroup (Bagas and Van Kranendonk, in prep.).

Kelly Subgroup

The Kelly Subgroup conformably overlies the Salgash Subgroup and consists of the Euro Basalt, Wyman Formation, and Charteris Basalt.

After deposition of the Strelley Pool Chert, volcanism in the Kelly greenstone belt resumed with deposition of high-Mg basaltic rocks and komatiite of the Euro Basalt. The date at which this volcanism resumed is unknown, but probably occurred at c. 3420–3410 Ma, which is the age of gold mineralization (Thorpe et al., 1992a) and zircon overgrowths (Zegers, 1996; Van Kranendonk, in prep.). The duration of volcanism is a major outstanding problem, but indications are that this succession was deposited over an approximately 100 million-year period from c. 3420 to 3325 Ma, the younger limit being the age of the conformably overlying Wyman Formation in the southeastern part of the Kelly greenstone belt.

Table 2. Ages of units in and around the Kelly greenstone belt

Unit	*Age (Ma)*
Fortescue Group	2770–2630
Gorge Creek Group	3240–2940
Budjan Creek Formation	3308 ± 5
Boobina Porphyry	3315 ± 4
Kelly porphyry	3324 ± 4
Warrawoona Group	c. 3490–3320
Kelly Subgroup	
Charteris Basalt	c. 3320 (inferred)
Wyman Formation	c. 3325–3320
Euro Basalt	3420–3325
Salgash Subgroup	
Strelley Pool Chert	c. 3425 (inferred)
Panorama Formation	3433–3427

In the Kelly greenstone belt the Euro Basalt consists dominantly of tholeiitic pillow basalt, with subordinate interbedded pillowed, ocellar, and occasionally vesicular, high-Mg basalt. The base of the formation typically contains a unit of komatiite or komatiitic basalt up to 500 m thick. The formation is also interbedded with chert that is locally stromatolitic (Williams and Bagas, in prep.). The Euro Basalt has a stratigraphic thickness of about 4 km in the northeastern part of the Kelly greenstone belt. However, this is a minimum thickness for the formation as its top is locally faulted out, and elsewhere in the belt its base is intruded by granitoid rocks of the CDGC.

West of the Copper Hills mine, the Euro Basalt contains several bands of chert interbedded with minor mafic and felsic tuff. Chert in the upper part of the formation contains zircon populations of 3363 ± 6, 3346 ± 6, and 3311 ± 9 Ma (Nelson, 2001). The age of the youngest population (6 of 22 zircons analysed) is within the error margins of the 3315 ± 4 Ma age of the Boobina Porphyry (Barley and Pickard, 1999), which intruded the Euro Basalt about 500 m to the south. The age of the youngest zircon population is therefore interpreted to represent an overgrowth event associated with porphyry intrusion (Bagas and Van Kranendonk, in prep.). The c. 3346 Ma age of the largest population (14 of 22 samples) is interpreted as the depositional age of the tuff, whereas the oldest population is considered to be xenocrystic.

The c. 3325 Ma Wyman Formation conformably overlies the Euro Basalt across a transitional zone of interbedded rhyolite and basalt that is about 50 m thick (e.g. at point A on Fig. 2) and is now therefore included in the Warrawoona Group. The Wyman Formation was excluded from the Warrawoona Group by Hickman (1990) for two reasons. Firstly, geochronological data available in the late 1980s suggested that the contact between the Wyman Formation and underlying Euro Basalt represented a time break of about 125 million years. Recent geochronological data, however, indicate that the upper part of the Euro Basalt is about 3346 Ma. Secondly, mapping in the 1970s suggested that the Wyman Formation unconformably overlies the Salgash Subgroup 7 km southwest of Budjan Creek (Hickman, 1983). New mapping has established that the unconformity in this area is between the Euro Basalt and the Budjan Creek Formation.

The Wyman Formation is about 1 km thick and consists of felsic tuff interbedded with porphyritic rhyolite to rhyodacite, felsic agglomerate and volcaniclastic sandstone, and fine-grained quartz sandstone. The formation has been dated in three places in the Kelly greenstone belt with a conventional zircon age of 3325 ± 4 Ma (Thorpe et al., 1992b; McNaughton et al., 1993), and sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon ages of 3323 ± 3 Ma (Nelson, 2001), and 3321 ± 4 Ma (Barley and Pickard, 1999). These ages are identical within analytical error to the 3324 ± 4 Ma SHRIMP U–Pb zircon age for intrusive felsic rocks from the informally named Kelly porphyry (McNaughton et al., 1993). The porphyry has been shown to be an intrusive unit by Bagas and Van Kranendonk (in prep.) rather than an extrusive unit as suggested by Hickman (1983) and McNaughton et al. (1993). These data confirm that there is a synchronous relationship between volcanism (Wyman Formation) and subvolcanic intrusions (Kelly porphyry) in the Kelly greenstone belt.

The Charteris Basalt outcrops in the northeastern part of the Kelly greenstone belt, on the northwestern part of NULLAGINE and southwestern part of MOUNT EDGAR (Fig. 2), where it is between 500 and 2000 m thick and consists mainly of pillowed high-Mg and tholeiitic basalt. The basalt lies conformably on the Wyman Formation (e.g. at point B on Fig. 2; Williams and Bagas, in prep.) and is unconformably overlain by clastic sedimentary rocks of the 3240–2940 Ma Gorge Creek Group (e.g. at point C on Fig. 2; Williams and Bagas, in prep.). The Charteris Basalt must therefore be aged between 3320 and 3240 Ma, and has thus been reassigned from the unconformably overlying Gorge Creek Group (Hickman, 1983; Lipple, 1975) to the top of the Warrawoona Group (Table 1).

Rocks similar to the Charteris Basalt within the Wyman Formation about 50 km west of the Kelly greenstone belt in the Warrawoona area (Hickman, in prep.) indicate that the ultramafic and mafic volcanic rocks of the Charteris Basalt do not necessarily represent a new volcanic cycle above the Kelly Subgroup.

Budjan Creek Formation

The Budjan Creek Formation only outcrops in the Kelly greenstone belt where the upward-fining boulder conglomerate at the base of the formation unconformably overlies the Warrawoona Group (e.g. at point D on Fig. 2). The formation grades upward into interbedded sandstone and siltstone, which are overlain across a low-angle unconformity by pebble conglomerate at the base of the Gorge Creek Group (e.g. at point E on Fig 2; Bagas and Van Kranendonk, in prep.). The lower unconformity with the Warrawoona Group was previously equated with the one above the Gorge Creek Group (Lipple, 1975; Hickman, 1983; Hickman, 1990), and the formation was correlated with the Lalla Rookh Sandstone of the De Grey Group (Table 1). The unconformity above the Budjan Creek Formation was not previously recognized and shows that the formation cannot be correlated with the much younger De Grey Group.

The thickness of the Budjan Creek Formation varies along strike from about 1.5 km southeast of the Kelly mine to about 500 m east of the Copper Hills mine. The basal part of the formation southeast of the Kelly mine is an approximately 1 km-thick succession, starting with a boulder conglomerate that fines upward into a pebble conglomerate interbedded with arkosic sandstone, and then into siltstone and shale. The clasts in the conglomerate consist predominantly of vein quartz and chert with rare felsic volcanic rocks, and are consistent with derivation from a local Warrawoona Group source. In addition, the arkosic composition of the sandstone and the rare south- to southeast-trending palaeocurrent direction within the sandstone are consistent with the derivation of at least part of the formation from the CDGC.

The basal clastic unit of the Budjan Creek Formation is conformably and sharply overlain by an approximately 500 m-thick marker horizon, which extends to north of the Copper Hills mine, and consists of lithic wacke, siltstone, minor conglomerate, crystal-lithic felsic tuff and agglomerate, and fine-grained volcanogenic sandstone. Crystal-lithic tuff from 1 km southeast of the Copper Hills mine (Fig. 2) was dated at 3308 ± 5 Ma (Nelson, 2001). This date provides a tight constraint on the age of folding and faulting of the Warrawoona Group in the Kelly greenstone belt.

Gorge Creek Group

The Gorge Creek Group overlies the Budjan Creek Formation with a low-angle unconformity on SPLIT ROCK, disconformably overlies the c. 3240 Ma Sulphur Springs Group on adjoining NORTH SHAW and TAMBOURAH (Van Kranendonk and Morant, 1998), and is unconformably overlain by the c. 2940 Ma De Grey Group (Van Kranendonk et al., 2002). The Gorge Creek Group is therefore between 3240 and 2940 Ma in age.

The Gorge Creek Group on eastern SPLIT ROCK and southern MOUNT EDGAR is at least 750 m thick. Its basal unit consists of a lensoidal, upward-fining, clast- to matrix-supported, cobble to pebble conglomerate that probably correlates lithologically with the Corboy Formation (Table 1). The conglomerate contains clasts of chert, felsic porphyry, and rare mafic volcanic rocks, which are identical to rocks in the underlying Warrawoona Group. The conglomerate is conformably overlain by a succession of silicified and ferruginized shale, banded iron-formation and grey and white layered chert, banded and ferruginous chert, black carbonaceous shale and minor siltstone, and thinly bedded banded iron-formation interbedded with ferruginous chert. This succession is lithologically similar to, and probably correlates with, the Paddy Market Formation (Table 1).

Discussion and conclusion

The volcanic and volcaniclastic rocks of the Warrawoona Group in the Kelly greenstone belt are unconformably overlain by successively younger groups with shallowing dips to the east away from the margin of the CDGC and Mount Edgar Granitoid Complex.

The unconformable relationships between the c. 3325–3320 Ma Wyman Formation of the Warrawoona Group and the 3308 Ma Budjan Creek Formation, and between the Budjan Creek Formation and the c. 3235–2970 Ma Gorge Creek Group have a number of implications. Several different types of tectonic structures formed during the short period between 3320 and 3308 Ma, and between 3308 and c. 3240 Ma (Bagas and Van Kranendonk, in prep.). The first period of deformation may be related to the development of the dome forming around the CDGC, and points to a discernible episode of compression related to the formation of the Spinaway Anticline, Cookindina Syncline, and the CDGC (Fig. 2). The maximum age limit of the first event is slightly older than the granitic rocks near the eastern edge of the CDGC, which decrease in age westward from 3317 ± 2 Ma (Barley and Pickard, 1999) to 3307 ± 4 Ma (Nelson, 2000). These limited geochronological data indicate that granitoid magmatism was synchronous with the older deformation event.

The Budjan Creek Formation and Gorge Creek Group dip at about 30° away from the centre of the CDGC in the same direction as limited palaeocurrents measured in the formations (Bagas and Van Kranendonk, in prep.). This tilting away from the complex is indicative of its upward and outward growth after the earlier deformation event. The Gorge Creek Group overlies the Budjan Creek Formation with a low-angle unconformity on the eastern side of SPLIT ROCK, indicating that tilting was intermittent during the deposition of these units.

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Geochemistry of the Corunna Downs Granitoid Complex, East Pilbara Granite–Greenstone Terrane, Western Australia

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Abstract

About 80% of the Archaean Corunna Downs Granitoid Complex in the East Pilbara Granite–Greenstone Terrane consists of c. 3315 Ma monzogranites. The monzogranites are typically highly fractionated, K rich, Al poor, and have trace element compositions consistent with remelting of an older tonalitic–trondhjemitic–granodioritic (TTG) crust at a mid-crustal level. The remaining 20% of the complex comprises tonalites, trondhjemites, and granodiorites. Some of these granitoids are as old as c. 3400 Ma, but the majority are similar in age to the monzogranites. The tonalites, trondhjemites, and granodiorites have high Y and Yb, and low Sr and Al_2O_3 concentrations compared to classic Archaean TTGs, which are thought to form through high-pressure melting of hydrated mafic crust. In contrast to TTGs, the tonalitic, trondhjemitic, and granodioritic rocks of the complex have a low-pressure, mid- to lower-crustal, amphibolite source that was garnet free and probably also had residual plagioclase. It is proposed that at the same time as mid-crustal melting of TTG occurred to form the monzogranites, melting of an associated mafic intraplate formed the tonalites, trondhjemites, and granodiorites.

KEYWORDS: Archaean, Pilbara Craton, Corunna Downs Granitoid Complex, tonalite, trondhjemite, granodiorite, granite.

Introduction

Rocks of the Archaean tonalite–trondhjemite–granodiorite (TTG) series formed by melting of hydrous mafic crust at high pressure (e.g. Rapp et al., 1991). Although it is still widely accepted that most Archaean granite–greenstones are dominated by TTG (e.g. Condie, 1981; Windley, 1995), some late Archaean terrains (e.g. the Yilgarn Craton) are clearly dominated by K-rich granitoid rocks that are derived through remelting of older felsic (TTG-dominated) crust (Sylvester, 1994; Champion and Sheraton, 1997; Champion and Smithies, 2000). The evidence so far from the granitoid complexes of the Pilbara Craton is that the amount of TTG preserved is very small, and that these complexes are dominated by K-rich granitoids (Collins, 1993; Champion and Smithies 1999, 2000). This observation is important because it implies that a much greater degree of crustal reworking has occurred in the Pilbara Craton than is required by TTG-dominated crust. Here we discuss the geology and geochemistry of the Corunna Downs Granitoid Complex (CDGC) in the southeastern part of the East Pilbara Granite–Greenstone Terrane (EPGGT; Fig. 1). This complex is unusual for the Pilbara Craton because it lacks rocks of the classic Archaean TTG series (Rapp et al., 1999), although it does contain tonalite, trondhjemite, and granodiorite (Fig. 2). This study is based largely on geochemical analyses of about 200 samples that were collected in the early 1980s (Davy, 1988) and have recently been reanalysed by Geoscience Australia (formerly Australian Geological Survey Organisation).

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Geological setting

The CDGC has an elliptical and domal shape with a long axis of about 50 km, and is surrounded by greenstone belts (Figs 1 and 2). The greenstones comprise dominantly greenschist-facies volcanic rocks of the Warrawoona Group, which is dated between c. 3480 and 3325 Ma, and lesser amounts of metamorphosed sedimentary rocks, and ultramafic, mafic, felsic, and intrusive rocks (Bagas and Van Kranendonk, in prep.). This succession is unconformably overlain by the c. 3310 Ma Budjan Creek Formation, which in turn is unconformably overlain by the dominantly clastic rocks of the Gorge Creek Group dated at younger than 3235 Ma. The entire volcano-sedimentary succession dips and youngs away from the CDGC, and all granite–greenstone contacts are intrusive.

Several generations of granitic magmatism have been documented from granitoid complexes of the EPGGT (Hickman, 1983). Major magmatic age ranges include 3470–3410, 3330–3100, 3000–2930, and c. 2850–2830 Ma (Champion and

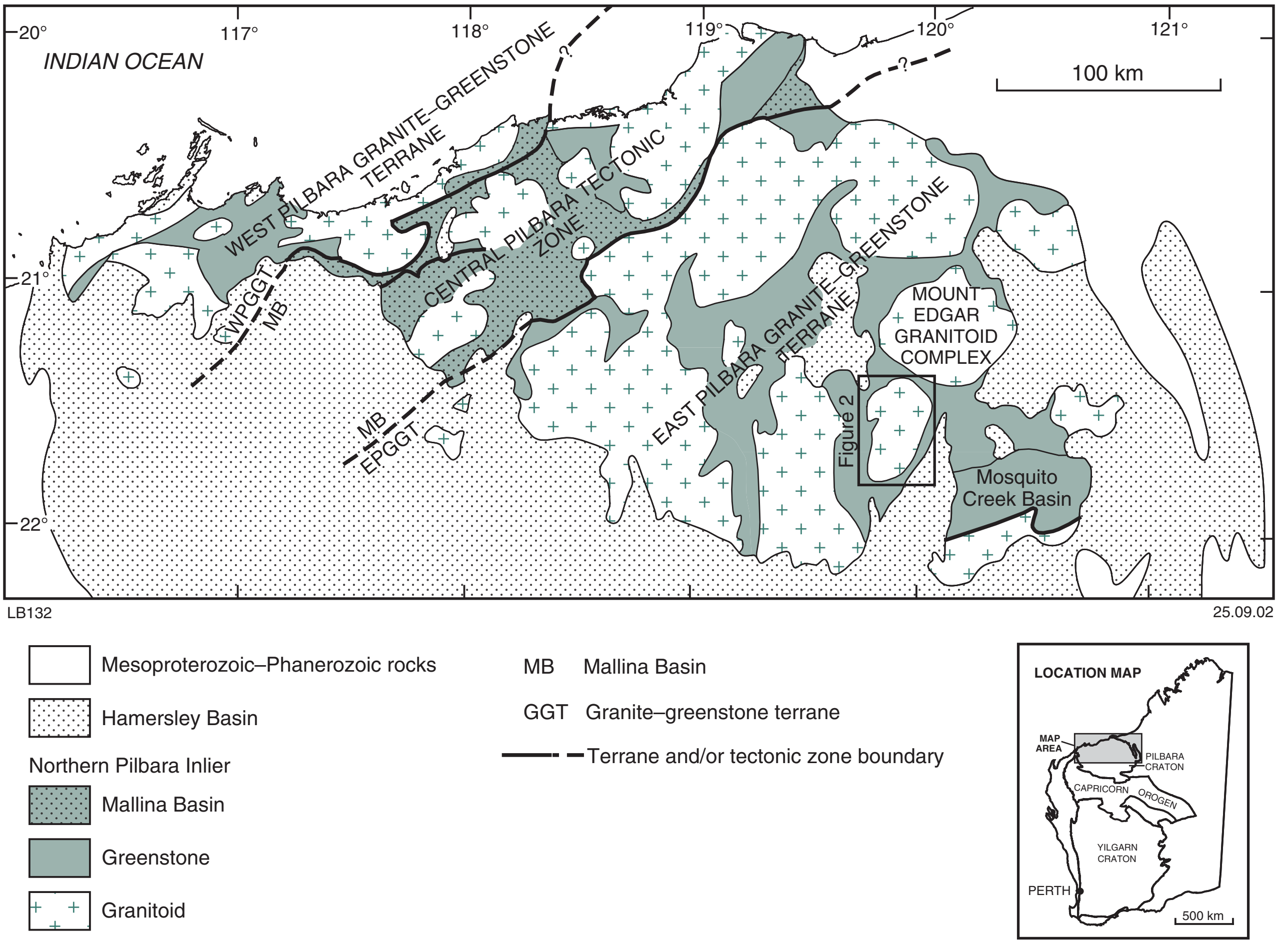

Figure 1. Location of the Corunna Downs Granitoid Complex and distribution of granitoids

Smithies, 1999). The older period of magmatism (3470–3410 Ma) included locally significant TTG magmatism representing high-pressure melting of a mafic source (Champion and Smithies, 1999). Younger TTG-type rocks are present in the West Pilbara Granite–Greenstone Terrane and Central Pilbara Tectonic Zone (Fig. 1; Champion and Smithies, 1999, 2000), but are rare in the EPGGT. Most magmatism after c. 3400 Ma represents remelting of older crust, including TTG older than 3400 Ma, to produce moderate- to high-K monzogranite (Champion and Smithies, 1999).

In contrast to most other granitoid complexes of the EPGGT, most granitoids in the CDGC fall within a narrow intrusive age range of around 3317 to 3307 Ma (Nelson, 2001, 2002, in prep.), including the 3315 Ma Boobina Porphyry (Barley and Pickard, 1999). These rocks were emplaced contemporaneously with felsic volcanic rocks in the surrounding greenstone belts, including the c. 3325 Ma Wyman Formation and felsic lithic tuff in the c. 3308 Ma Budjan Creek Formation (Nelson, 2001).

Geology of the Corunna Downs Granitoid Complex

The Corunna Downs Granitoid Complex can be subdivided into the following readily mappable units (Fig. 2).

Nandingarra Granodiorite

The Nandingarra Granodiorite (Bagas and Van Kranendonk, in prep.; *AgOna**) forms an elliptical body of fine- to coarse-grained, equigranular, biotite granodiorite, with lesser amounts of tonalite and monzogranite. Rocks along the eastern margin of the body show a more restricted compositional range from tonalite to granodiorite, and contain hornblende as an additional mafic mineral. The eastern edge of the Nandingarra Granodiorite contains biotite tonalite to granodiorite with minor microcline.

Sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon ages of c. 3427–3408, 3313 ± 3, and 3300 ± 3 Ma from tonalites (Nelson, 2002) indicate that the Nandingarra Granodiorite is a composite body that includes older components.

Tonalite

Fine- to medium-grained tonalite (*AgOt*), containing minor amounts of hornblende and microcline, is

* Codes refer to units shown on the SPLIT ROCK 1:100 000 geological series map (Bagas and Van Kranendonk, 2002).

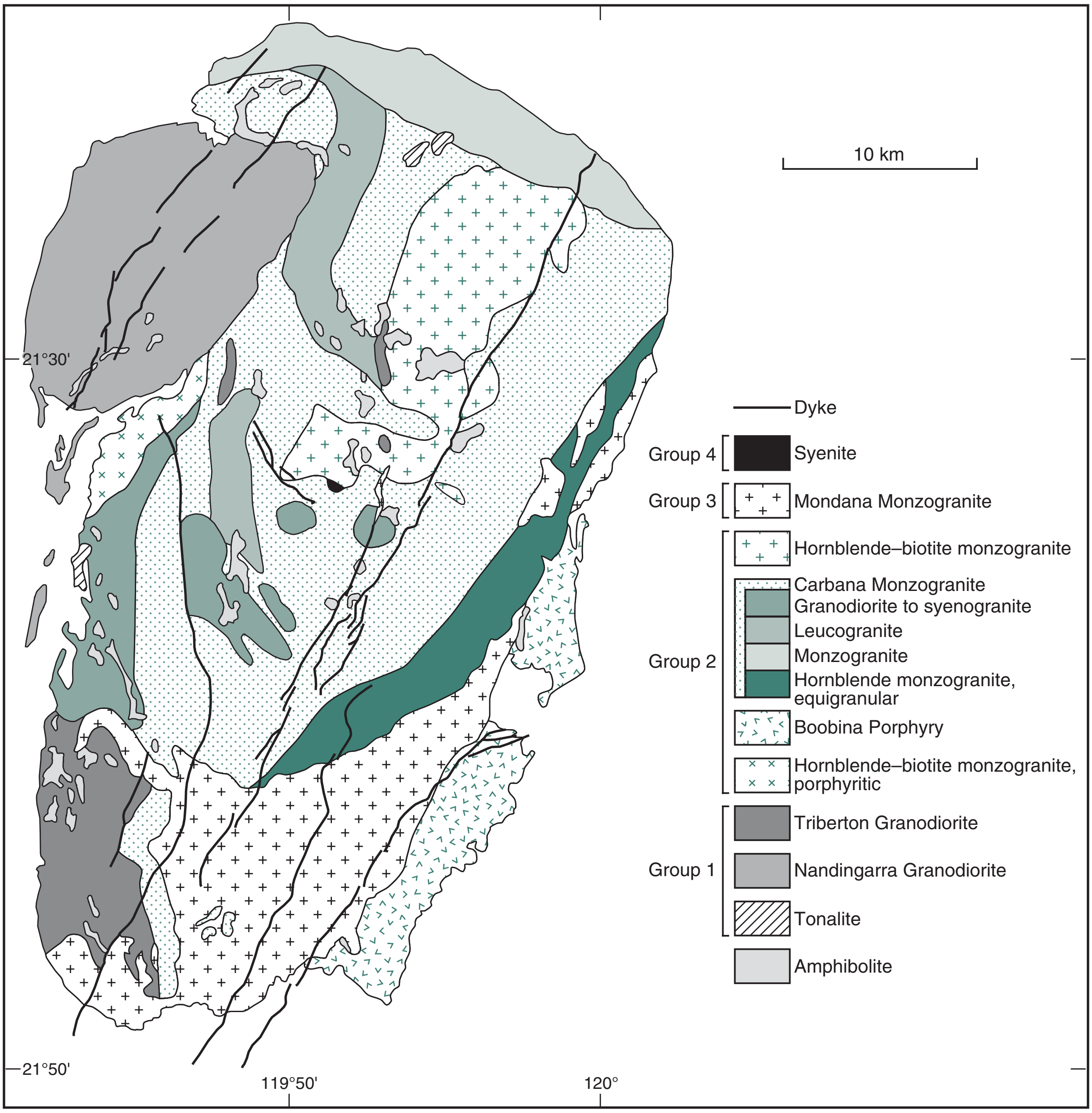

Figure 2. Geology of the Corunna Downs Granitoid Complex

exposed near the western and northern edges of the Carbana Monzogranite (Fig. 2).

Triberton Granodiorite

The Triberton Granodiorite (Bagas and Van Kranendonk, 2002; *Ag*o*tr*) is a porphyritic, medium- to coarse-grained, biotite–hornblende granodiorite with minor medium-grained tonalite and porphyritic monzogranite containing abundant mafic xenoliths.

Carbana Monzogranite

The Carbana Monzogranite was previously called the 'Carbana Pool Adamellite' by Hickman and Lipple (1978). The redefined Carbana Monzogranite now includes the granitic rocks forming most of the northern two-thirds of the CDGC. The Carbana Monzogranite includes fine- to coarse-grained, plagioclase-phyric biotite monzogranite to granodiorite (*Ag*o*ca*) with minor pegmatitic dykes, as well as fine- to medium-grained, equigranular to slightly porphyritic, hornblende monzogranite. The Carbana Monzogranite commonly contains abundant mafic xenoliths that were probably derived from the Warrawoona Group.

Four samples of the Carbana Monzogranite give SHRIMP U–Pb zircon ages of 3313 ± 9 and 3317 ± 2 Ma (Barley and Pickard, 1999), and 3315 ± 6 and 3314 ± 4 Ma (Nelson, in prep.). The monzogranite is locally intruded by hornblende-bearing monzogranite (*Ag*o*mh*) with a SHRIMP U–Pb zircon age of 3307 ± 4 Ma (Nelson, 2000).

Boobina Porphyry

The Boobina Porphyry (*AgObo*), originally defined by Lipple (1975), is a hornblende-bearing, quartz–feldspar porphyry with a glassy pink to purple matrix, which has intruded the Warrawoona Group along the eastern margin of the CDGC (Fig. 2). The Boobina Porphyry hosts a number of copper-mineralized quartz veins and has a SHRIMP U–Pb zircon age of 3315 ± 4 Ma (Barley and Pickard, 1999).

Mondana Monzogranite

The Mondana Monzogranite (*AgOmo*) was originally defined as the 'Mondana Adamellite' by Hickman and Lipple (1978), and is now known to have a smaller areal extent (Fig. 2). The monzogranite has intruded both the Triberton Granodiorite and the Boobina Porphyry in the southeastern part of the CDGC, and extends as a series of narrow bodies along the northeastern margin of the complex. The monzogranite is fine to medium grained and leucocratic, and includes abundant quartz-rich aplite dykes.

Syenite

A small and isolated outcrop of fine- to medium-grained, equigranular to porphyritic syenite (*AgOs*) in the centre of the Carbana Monzogranite (Fig. 2) consists of microcline, euhedral plagioclase commonly altered to epidote–sericite–albite–carbonate, relic biotite altered to chlorite, and less than 10% quartz. This syenite has not yet been dated.

Geochemistry

The samples collected by Davy (1988) included low-silica, mafic-xenocrystic granodiorite from the Nandingarra Granodiorite, mafic hornfels, and samples of dolerite dykes. These samples were considered to be contaminated or xenolithic and have been excluded from this study.

Selected trace element concentrations plotted against SiO_2 content (Fig. 3) for granitoids of the CDGC show a decrease in Na_2O with increasing K_2O and SiO_2 in contrast to a typical tonalite trend, which has increasing Na_2O with increasing SiO_2. The K–Na–Ca plot of Defant and Drummond (1993) also shows that the granitoids of the complex do not have typical TTG trends (Fig. 4). Most of the granitoids in the complex fall in the high-K calc-alkaline field of Le Maître (1989; Fig. 2). The tonalitic, trondhjemitic, and granodioritic rocks fall in the medium-K field and comprise about 20% of the analysed sample suite and a similar proportion of the outcrop area of the CDGC.

The rocks of the CDGC can be broadly subdivided into four groups that show progressively higher K_2O/Na_2O values (Fig. 3):

- Group 1 includes medium-K rocks with high Na_2O and Al_2O_3 and low K_2O/Na_2O (Fig. 3), which includes the Nandingarra Granodiorite, Triberton Granodiorite, and an unnamed tonalite from the northern part of the complex. This group commonly has the highest Mg# (Mg number*), which is typically between 35 and 43 (Fig. 5). This group also has notably lower SiO_2 than Groups 2 and 3.
- Group 2 includes high-K rocks with higher K_2O/Na_2O and lower Al_2O_3 than Group 1 rocks, and includes various granitoids of the Carbana Monzogranite, Boobina Porphyry, and the unnamed bodies of hornblende monzogranite.
- Group 3 includes highly leucocratic high-K rocks that commonly have higher SiO_2 and K_2O/Na_2O than Group 1 and 2 rocks, and the lowest Al_2O_3, CaO, MgO, and Fe_2O_3. These compositions are consistent with these rocks representing highly fractionated examples of Group 2. However, rocks of Group 3 form discrete intrusions, including the voluminous Mondana Monzogranite in the southwest of the CDGC.
- Group 4 is the syenite to quartz syenite that forms an isolated outcrop in the centre of the complex (Fig. 2). The syenite has higher total alkalies and Al_2O_3 and lower SiO_2 compared to rocks of the other groups.

Although rocks from Groups 1 and 2 partially overlap in terms of major element composition (Fig. 3), distinct trends for Y versus K_2O (Fig. 6) indicate that these two groups cannot be cogenetic. The highly fractionated Mondana Monzogranite (Group 3) has significantly higher Y, Rb, and Th concentrations and lower Sr concentrations than rocks of Group 2 for a given silica content. The combined major and trace element geochemistry of the CDGC granitoids suggests that compositional trends from Groups 1 to 2 and 3 commonly reflect progressively more fractionated compositions, whereas rocks of Group 1 are not directly related to rocks of Groups 2 and 3 genetically.

Average chondrite-normalized rare earth element (REE) patterns for the four groups in the CDGC are shown in Figure 7. The rocks exhibit strongly fractionated light REE (LREE) patterns with high La/Gd values, but nearly constant normalized heavy REE (HREE) concentrations. The tonalitic, trondhjemitic, and granodioritic rocks of Group 1 have a small negative Eu anomaly, whereas Group 2 shows a moderately negative Eu anomaly. Group 3 (Mondana Monzogranite) and Group 4 (syenite) have large negative Eu anomalies. Group 3 differs from Group 4 in having less variation in the LREE patterns. The REE pattern for rocks in Groups 2 and 3 are very similar to those of post-3300 Ma monzogranites in other parts of the East Pilbara Granite–Greenstone Terrane (Champion and Smithies, 2000).

Archaean TTG suites are typically characterized by a large silica range with an average SiO_2 content of about 70 wt % (Barker and Arth, 1976; Barker, 1979). They are sodic, with moderate K_2O and high Na_2O/K_2O (>1). They also are typically aluminous rocks (Al_2O_3 >15 wt % at 70% SiO_2), with high Sr and Ba (both >500 ppm), are LREE enriched (e.g. La/Yb >30), and HREE depleted (e.g. Yb<0.5 ppm) (Barker and Arth, 1976; Barker, 1979; Martin, 1994, 1999). Using these criteria, none of the rocks of the voluminous CDGC conform to a classic Archaean TTG suite. Most notably, even the tonalitic, trondhjemitic, and granodioritic rocks of Group 1 are too low in Al_2O_3 and too rich in Y (and HREE; see Figs 3 and 7). This supports the suggestions that the majority of true

* Mg # = 100×Mg/(Mg+ΣFe^{2+})

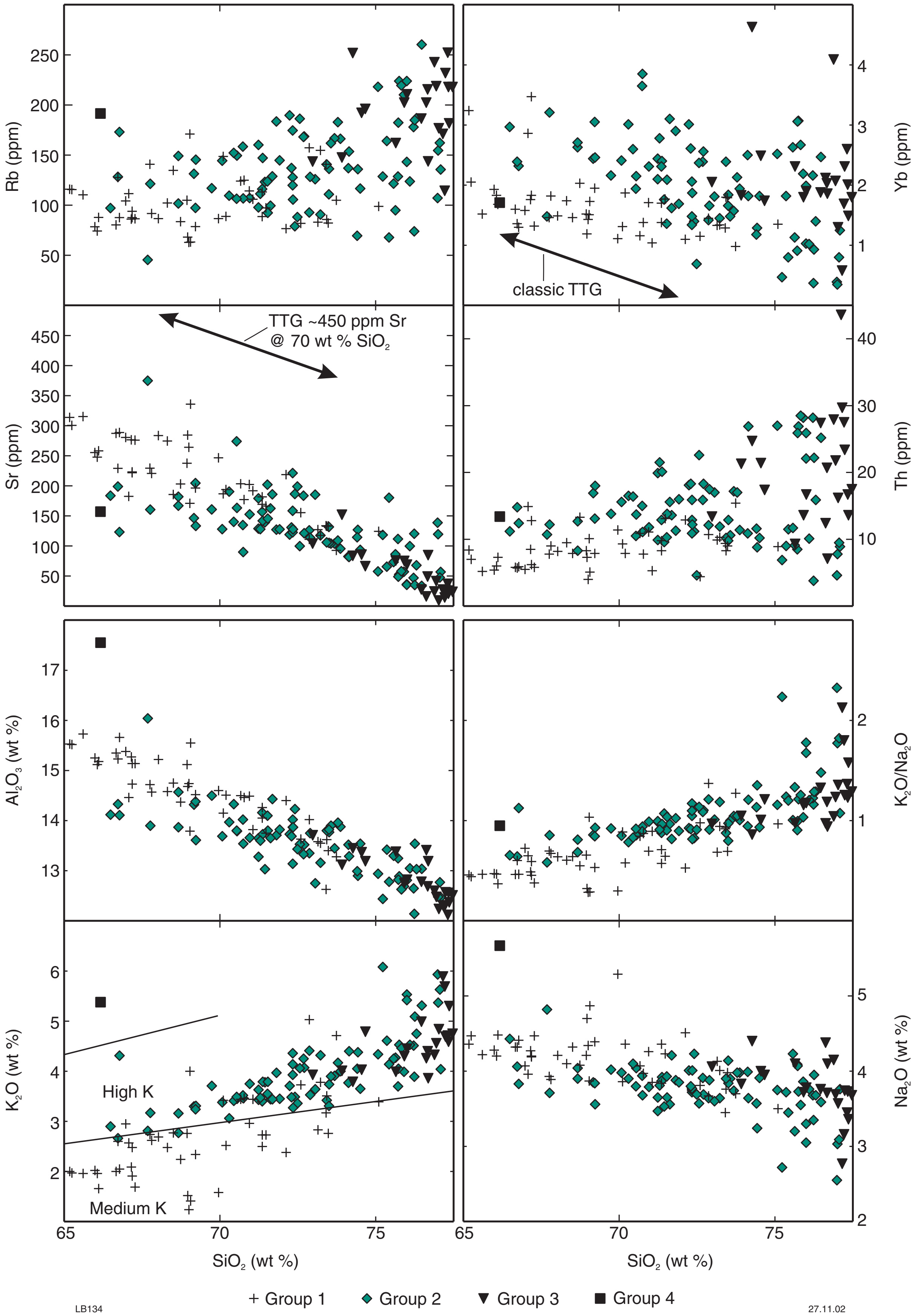

Figure 3. Harker (1909) variation diagrams showing the four major subdivisions of granitoids from the Corunna Downs Granitoid Complex

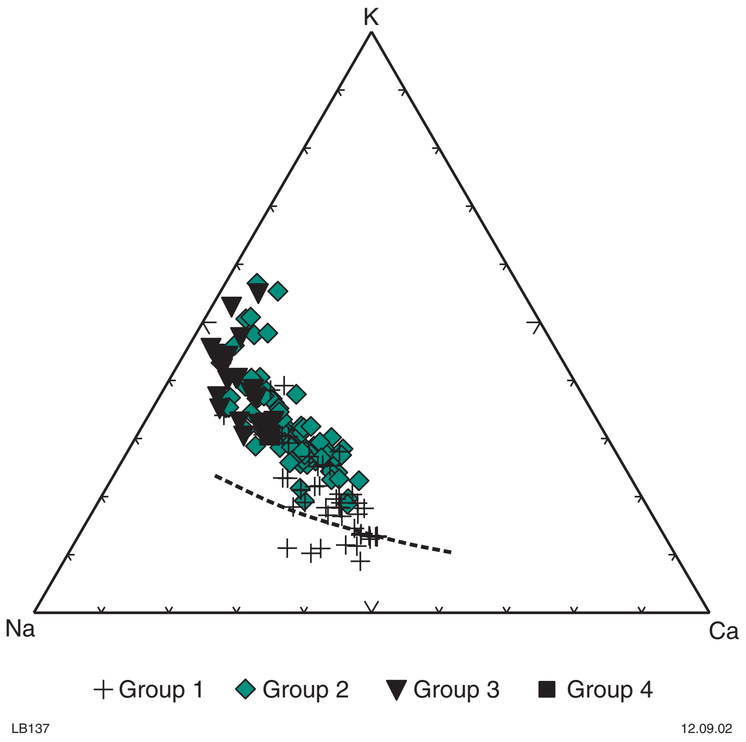

Figure 4. Ternary Ca–Na–K diagram of Archaean tonalite–trondhjemite–granodiorite. The dashed curve represents the trend of Defant and Drummond (1993)

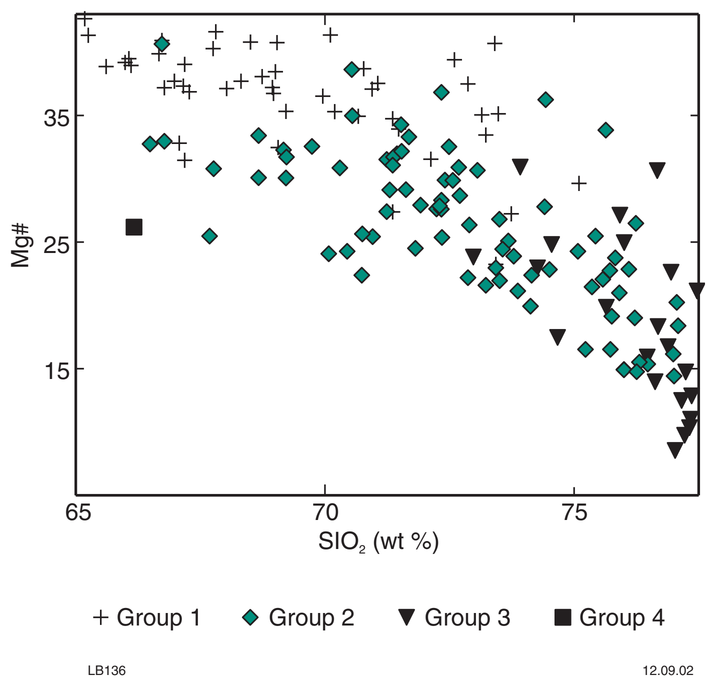

Figure 5. Plot of Mg# versus SiO_2 for the granitoid rocks in the Corunna Downs Granitoid Complex

TTGs in the Pilbara Craton are restricted to the older (>3440 Ma) rocks of the granitic complexes of the East Pilbara Granite–Greenstone Terrane, and that extensive recycling of old TTG to produce voluminous high-K magmatism was not restricted to the late Archaean (i.e. post-2800 Ma; Champion and Smithies, 1999).

Petrogenesis

A large proportion of the rocks of the CDGC (Groups 2–4) have compositions very similar to many (mostly post-3.3 Ga) high-K monzogranites throughout the Pilbara Craton (Champion and Smithies, 2000). These high-K monzogranites have a fairly narrow silica range (66–76%), are calc-alkaline, Sr depleted, and Y undepleted, and have mostly moderate to large negative Eu anomalies (Champion and Smithies, 1999, 2000). Such characteristics are thought to result from remelting of older TTG (Champion and Smithies, 1999, 2000). The tonalitic, trondhjemitic, and granodioritic rocks (Group 1) comprise 20% of the CDGC, but cannot be explained by the same process because they require a more mafic source.

Experimental results show that tonalitic to low- to medium-K granodioritic melts can be generated by low degrees of partial melting (<10%) of mafic crust at 8–16 kbar (e.g. Rapp et al., 1991). Melting in the presence of garnet leads to melts with high La/Yb values and very low Y and HREE concentrations (e.g. Sen and Dunn, 1994), whereas an absence of plagioclase in the residual assemblage results in melts with high Eu and Sr concentration (i.e. with no normalized negative Sr or Eu anomalies). Thus, the compositions of typical Archaean TTG are interpreted to reflect melting of mafic crust at pressures too high for plagioclase to be stable, but high enough to stabilize garnet in the residue (e.g. Martin, 1994).

Most rocks of the CDGC have high La/Yb values, but they also have low Gd/Yb values (flat middle to HREE normalized patterns) and high Y and Yb. These patterns contrast with those of classic Archaean TTG and indicate that garnet was probably not stable during melting of the source. The negative Eu anomalies in most of the rocks of the CDGC, including the tonalites, trondhjemites, and granodiorites of Group 1, also suggest that plagioclase was a residual mineral, or that the magmas underwent significant fractionation of plagioclase, or both. This is also indicated by the low Sr concentrations of these rocks compared with those of TTG at similar silica contents (Fig. 3). The geochemistry of the rocks of the CDGC reflects a hornblende- and plagioclase-bearing source and possibly also some fractionation of those minerals. The source must have melted at pressures lower than the garnet stability field (i.e. <10 kbar; Wyllie et al., 1997), and thus at higher crustal levels (~35–40 km) than was typical of the TTG series.

Available geochronology data suggest that the majority of the monzogranitic rocks of the CDGC were derived over the same period (~3320–3310 Ma). At least some tonalites, trondhjemites, and granodiorites are also of this age. A 3313–3300 Ma age for the Nandingarra Granodiorite suggests that it intruded the surrounding monzogranite; however, an age of c. 3427 Ma from a single tonalite indicates an additional older component.

We invoke a two-step process for the formation of the CDGC. First, high-pressure melting of young mafic lower crust produced TTG magmas (such as those presently exposed in the Shaw Granitoid Complex; Bickle et al., 1993). The thermal anomaly was also associated with basaltic magmatism that formed a mid-crustal intraplate. A second thermal event at c. 3.3 Ga then caused widespread crustal melting at a depth of 35–40 km. This event involved the re-melting of the older TTG to produce the monzogranites of the CDGC, whereas re-melting of the mafic intraplate produced the tonalitic to granodioritic rocks of the complex.

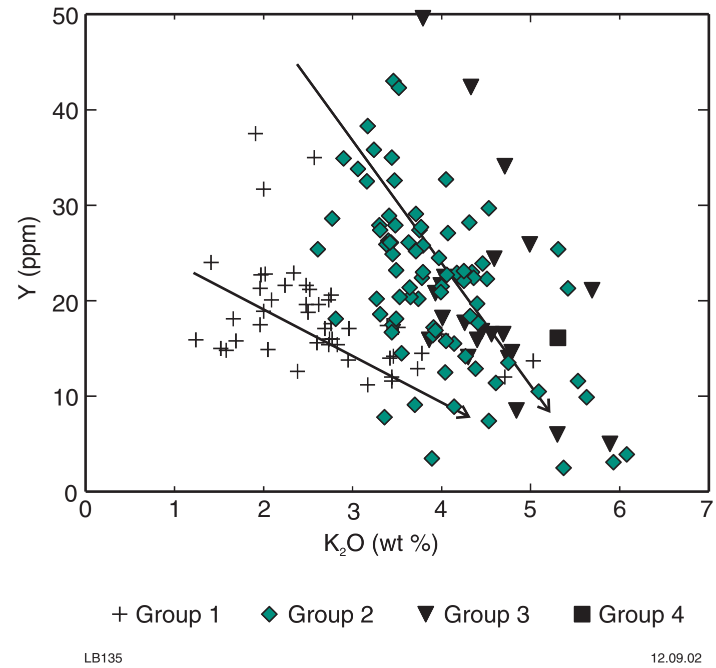

Figure 6. Compositional variation diagram for the four main groups in the Corunna Downs Granitoid Complex showing trends for Group 1 and Groups 2–4

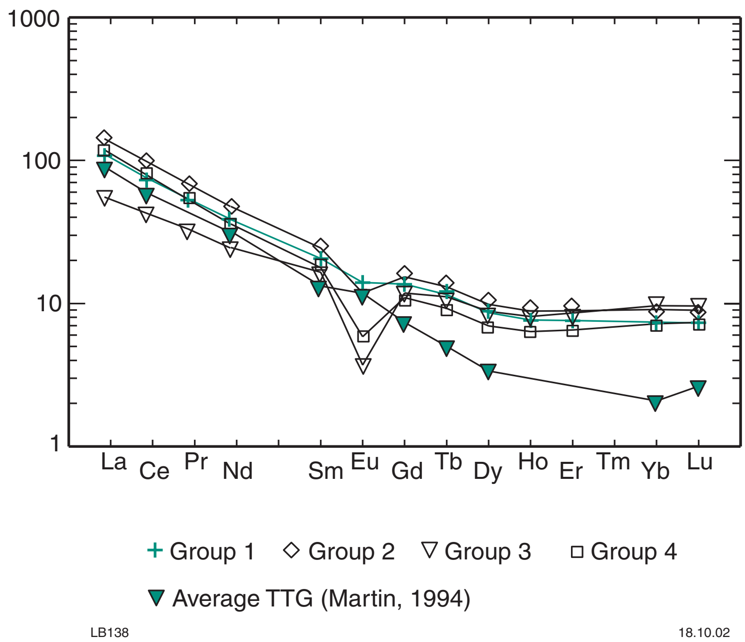

Figure 7. Average chondrite-normalized rare earth element patterns for the various rocks in the Corunna Downs Granitoid Complex. Also shown is the average tonalite–trondhjemite–granodiorite composition from Martin (1994)

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Stratigraphic and tectonic significance of eight local unconformities in the Fortescue Group, Pear Creek Centrocline, Pilbara Craton, Western Australia

by M. J. Van Kranendonk[1]

Abstract

Detailed geological mapping shows that the late Archaean Fortescue Group in the Pear Creek Centrocline of the Marble Bar Sub-basin, Hamersley Basin, consists of four distinct, unconformity-bound formations. From base to top these are the Mount Roe Basalt, Hardey Formation, Kylena Formation, and the newly defined Pear Creek Formation, which consists of five unnamed units equivalent to member rank. Each formation, as well as the units of the Pear Creek Formation, is separated by disconformable to unconformable contacts with underlying units, brought about by periods of tilting and faulting with or without folding.

The eight sets of structures recognized can be ascribed to three styles of deformation. Local tight folds of sets 1 and 2 resulted from two episodes of approximately easterly trending shortening across the centrocline before deposition of the Kylena Formation. Set 3 structures include approximately west-southwesterly trending extensional faults that affect the Kylena Formation. A series of northeast-trending, northwest-side-down normal faults of structure sets 4 to 7 step to the southeast. These were probably active throughout deposition of the lower four units of the Pear Creek Formation, and include the long-lived Pear Creek Fault. They controlled deposition within, and modified the geometry of, the Pear Creek Centrocline. Structure set 8 resulted in a subordinate, separate centrocline south of the Pear Creek Fault, outlined by the stratigraphically highest unit 5 of the Pear Creek Formation. The deformation documented in the Pear Creek Centrocline is interpreted as due to reactivation of adjacent granitoid domes.

KEYWORDS: Archaean, Fortescue Group, Marble Bar Sub-basin, stratigraphy, structural geology.

Introduction

The 2.77 – 2.63 Ga Fortescue Group of the Hamersley Basin represents a flood basalt province that erupted onto older basement rocks of the Pilbara Craton, after cratonization at c. 2.85 Ga (Blake, 1993, 2001; Thorne and Trendall, 2001; Van Kranendonk et al., 2002). Most of the Fortescue Group is preserved above a shallow-dipping, regionally extensive unconformity along the southern margin of the main outcrop of granitoid rocks and greenstones in the northern part of the Pilbara Craton (Van Kranendonk et al., 2002). However, outliers of the group are preserved in centroclines (equidimensional basins) between domical granitoid complexes in the basement, and show the same general structural style as flanking basement greenstones, with basal formations of the group recording bedding dips of up to 75° (e.g. Hickman and Lipple, 1978; Hickman, 1984; Van Kranendonk, 2000).

This paper presents the results of detailed mapping of the Fortescue Group in the northern part of the Marble Bar Sub-basin of the Hamersley Basin (Fig. 1; Thorne and Trendall, 2001). The data show that the stratigraphy of the Marble Bar Sub-basin should be revised, and that deposition of the Fortescue Group in this area occurred during ongoing local deformation related to the continued rise of adjacent basement granitoid domes.

Regional geology

The Archaean Pilbara Craton is composed of a metamorphosed basement of granitoid rocks and greenstones that evolved from before 3515 to 2830 Ma (Van Kranendonk et al., 2002), and an overlying cover succession known as the Mount Bruce Supergroup that was deposited in the Hamersley Basin from c. 2770 to 2400 Ma (Trendall, 1990). The cover succession is divided from base to top into the Fortescue Group, Hamersley Group, and Turee Creek Group (Thorne and Trendall, 2001), but only the Fortescue Group is discussed here.

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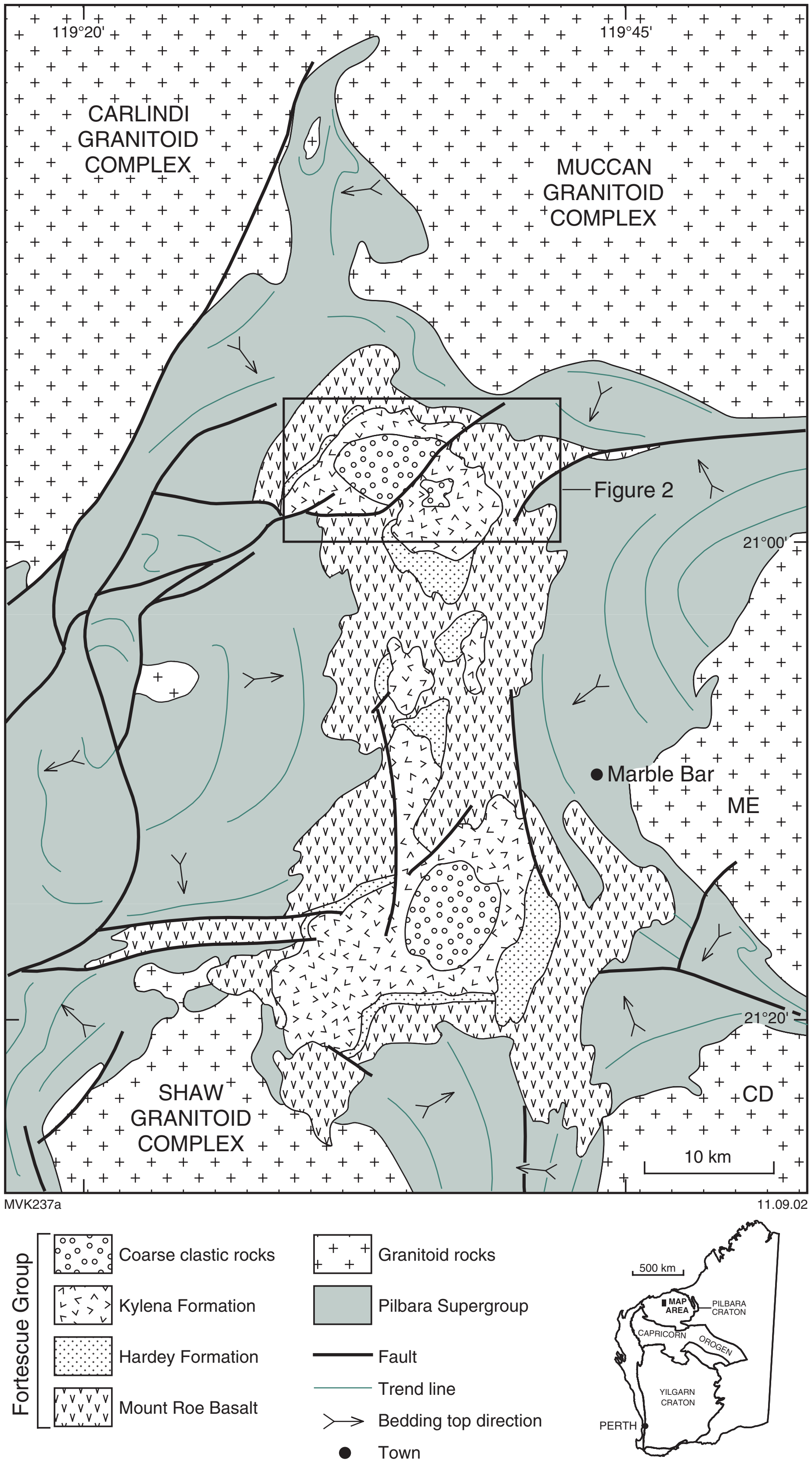


Figure 1. Simplified geological sketch map of the Marble Bar Sub-basin of the Fortescue Group, Hamersley Basin, showing its location between surrounding dome-shaped basement granitoid complexes. Box indicates Pear Creek Centrocline. CD = Corunna Downs Granitoid Complex; ME = Mount Edgar Granitoid Complex (after Hickman and Lipple, 1978; and Hickman and Gibson, 1981)

The basement underlying and surrounding the Marble Bar Sub-basin of the Hamersley Basin is part of the East Pilbara Granite–Greenstone Terrane (Van Kranendonk et al., 2002). This terrane is characterized by a large-scale (60–120 km) dome-and-keel structural pattern (Fig. 1) comprising domical, multicomponent granitoid complexes and intervening synclines containing up to five groups of volcano-sedimentary rocks (Van Kranendonk et al., 2002). Formation of the dome-and-keel structure commenced with the emplacement of synvolcanic laccoliths during a voluminous episode of felsic magmatism at 3490–3430 Ma, and then became pronounced as a result of partial convective overturn of the upper and middle crust at 3325–3310 Ma following the eruption of the 5–9 km-thick Euro Basalt (Hickman, 1984; Williams and Collins, 1990; Van Kranendonk et al., 2002; Sandiford et al., in prep.). Partial convective overturn of the basement continued during punctuated intervals until at least 2930 Ma, but also affected the Fortescue Group (Hickman, 1984; Van Kranendonk, 2000) as described below.

In the northern part of the Hamersley Basin the Fortescue Group is divided into six formations, with three thick, dominantly basaltic formations alternating with sedimentary rocks (Thorne and Trendall, 2001). The contact between the basement and the Fortescue Group is marked by a pronounced, commonly high-angle unconformity and includes restricted areas of basal conglomerate infilling relict topography in the basement (Blake, 1984, 1993; Thorne and Trendall, 2001).

Two contrasting interpretations of the stratigraphy of the Marble Bar Sub-basin have been proposed (Table 1). In one view, Hickman and Lipple (1978) and Hickman and Gibson (1981) suggested that the Fortescue Group consisted of the basal Mount Roe Basalt, the overlying clastic sedimentary rocks of the Hardey Formation, and a second main basaltic unit belonging to the Kylena Formation (Kojan and Hickman, 1998) that includes overlying sedimentary rocks. Alternatively, Blake (1993) suggested that the stratigraphy consists of the basal Mount Roe Sequence and the overlying Hardey Sequence Package. In this model the Hardey Sequence Package was interpreted to consist of the lower Glen Herring Sequence of basal clastic sedimentary rocks and a basaltic unit, and the overlying Pear Creek Sequence of clastic sedimentary rocks. In the following sections a lithostratigraphic nomenclature for the Fortescue Group is used following the reasons given in Thorne and Trendall (2001).

Pear Creek Centrocline

Lithostratigraphy

The results of detailed geological mapping in the northern part of the Marble Bar Sub-basin — the Pear Creek Centrocline (Blake, 1993) — are shown in Figure 2. Basement rocks flanking the sub-basin include folded, low-grade volcanic and sedimentary rocks of the Warrawoona, Gorge Creek, and De Grey Groups, whereas small, fault-bound basement inliers in the south-central and northeast-central parts of the map area consist of unassigned, highly altered basalt and subvertically dipping quartzite.

Unconformably overlying the basement (e.g. A and B on Fig. 2) is the Mount Roe Basalt that is up to 3 km thick in the map area. Most of the unit is composed of thick flows of massive to vesicular (locally amygdaloidal), and commonly plagioclase-glomeroporphyritic, basalt, in places with pillows at the base of the formation. A wedge of coarse conglomerate to sandstone, and massive basaltic agglomerate belonging to the basal part of the Mount Roe Basalt, lies on the basement with a sharp angular unconformity in the far eastern part of the map area (A on Fig. 2), and is disconformably overlain by the main basaltic flows of the formation. The Mount Roe Basalt is tightly folded south of the main Pear Creek Fault, with bedding dips of up to 75°, but the formation dips less than 30° north of the fault (Fig. 2).

Yellowish-orange weathering, well-bedded conglomerate, sandstone, and minor grey-green or brown shale of the Hardey Formation unconformably overlie the folded Mount Roe Basalt, in places across a high-angle unconformity (C on Fig. 2). Lateral thickness variations in the Hardey Formation indicate a relict topography in the Mount Roe Basalt during deposition of this clastic succession, which Blake (1993) suggested was laid down by fluvial transport. The dominant rock type is thickly bedded, very pure quartz sandstone with local cross-

Table 1. Previous interpretations of the stratigraphy of the Fortescue Group in the Pear Creek Centrocline

<table>
<tr><th>Hickman and Lipple (1978), Hickman and Gibson (1981)</th><th>Lithology</th><th colspan="2">Blake (1993)</th></tr>
<tr><td rowspan="2">Kylena Formation</td><td>Conglomerate and sandstone</td><td>Pear Creek Sequence</td><td rowspan="3">Hardey Sequence Package</td></tr>
<tr><td>Basalt</td><td rowspan="2">Glen Herring Sequence</td></tr>
<tr><td>Hardey Formation</td><td>Conglomerate and sandstone</td></tr>
<tr><td rowspan="2">Mount Roe Basalt</td><td>Basalt</td><td rowspan="2">Mount Roe Sequence</td><td rowspan="2"></td></tr>
<tr><td>Conglomerate and sandstone</td></tr>
</table>

bedding. The sandstone overlies a basal unit of cobble conglomerate up to 10 m thick, and may contain 1–3 m-thick conglomerate interbeds. Clasts in the conglomerate include predominantly white vein quartz and black and layered cherts, indicating derivation from erosion of the basement, but also include cobbles of Mount Roe Basalt.

A thick, regionally persistent, unit of coarse, blocky basaltic agglomerate assigned to the Kylena Formation was deposited unconformably on the Hardey Formation and locally cuts down through this unit to the Mount Roe Basalt (D and E on Fig. 2). The base of the agglomerate has local pillow basalt and brecciated flows that are transitional into the agglomerate, indicating subaqueous eruption, although probably in shallow water. The upper part of the unit is composed of metre-thick massive to vesicular flows, suggesting subaerial eruption, and includes a unit of plagioclase-glomeroporphyritic basalt. Two dolerite sills are possibly associated with the eruption of this unit: one was emplaced into the Hardey Formation, and the other intruded more massive parts of the Kylena Formation (Fig. 2). Dips of the Kylena Formation are distinctly steeper north of the Pear Creek Fault (20–52°) than to the south (10–15°), in contrast to the underlying Mount Roe Basalt (Fig. 2).

Unconformably overlying the Kylena Formation is an approximately 1 km-thick succession of brown- to green-weathering, very well preserved clastic sedimentary rocks. These rocks can be subdivided into four distinct but unnamed units, equivalent to member rank, based on grain size, contact relationships, and clast composition. Relationships along the northern side of the Pear Creek Centrocline indicate that there was a significant episode of faulting and tilting of the Kylena Formation before deposition of the overlying clastic succession (F on Fig. 2; see **Structural geology**). For this reason the clastic rocks are separated from the underlying Kylena Formation and assigned formation status, but because they differ in composition and depositional environment from rocks typical of the Tumbiana Formation (which would normally overlie the Kylena Formation) they are given a new formation name — the Pear Creek Formation. This is equivalent to the Pear Creek Sequence of Blake (1993; Table 1).

Unit 1 at the base of the Pear Creek Formation is 375 m thick and includes a basal unit of fine-grained, thin-bedded, green-brown siltstone and minor sandstone. Beds with rip-up clasts of mudstone are common (Fig. 3a) and there are also rare, 10 cm-thick beds of cobble conglomerate with well-developed cross-bedding. Green sandstone in the upper part of the unit is commonly homogeneous, with 10–30 cm-thick planar bedding, and is lithologically indistinguishable from the overlying unit 2.

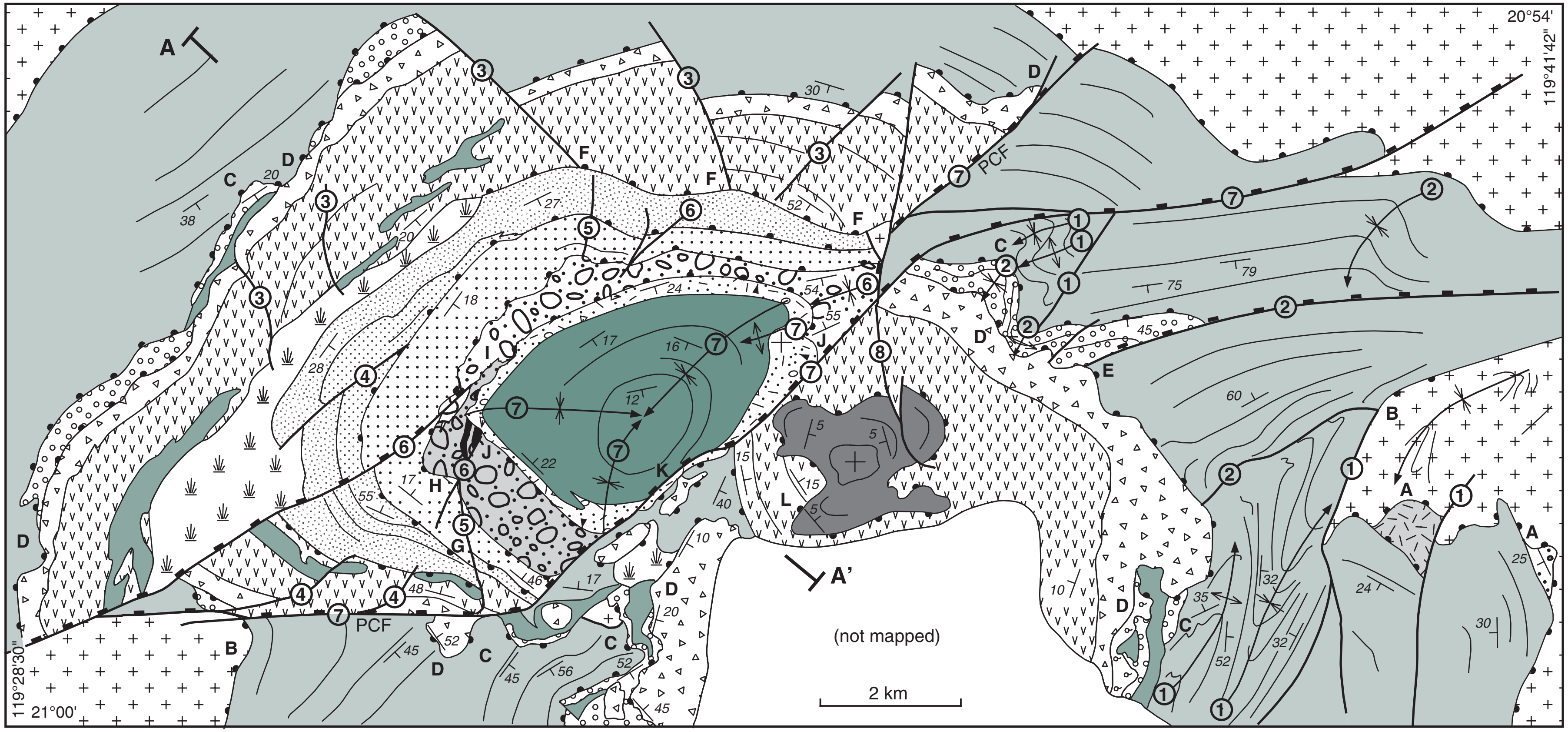
Unit 2 is about 250 m thick and cuts down-section through almost all of unit 1 along the southwestern side of the centrocline to the underlying Kylena Formation (G on Fig. 2). Unit 2 fines upwards from orange-weathering, medium-bedded, coarse sandstone at the base, through brown-weathering, green-grey, coarse- to medium-grained turbiditic sandstone with thin pebbly beds and some trough cross-bedding, to an upper unit of siltstone and mudstone with beds of rip-up clasts.

Unit 3 is composed of brown-weathering boulder to pebble conglomerate and sandstone that lies disconformably on unit 2 (H on Fig. 2). In places the basal contact of unit 3 with unit 2 varies from knife-sharp (Fig. 3b) to gradational (Fig. 3c) over a distance of only a few metres. Unit 3 consists of two distinct components, identified on the basis of clast compositions. In the southwest, unit 3 is composed of poorly bedded, oligomictic cobble to boulder conglomerate and breccia that contains angular to very well rounded clasts, up to 80 cm across, of solely basaltic composition in a fine- to medium-grained, quartz-bearing, sandy matrix (Fig. 3d). The basaltic clasts are undeformed and have a variety of textures, including massive, doleritic, vesicular, and plagioclase glomeroporphyritic; these basalt types are common in the underlying Mount Roe Basalt and Kylena Formation. The clasts show an increase in angularity with decreasing size, with boulder-sized clasts always well rounded. The unit is very coarse grained and massive at its thickest point in the southwest, and becomes finer grained and poorly bedded along strike to the north, where it includes brown sandstone beds near the top of the unit (western point J on Fig. 2).

Across the northern side of the centrocline (I on Fig. 2), the basalt-cobble conglomerate of unit 3 is interfingered with polymictic cobble to pebble conglomerate (<200 m thick) containing the same assortment of basaltic clasts as the oligomictic conglomerate to the south, but also containing well-rounded clasts of quartzite and other basement rocks, including dominantly black chert and white vein quartz, foliated and gneissic granites, and felsic volcanic rocks (Fig. 3e). In the southwest the lower part of the unit contains 95–98% basalt clasts, with less than 5% clasts of chert and sandstone, whereas towards the top the unit contains a more even mixture of chert, quartzite, granite, and basalt clasts. Clasts of basement rocks are more common to the northeast, where unit 3 has a sharp erosional contact with the underlying unit 2. A unit of pebbly sandstone at the top of unit 3 separates it from the overlying unit 4.

Unit 4 includes 75 m of basal, polymictic, matrix-supported conglomerate and about 390 m of medium-grained to pebbly sandstone. Clasts are well rounded and consist of both basalt- and basement-derived detritus, although basement material — particularly granitic clasts — is far more abundant than in the underlying units (Fig. 3f). Unit 4 is largely conformable on the underlying unit 3, but a high-angle unconformity is developed between these units in two places (J on Fig. 2). At the eastern locality the polymictic basal conglomerate of unit 4 dips 20° to the southwest, and overlies basalt-cobble breccia and sandstone that dip 50–60° to the north-northwest. On the southern side of the Pear Creek Fault, basal conglomerate of unit 4 lies unconformably on the Mount Roe Basalt across 0.4 – 1 m of iron-altered basalt and ferruginous grit and up to 4 m of fine-grained ?mafic tuff and ?vitric crystal tuff with accretionary lapilli that probably belongs to unit 1 (K on Fig. 2).

Unit 5 is a shallow-dipping (~5°) unit of orange-weathering, coarse sandstone and pebble conglomerate that lies unconformably on the



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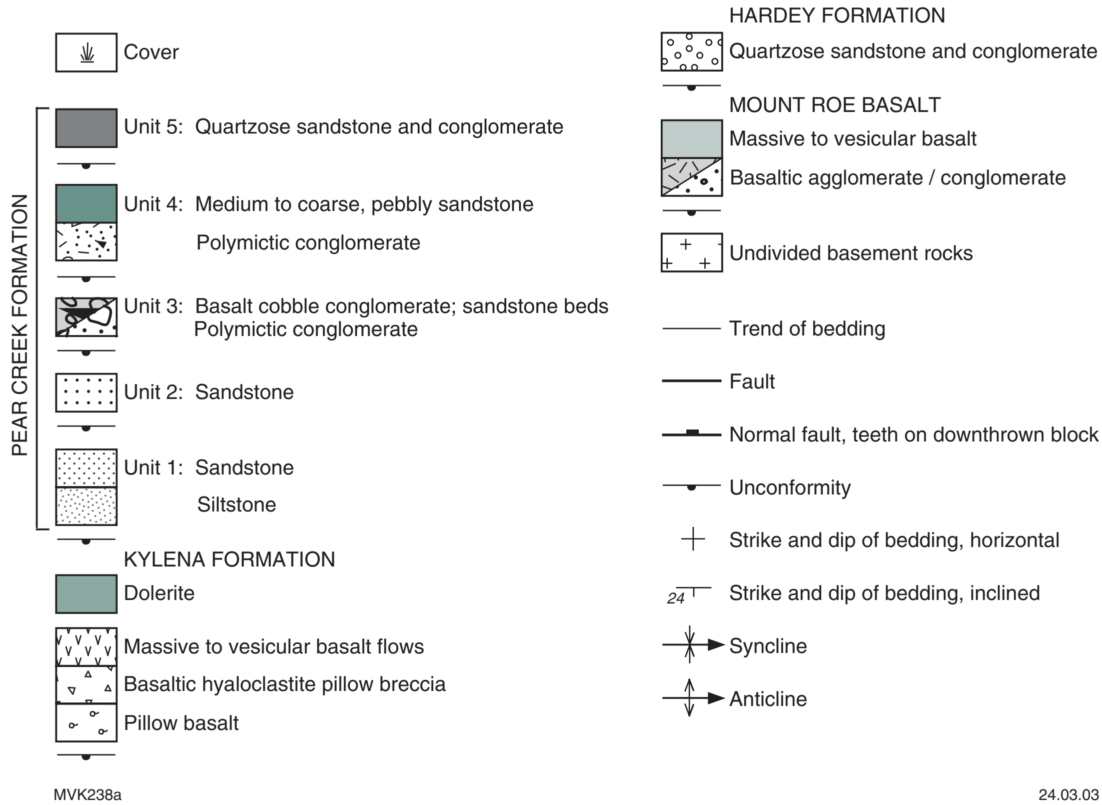


Figure 2. Geological map of the Pear Creek Centrocline. Bold letters indicate localities described in the text. Circled numbers refer to structure sets described in the text and in Table 2. PCF = Pear Creek Fault. Line A–A′ is line of cross-section shown in Figure 4

Kylena Formation south of the Pear Creek Fault (L on Fig. 2; Fig. 3g). This unit contains only basement clasts, and is thereby distinct from other units of the Pear Creek Formation, as well as physically separate and more shallowly dipping. The bedding dips in this unit outline a separate centrocline of unknown age relative to the Pear Creek Centrocline to the north, although it can be argued that structural considerations favour a younger age relative to the rest of the Pear Creek Formation (see below).

Structural geology

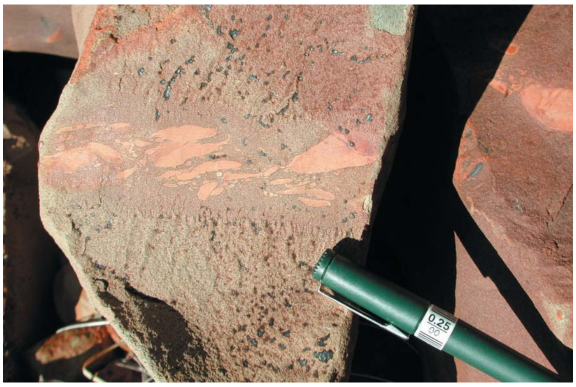
Eight sets of structures have been identified in the Fortescue Group of the Pear Creek Centrocline (Table 2). Sets 1, 2, and 8 are restricted to south of the Pear Creek Fault, whereas sets 3 to 7 are only to the north of this fault (Fig. 2).

The first set of structures include tight folds of bedding in the Mount Roe Basalt south of the Pear Creek Fault, where dips on fold limbs reach up to 75° (central-eastern part of Fig. 2). In the northeastern part of the map area the axial zone of a set 1 fold contains a set 1 fault.

Set 1 folds are unconformably overlain by the Hardey Formation (C on Fig. 2), which is folded on axial planes subparallel to, but different from, set 1 folds. Folding (set 2) of the Hardey Formation was followed by the development of two east-northeasterly trending, north-side-down normal faults (set 2) in the eastern part of the map area (labelled 2 on Fig. 2). Basal agglomerate of the Kylena Formation unconformably overlies set 2 structures (D on Fig. 2), and is unaffected by them. The geometry of set 1 and 2 folds indicate approximately west-northwest–east-southeast shortening across the centrocline, whereas late set 2 faults indicate the onset of north- to northwest-side-down normal faulting.

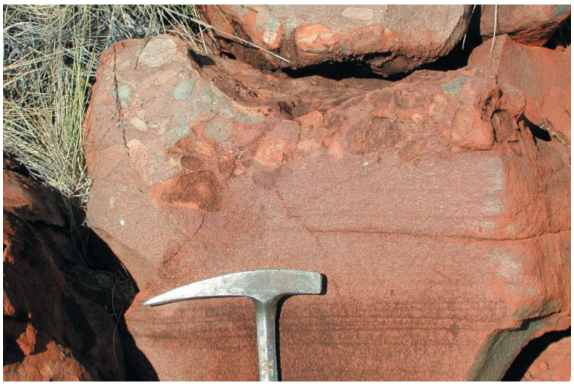
Deposition of the Kylena Formation occurred under stable conditions, as indicated by texturally distinct basalt flows conformable on one another throughout the formation. Following deposition of the formation, these rocks were affected by set 3 extensional faults across the northern part of the map area (Fig. 2). The geometry of the faults suggests approximately east–west extension across this part of the centrocline.

Unit 1 of the Pear Creek Formation has a well-exposed basal contact across the northern part of the centrocline, where it unconformably overlies the Kylena Formation and set 3 faults (F on Fig. 2). Unit 1 is affected by northeast-trending set 4 faults (labelled 4 on Fig. 2) that are the oldest of a succession of faults with this same trend (sets 4 to 7) that migrated to the southeast throughout the deposition of the Pear Creek Formation (Fig. 4; Table 2). Set 4 faults extend either partway up through unit 1 (southwestern map area) or through all of unit 1 to the base of unit 2 (west-central map area), which is unaffected by these a)

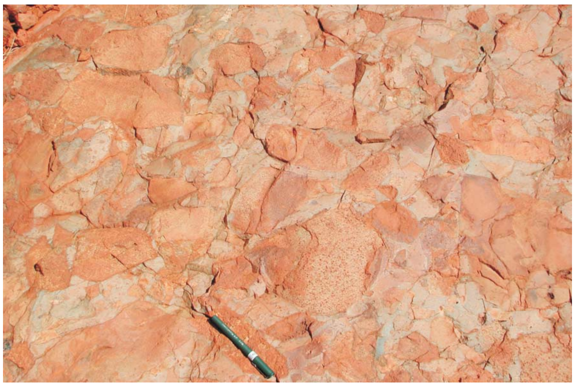


b)

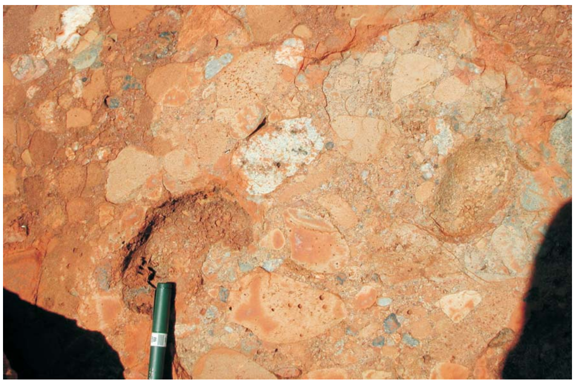
c)



d)



e)



f)

g)

Figure 3. *Outcrop features of the Pear Creek Formation: a) Mud rip-ups in unit 1; b) sharp basal contact between unit 2 and overlying polymictic conglomerate of unit 3; c) downcutting, but gradational contact between unit 2 and overlying polymictic conglomerate of unit 3; d) basaltic conglomerate of unit 3; e) polymictic conglomerate of unit 3, with basaltic and basement clasts; f) polymictic conglomerate of unit 4 at the unconformity with the underlying unit 3 at the eastern point J in Figure 2 (see Fig. 4). Note the black chert pebbles in the lower right and the strongly foliated granite boulder above left of the pen; g) view looking east of unit 5 south of the Pear Creek Fault, showing the shallow north dip (<5°) of this unit and its unconformable relationship on the Kylena Formation in the foreground, which dips 15° to the north (arrows)*

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Table 2. Relationship between structures and lithostratigraphic units of the Fortescue Group in the Pear Creek Centrocline

Formation	*Member*	*Basal contact*	*Structure set*	*Structures*
			8	Gently tilted strata and younger E-side-down faults
Pear Creek	Unit 5	Unconformity on Kylena Formation		
			7	Tilted strata and NW-side-down faults
	Unit 4	Disconformity to angular unconformity on Member 3 and (locally) Mount Roe Basalt		
			6	Tilted strata and NW-side-down faults
	Unit 3	Conformity to low-angle unconformity on Member 2		
			5	Tilted strata and NW-side-down faults
	Unit 2	Disconformity to low-angle unconformity on Member 1		
			4	Tilted strata and NW-side-down faults
	Unit 1	Disconformity to angular unconformity on Kylena Formation		
			3	Tilted strata and extensional faults
Kylena		Conformity to angular unconformity on Hardey Formation and Mount Roe Basalt		
			2	NE-trending folds, younger N-side-down faults
Hardey		Disconformity to angular unconformity on Mount Roe Basalt		
			1	Tilting, NE-trending folds, and W- to NW-side-down faults
Mount Roe Basalt		Disconformity to angular unconformity on basement rocks		

faults. Unit 2 is affected by set 5 faults and overlain by unit 3, which is affected by set 6 faults. Unit 4 is affected only by the Pear Creek Fault, which was probably active throughout the deposition of the Pear Creek Formation, and by gentle downwarping in the core of the centrocline.

Unit 5, south of the Pear Creek Fault, dips radially inward at point 5 (set 8) and unconformably overlies more steeply dipping bedding in the Kylena Formation (Fig. 3g). The shallowly dipping bedding of unit 5 is cut by north-striking faults (set 8) with east-side-down displacement. The structure of unit 5 defines a second centrocline, which probably formed after the Pear Creek Centrocline as suggested by the southerly shift in deformation through sets 4 to 7.

Interplay between deformation and sedimentation

Relationships between units in the Fortescue Group and sets of folds and faults indicate that the Pear Creek Centrocline developed progressively throughout deposition of the group. The deformation style changed from northwest–southeast

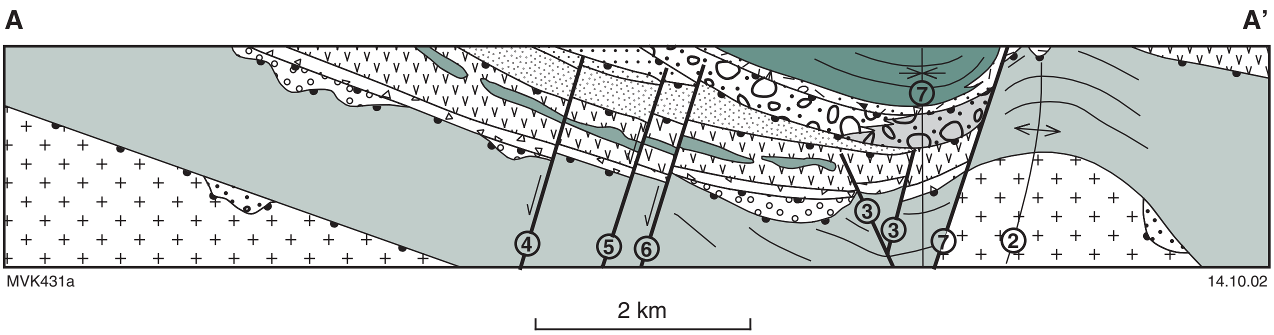

Figure 4. Northwest–southeast cross-section A–A’ (from Fig. 2, but note different scale) of the Fortescue Group in the Pear Creek Centrocline, Marble Bar Sub-basin. Legend as in Figure 2

shortening during sets 1 and 2, to east–west extension during set 3, to northwest–southeast extension during sets 4 to 7.

Previous work in the Hamersley Basin has shown that the Mount Roe Basalt and underlying sedimentary rocks of the basal Fortescue Group were deposited on a relict topography in the basement that was caused by topographically high granitoid domes during west-northwesterly directed extension (Fig. 5a: Blake, 1993; Thorne and Trendall, 2001). Set 1 structures in the Pear Creek Centrocline, as well as in the southwestern part of the Marble Bar Sub-basin (Van Kranendonk, 2000), are consistent with a significant amount of shortening between reactivated granitoid domes after deposition of the Mount Roe Basalt, but before deposition of the Hardey Formation. Data from the two areas indicate different orientations of shortening at this time (northwest–southeast in the Pear Creek Centrocline versus north–south in the southwestern part of the Marble Bar Sub-basin), similar to the orientation of structures in the underlying greenstones. Although this style of deformation is inconsistent with regional orogenesis due to plate interactions, it is consistent with folding of the Fortescue Group as a result of bed-length shortening in synclines between reactivated granitoid domes during diapirism (Fig. 5b; Dixon and Summers, 1983; Hickman, 1984; Van Kranendonk et al., 2002).

Uplift and erosion of granitoid rocks and flanking greenstones provided detritus for the Hardey Formation that was deposited in shallow basins between granitoid domes (Fig. 5b). Deposition was coeval with continued uplift, which caused folding of these clastic rocks on set 2 fold axes that are subparallel to set 1 folds.

This period of uplift and erosion was followed by the deposition of the Kylena Formation and a period of extension that affected the Fortescue Group throughout the Hamersley Basin (Thorne and Trendall, 2001). In the Pear Creek Centrocline this extension was manifest as set 3 faults (Fig. 5c).

Deformation changed to northwest-side-down normal faulting throughout deposition of the Pear Creek Formation (structure sets 4 to 7:

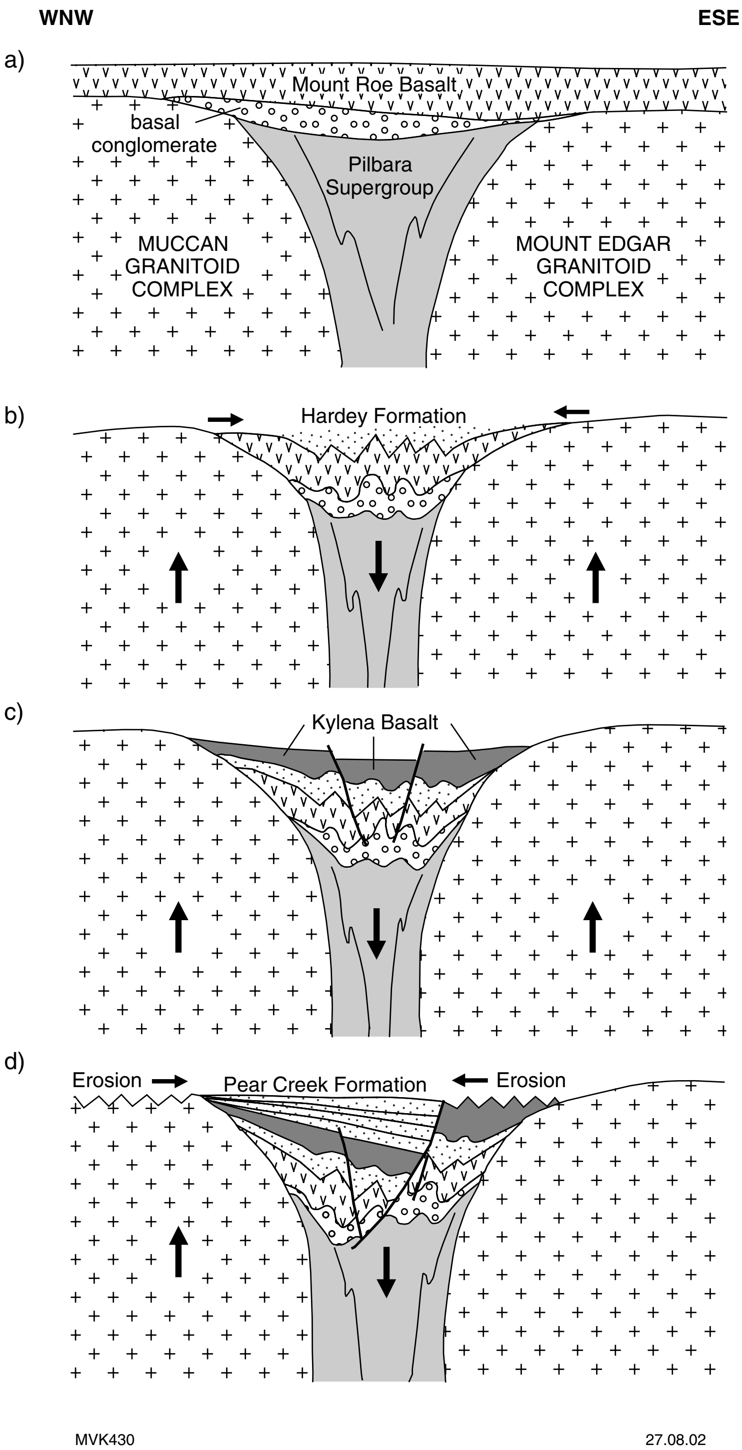

Figure 5. Schematic evolution of the Pear Creek Centrocline: a) deposition of the Mount Roe Basalt and basal conglomerates on a basement with relict topography defined by domical granitoid complexes; b) deformation of the Mount Roe Basalt due to shortening between uplifted granitoid domes, which were eroded to provide detritus for deposition in the unconformably overlying Hardey Formation; c) deposition of the Kylena Formation followed by extension; d) asymmetric downdrop across the Pear Creek Fault results in deposition of the Pear Creek Formation in the Pear Creek Centrocline

Fig. 5d). A decrease in clast size from southeast to northwest in the basalt-cobble conglomerate of unit 3 on the southern side of the centrocline provides evidence for a structural control on sedimentation, indicating a source from the uplifted block on the southern side of the Pear Creek Fault. Additionally, the change from basalt-cobble to polymictic conglomerate to the north and east within unit 3 is consistent with the structural history outlined above. This indicates that the Pear Creek Centrocline formed through southeast-side-down tilting of the northern block across the Pear Creek Fault and associated structures, resulting in uplifted basement rocks in the northwest and an uplifted area of the Mount Roe Basalt and Kylena Formation in the footwall to the southeast (Figs 4 and 5).

Conclusions

Detailed geological mapping of the Pear Creek Centrocline has shown that the composition and depositional style of the sedimentary rocks overlying and underlying the Kylena Formation in the core of the Pear Creek Centrocline are distinctly different. On this basis it is proposed that the stratigraphy of the Pear Creek Centrocline be revised to include, from base to top, the Mount Roe Basalt, Hardey Formation, Kylena Formation, and Pear Creek Formation, the latter consisting of five sedimentary units bound by locally disconformable to unconformable contacts.

The mapping shows that local deformation affected the Pear Creek Centrocline throughout deposition of the Fortescue Group, and that this deformation was controlled by the reactivation of granitoid domes. Early deformation (structure sets 1 and 2) involved local tight folding due to west-northwest – east-southeast compression between rising domes. This was followed by deposition of the Kylena Formation and subsequent east–west extension. Deposition of the Pear Creek Formation was accompanied, and probably controlled, by northwest-side-down normal faulting across the Pear Creek Fault and associated splays, which stepped back to the southeast through time. The final deformation resulted in the formation of a second, gentle centrocline south of the Pear Creek Fault in which unit 5 was deposited.

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Seismic stratigraphic framework of the Neoproterozoic successions, Officer Basin, Western Australia

by S. N. Apak[1] and G. M. Carlsen[2]

Abstract

Three unconformity-bound sedimentary successions are present in most parts of the Officer Basin in Western Australia: Supersequences 1, 3, and 4. These supersequence sets are now further subdivided into parasequence sets. Seismically, Supersequence 1 unconformably overlies poorly imaged older rocks and is characterized by continuous parallel reflectors that truncate against younger unconformities.

The Areyonga Movement (c. 750 Ma) is responsible for the strongest thrust-related deformation in parts of the Officer Basin, initiating salt movement that pierced through the strata creating salt-cored folds. This tectonic movement created the regional unconformity that separates Supersequence 1 from Supersequence 3. There are no preserved Supersequence 2 rocks in the Officer Basin. Supersequence 3 and 4 strata fill structural and topographic lows, and onlap and overlap highs. Later deformations including further salt movement during the Petermann Ranges Orogeny and Palaeozoic tectonic events resulted in greater stratigraphic diversity within Supersequences 3 and 4.

KEYWORDS: Structure, stratigraphy, sequence stratigraphy, basin analysis, Yowalga, Lennis, Gibson, Officer Basin, Western Australia.

Introduction

The Neoproterozoic sedimentary rocks of the Officer Basin in Western Australia were deposited unconformably over the Archaean Yilgarn Craton, the Palaeo-proterozoic and Mesoproterozoic sedimentary and volcanic rocks of the Earaheedy, Edmund, and Collier Basins, and the Mesoproterozoic igneous and metamorphic rocks of the Musgrave Complex and Albany–Fraser Orogen. The 6–10 km-thick Officer Basin sedimentary succession is still poorly known due to limited seismic, outcrop, and well control, particularly in the Waigen, Lennis, and Gibson areas (Fig. 1). Information on the Officer Basin is provided by Jackson and van de Graaff (1981); Iasky (1990); Stevens and Apak (1999); Carlsen et al. (1999); Apak and Moors (2000b); Apak and Moors (2000c); Tyler and Hocking (2001); Moors and Apak (2002).

The interpreted seismic data illustrated in this paper benefited from the data reprocessing and interpretation of Japan National Oil Company (1997), Perincek (1998), and Durrant and Associates (1998). Most of these data have since been reinterpreted and seismic stratigraphic concepts applied to establish a regional distribution of the Neoproterozoic strata in the Officer Basin (Apak and Moors, 2000a,b; Moors and Apak, 2002).

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Seismic stratigraphy

Four major unconformities and three supersequences were previously recognized within the Western Australian part of the Officer Basin (Fig. 2; Apak and Moors, 2000a,b; 2001; Moors and Apak, 2002):

- the basal unconformity;
- Supersequence 1;
- post-Supersequence 1 unconformity;
- Supersequence 3;
- post-Supersequence 3 unconformity;
- Supersequence 4;
- post-Supersequence 4 unconformity.

There are no preserved Supersequence 2 rocks in the Officer Basin succession in Western Australia.

Apak and Moors (2000a,b) demonstrated the presence of laterally correlative sequences within Supersequence 1. Sequences B, H, K, and S coincide closely with the previously defined stratigraphic units of the Browne, Hussar, Kanpa, and Steptoe Formations respectively (Townson, 1985). Each sequence comprises numerous parasequence sets (e.g. B1 to B6 in Sequence B; Fig. 2) that show progradation, with coarse clastic beds or tidal flat to supratidal carbonate to evaporitic deposits spread across the deeper water deposits.

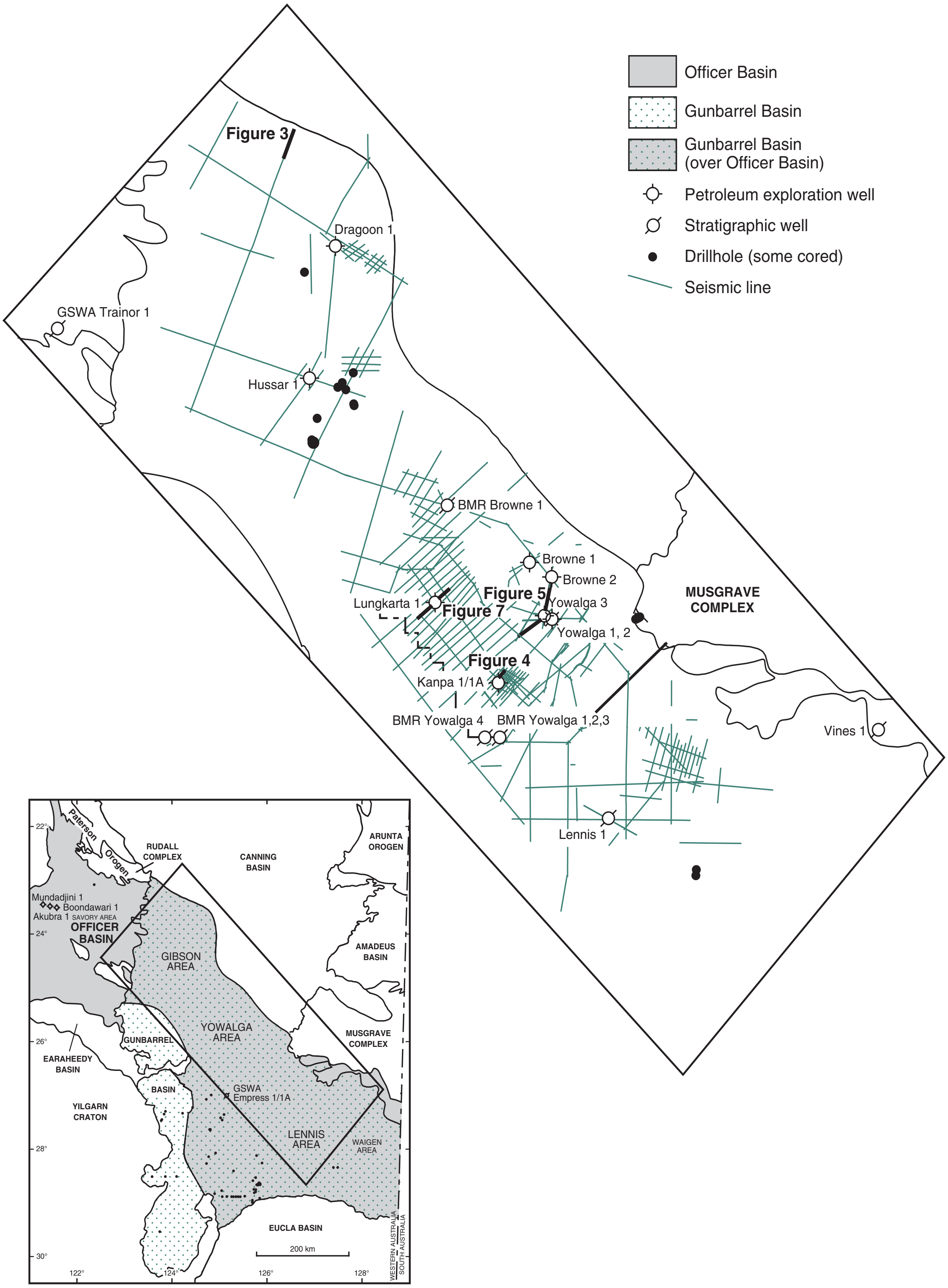

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Figure 1. Location map showing seismic coverage and wells in the Officer Basin

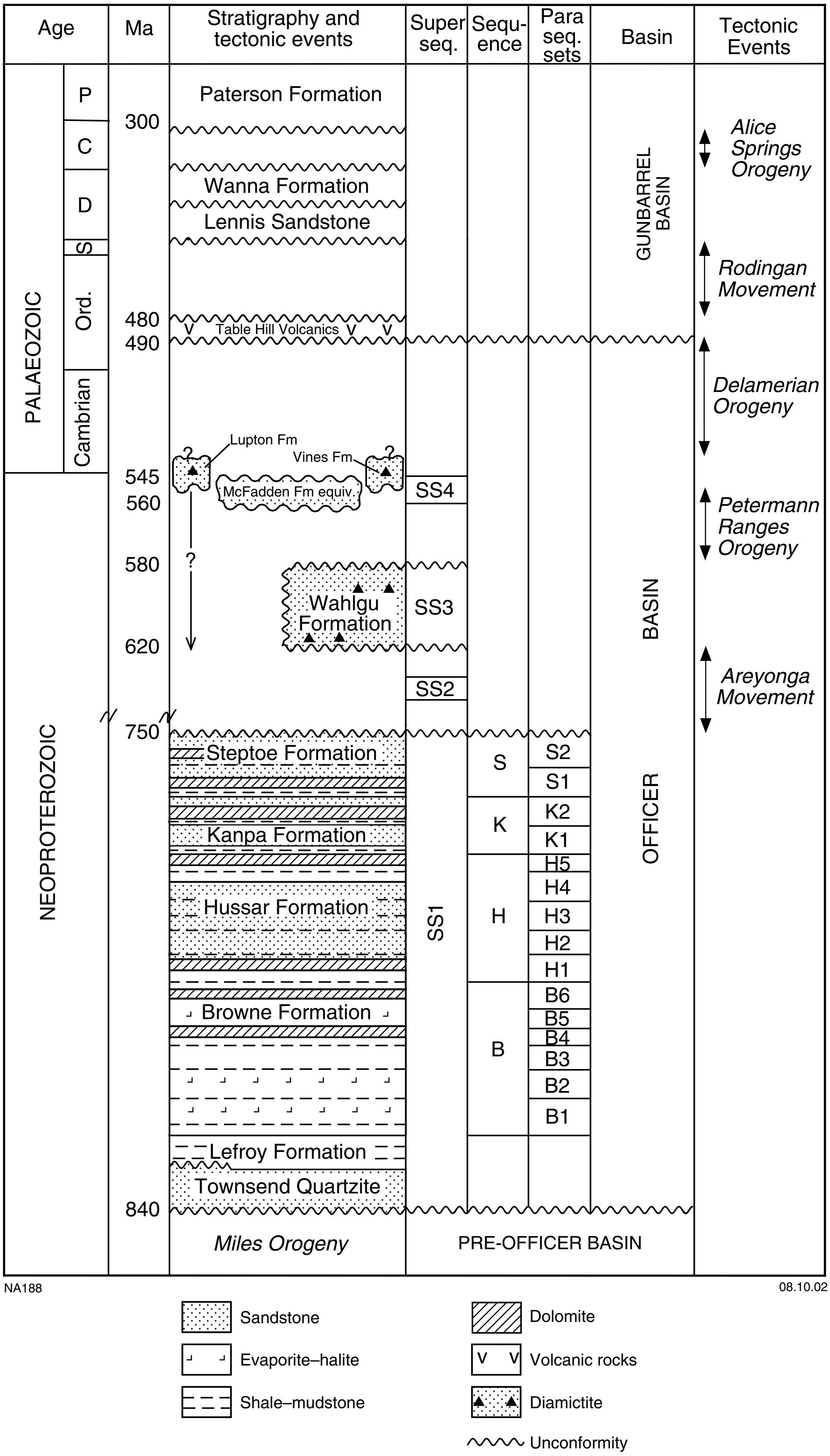

Figure 2. Stratigraphic column showing lithostratigraphy, sequence-stratigraphic units, and tectonic events in the western Officer Basin

The basal unconformity

The basal unconformity separates the Officer Basin from the underlying Mesoproterozoic and older rocks. This unconformity is not a prominent reflector because it is commonly masked by overlying massive salt. Elsewhere, such as in the Gibson area, the Officer Basin succession disconformably overlies similarly bedded Mesoproterozoic sedimentary rocks (Moors and Apak, 2002). However, where the contact relationship is angular the horizon can be picked with some confidence (Fig. 3).

Supersequence 1 stratigraphy and structure

The Townsend Quartzite, the lowest unit of Supersequence 1, contains fluvial to nearshore marine sandstones and is conformably overlain by marine sandstone, siltstone, and shale of the Lefroy Formation (Jackson and van de Graaff, 1981; Perincek, 1996, 1997, 1998; Apak and Moors, 2000b). The overlying Browne Formation (and the correlative Skates Hills Formation) correlates with part of the Alinya Formation from the eastern Officer Basin in South Australia and consists of mudstone, argillaceous siltstone, dolomite, and evaporite including halite. The Hussar, Kanpa, and Steptoe Formations consist of sandstone, dolomite, shale, and minor evaporite deposits. Major transgressions at the base of each sequence and secondary transgressions that separate parasequence sets are characterized by high-amplitude continuous seismic reflectors (Fig. 4). The thick halite deposits of the Browne Formation were actively mobilized (plastic deformation and flow) during several tectonic phases resulting in dramatic redistribution — both laterally and vertically — of the salt, producing complex structures (Fig. 5). In most seismic lines Supersequence 1 strata overlying the salt sequence of the Browne Formation are characterized by continuous parallel reflectors, which are traceable in most parts of the basin except where the reflectors are truncated by unconformities (Figs 4 and 5).

Salt mobilization was initiated in most parts of the basin during the Areyonga Movement. Japan National Oil Company (1997) subdivided the Yowalga area along structural boundaries largely imposed at this time. Their subdivision includes a salt-ruptured zone (closest to the Musgrave Complex), a central thrusted zone, and western platform (Fig. 6).

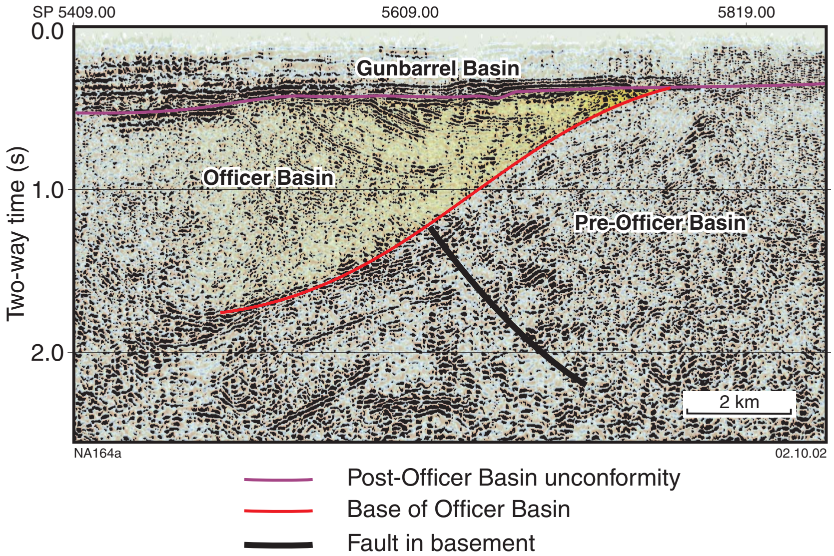

Figure 3. Seismic line N83-3A showing the unconformable relationships between the Neoproterozoic Officer Basin and the underlying Mesoproterozoic strata in the Gibson area. For location of seismic line see Figure 1

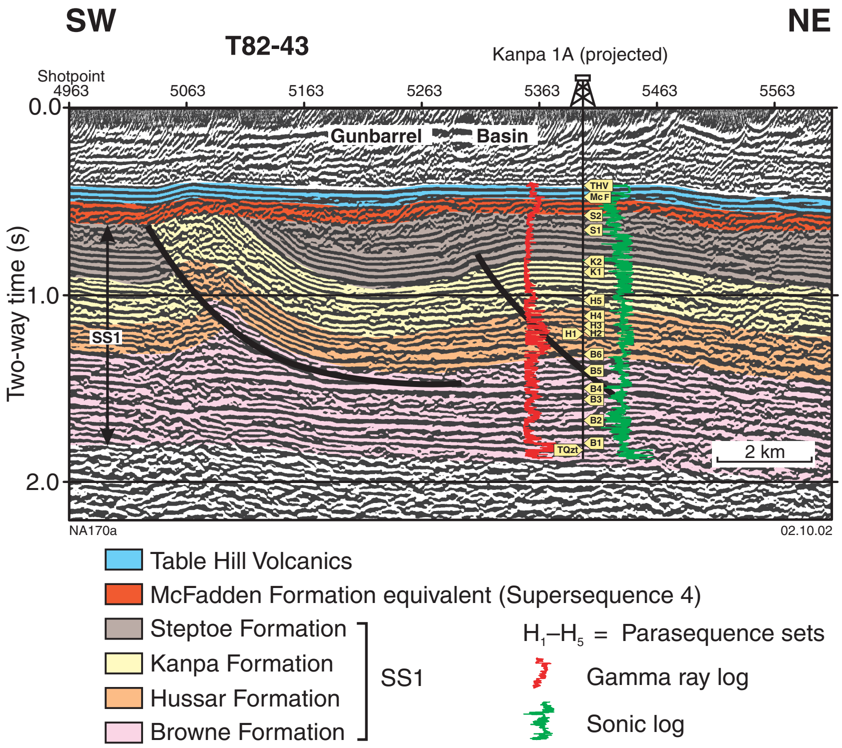

Figure 4. Seismic line T82-43 showing a salt-lubricated thrust fault in Sequence B (Browne Formation) and erosion of Supersequence 1 strata. Supersequence 3 strata are absent and Supersequence 4 strata unconformably overlie Supersequence 1. For location of seismic line see Figure 1

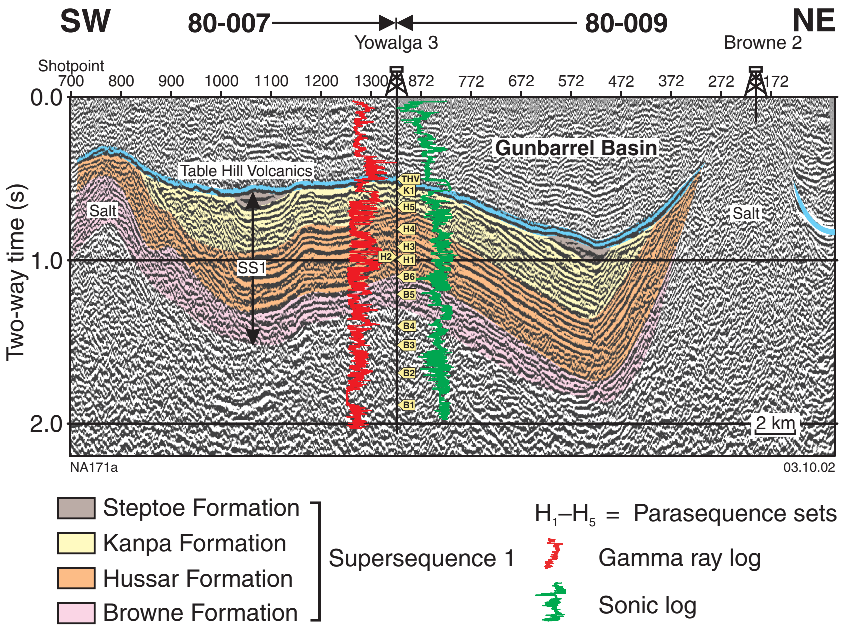

Figure 5. Composite seismic section of lines 80-007 and 80-009 showing the Yowalga 3 well and erosion of Supersequence 1 strata between salt emplacements in the Yowalga area. For location of seismic line see Figure 1

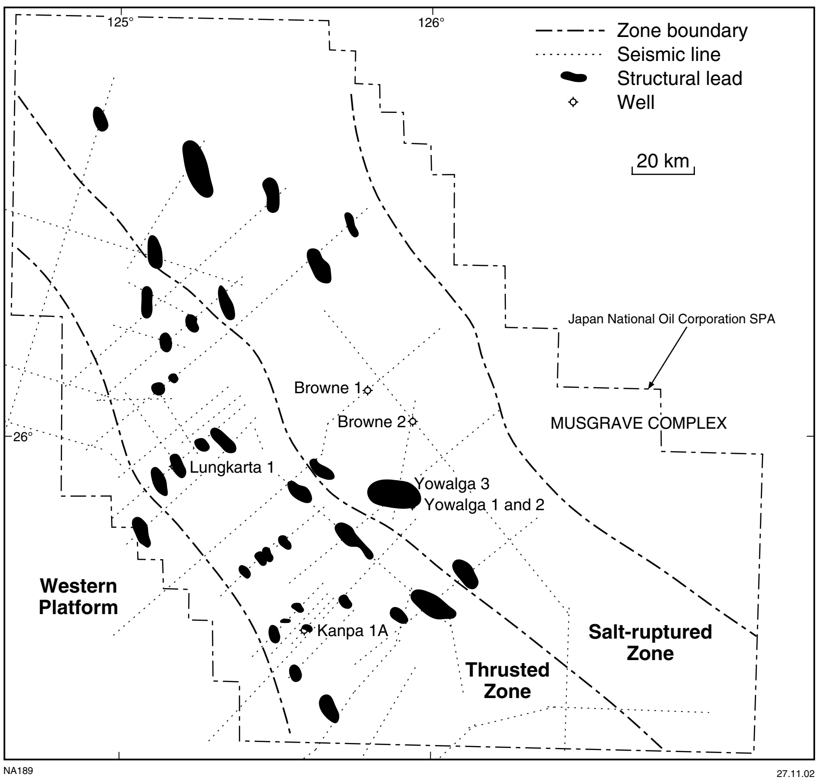

Figure 6. Distribution of structures and tectonic zoning in the Yowalga area (after Japan National Oil Company, 1997)

The salt-ruptured zone is an area of salt diapirism defined within the seismic dataset, and some salt diapirs, such as the Browne, Woolnough, and Madley diapirs, have been recognized from surface mapping. The Mount Samuel Salt Wall of the salt-ruptured zone is more than 10 km wide and 100 km long.

The thrusted zone is characterized by low-angle thrust faults. In the Yowalga area most faults are thin-skinned listric thrust faults that are detached along the salt horizon in Sequence B. Fault ramps are common below salt intrusions, indicating that the salt movement was activated along pre-existing zones of weakness (Durrant and Associates, 1998). Most displacements are confined to the Supersequence 1 strata (Figs 4 and 7), but exhibit minor reactivation that later extended the faults into younger units. Most large-scale folds are either halokinetic or ramp anticline folds (Fig. 4).

Listric faults lubricated by salt are less common in the Lennis area. In the Gibson area many of the thrust faults are listric and form high-angle reverse faults at shallow depths. Although the reflection record below salt is poor, these faults appear to flatten with depth and probably detach near the base of salt-forming, basal thrust planes.

Deformation that produced the thrusting pre-dates the deposition of Supersequence 3, and is correlated with the c. 750 Ma Areyonga Movement (Fig. 2). It represents a compressional event, and thrusting may be directly linked to basement uplift, represented by the Musgrave Complex to the northeast. Alternatively, it may represent gravitational collapse of the uplifted sedimentary pile adjacent to the Musgrave Complex, which became unstable, detached along the salt beds, and slipped to the southwest.

The thrusted zone is bound to the west by the western platform. This is a gentle structural ramp that flanks the entire southwestern margin of the Officer Basin. It is defined by drillholes Jubilee 1 and 2, Mason 1 and 2, Weedy 1 and 2, NJD 1, Empress 1A, and the seismic data.

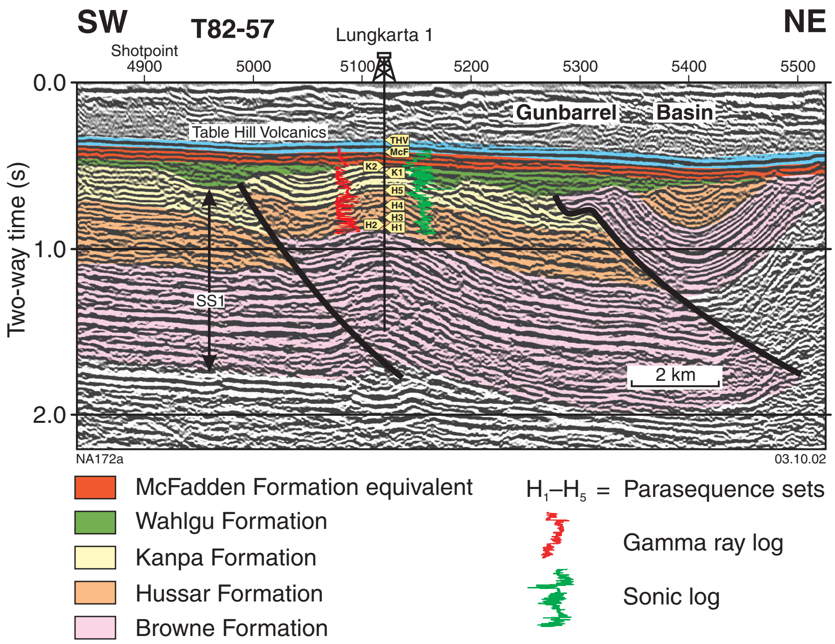

Figure 7. Seismic line T82-57 showing the Lungkarta 1 well drilled on a ramp anticline fold and the deep erosional surface of the post-Supersequence 1 unconformity. For location of seismic line see Figure 1

Post-Supersequence 1 unconformity

Following the Areyonga Movement, a significant amount of Supersequence 1 strata was eroded, particularly over salt-emplacement structures and along the basin margins. The major unconformity developed over these structures is characterized by sharply erosive valleys and channel-like features at the base of the overlying Wahlgu Formation (Fig. 7). The post-Supersequence 1 unconformity is correlatable throughout large parts of the basin. However, in places the Wahlgu Formation (Supersequence 3) and part of Supersequence 1 have been removed by younger erosional events (Figs 4 and 5).

Supersequence 3

Gentle subsidence coincided with the deposition of the Wahlgu Formation (Supersequence 3), which represents the Marinoan glaciation in the Officer Basin (Grey et al., 1999). Supersequence 3 has been eroded over many later formed structures (Fig. 7), particularly between the Gibson and Yowalga areas, but it still extends through most of the basin. Large channels are in places incised into the Kanpa Formation (Moors and Apak, 2002).

Post-Supersequence 3 unconformity

The Petermann Ranges Orogeny terminated deposition of Supersequence 3. The post-Supersequence 3 unconformity between the McFadden Formation equivalent and the underlying Wahlgu Formation or older units in the western Officer Basin developed over structures formed during this major deformation event. More than 15 km of uplift is recorded in the northern part of the Musgrave Complex during this orogeny with large-scale folding and thrusting of the southern Amadeus Basin; however, structures formed in the western Officer Basin at this time are of relatively small scale and there is no evidence for involvement of the basement underlying the basin.

In areas adjacent to salt emplacements this unconformity is angular (Moors and Apak, 2002), but within a few kilometres of the salt walls the contact between the Wahlgu Formation and McFadden Formation equivalent is merely disconformable.

Supersequence 4

Supersequence 4 consists of the McFadden Formation in the Savory region and a correlative unit, the McFadden Formation equivalent (Lungkarta Formation of Grey et al., in prep.), in the remainder of the basin. The formation onlaps and thins over pre-existing structural highs (Moors and Apak, 2002). Williams and Bagas (2000) suggested that the McFadden Formation in the Savory area was weakly deformed during the closing stages of the Paterson Orogeny, which is correlated with the Petermann Ranges Orogeny of central Australia (Bagas et al., 1995; Perincek, 1997; Tyler et al., 1998).

The Vines Formation defined in GSWA Vines 1 (Fig. 1) was deposited syntectonically with the uplift of the Musgrave Complex during the Petermann Ranges Orogeny (Apak et al., 2002). Gravity and magnetic data are consistent with the igneous and metamorphic rocks of the Musgrave Complex being thrust over the northeastern margin of the Officer Basin in this area. There are no correlative units interpreted from existing drillholes or seismic data in the western Officer Basin.

Post-Supersequence 4 unconformity

The Delamerian Orogeny terminated deposition of Supersequence 4 (Fig. 2). The Ordovician Table Hill Volcanics and younger rocks unconformably overlie the Supersequence 4 unconformity. High-amplitude and high-continuity reflections are commonly associated with the Table Hill Volcanics (Figs 4, 5, and 7). In some areas, particularly in the Gibson area, the McFadden Formation equivalent and parts of the underlying successions have been truncated by the Delamerian Orogeny and younger deformations (Moors and Apak, 2002).

In the Gibson area late salt movement in some structures penetrates Supersequences 1 through 4 and the overlying Gunbarrel Basin succession. Late salt movement does not affect all structures and is interpreted to be driven by overburden density imbalance. The deposition of a substantial thickness of Supersequence 3 (Wahlgu

Formation) and Supersequence 4 (McFadden Formation equivalent) successions in mini-basins formed by salt evacuation probably accounts for the continued mobility of the salt. Salt movement also displaces the Permian Paterson Formation and the Cainozoic deposits in the Madley diapirs, suggesting that in some regions minor salt movement may have continued up to the present time.

Gunbarrel Basin

The Table Hill Volcanics mark the commencement of a new depositional sequence that has been assigned to the Gunbarrel Basin (Hocking, 1994). The Table Hill Volcanics consist of Lower Ordovician (484 ± 4 Ma), porphyritic and amygdaloidal tholeitic basalt in Empress 1 and 1A (Stevens and Apak, 1999). The Table Hill Volcanics are widespread across the basin, but absent from some parts of the Gibson area. The seismic response of the top of the Table Hill Volcanics is clear and distinct on many seismic lines and is used as a regional marker in the eastern part of the Gibson area, and in the Yowalga and Lennis areas. Salt diapirs have penetrated or folded the Table Hill Volcanics in some structures. Salt-cored structures affect the Gunbarrel Basin sedimentary rocks in all areas, and other structural features such as the Westwood Fault post-date deposition of the Palaeozoic Gunbarrel Basin. The thickness and distribution of Gunbarrel Basin sedimentary rocks must be considered when defining the petroleum systems of the Officer Basin.

Conclusion

The application of seismic stratigraphic concepts has improved our understanding of the depositional and tectonic history of the Officer Basin. Three unconformity-bound supersequences are present. The unconformity at the top of Supersequence 1 correlates with the Areyonga Movement, which caused the strongest deformation in the basin. Younger unconformities at the top of Supersequences 3 and 4 correlate with the Petermann Ranges Orogeny and Delamerian Orogeny respectively. Salt movements related to these tectonic periods created further structural and stratigraphic variations in the basin. Understanding these features will assist in the identification of prospective areas for hydrocarbon exploration.

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Program review

SUBPROGRAM 3102: MINERAL AND PETROLEUM RESOURCE STUDIES
Interior basins petroleum initiatives project ... 91
Biostratigraphy and palaeontological services ... 93
Western margin petroleum initiatives project ... 94
Mineralization and exploration assessment ... 95
Resource mapping, assessment, and advice ... 97

SUBPROGRAM 3103: REGIONAL GEOSCIENCE MAPPING
Regolith mapping and geochemistry ... 98
King Leopold and Halls Creek Orogens project ... 100
Pilbara Craton project ... 101
Southern Gascoyne Complex project ... 103
Bangemall Supergroup project ... 105
Earaheedy Basin project ... 106
East Yilgarn project ... 108
Central Yilgarn (Southern Cross) project ... 111

SUBPROGRAM 3104: SCIENTIFIC, TECHNICAL, AND FIELD SUPPORT
Geoscientific specialist support ... 113
Geochronology ... 113
Geophysics ... 114
Logistics support and core libraries ... 115

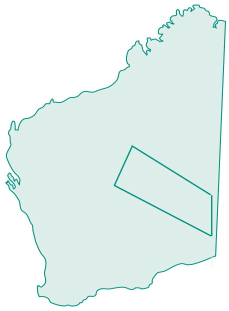
SUBPROGRAM 3105: GEOSCIENCE INFORMATION PRODUCTS
Publications and promotion ... 116

SUBPROGRAM 3106: GEOSCIENTIFIC AND EXPLORATION INFORMATION
Statutory exploration information group — Minerals section ... 118
Statutory exploration information group — Petroleum section ... 119

SUBPROGRAM 3107: INVENTORY OF ABANDONED MINE SITES
Inventory of abandoned mine sites ... 120

Program 3
Subprogram 3102
MINERAL AND PETROLEUM RESOURCE STUDIES

Interior basins petroleum initiatives project



Objective: *To encourage an increase in the level of onshore oil and gas exploration in Western Australia by undertaking studies of its sedimentary basins and their hydrocarbon prospectivity. The onshore sedimentary basins of Western Australia, such as the Canning and Officer Basins, are considered by many geoscientists to be highly prospective for oil and gas, yet remain underexplored.*

Highlights and activities 2001–02

The main activities during 2001–02 were the completion of the Gibson area prospectivity Report, the Vines 1 well completion Record, and the compilation of data, and preliminary drafting of other reports in progress.

GSWA, working in conjunction with Geoscience Australia (GA), collected 156 km of reflection seismic data in the Officer Basin. The data were released to the public domain at a joint GA–GSWA open workshop on the eastern Yilgarn. A semi-detailed 1 × 2 km-grid gravity survey, covering an area of 60 × 10 km, was made over the 'Line 3' extension of the seismic survey into the Officer Basin, and an acquisition and processing report was written and released with the new data. The seismic and gravity data will be used for structural studies to analyse the petroleum and mineral exploration potential on the faulted eastern margin of the Yilgarn Craton and western margin of the Officer Basin.

Approximately 750 km of 1980s vintage Officer Basin seismic data were reprocessed from field tapes and prepared for release to the public domain in July 2002. Reprocessing of a further 1000 km of data is in progress for release during the course of 2002–03 (Fig. 1). About 4500 km of Officer Basin seismic data in analogue format were scanned to digital SEG Y format.

More than 8500 km of Canning Basin seismic data were scanned to SEG Y format and included in the Eastern Canning Basin Specific Area Gazettal prospectivity package that was released at the Australian Petroleum Production and Exploration Association (APPEA) conference and exhibition held in Adelaide in April 2002.

The well completion Record for Vines 1 well, drilled for GSWA in 1999 to a total depth of 2017.5 m and continuously cored from 44.5 m, was published in June 2002. The Record contains details of all laboratory studies completed to date on this drillhole, including data on the gas show encountered at a depth of 1483 m. Further analyses are in progress and an additional publication is planned. The well data and outcrop studies will be used for correlation with previous wells drilled in the basin, and to extend the depositional model for organic facies in the Officer Basin. The model will be applied to other areas of the Officer Basin in the search for additional stratigraphic coring locations to test for source facies for hydrocarbon generation, migration, and entrapment.

2001–02 publications and products

- Report 80: 'Basin development and petroleum exploration potential of the Gibson area, western Officer Basin, Western Australia';
- Record 2001/18: 'Vines 1 well completion report, Waigen area, Officer Basin, Western Australia';
- Digital data release: GA–GSWA–pmd*CRC seismic reflection data, northern Yilgarn seismic survey;
- Digital data release: Canning Basin seismic data scanned to SEG Y format (8500 line km);
- Digital data release: East Canning Basin Specific Area Gazettal data package.

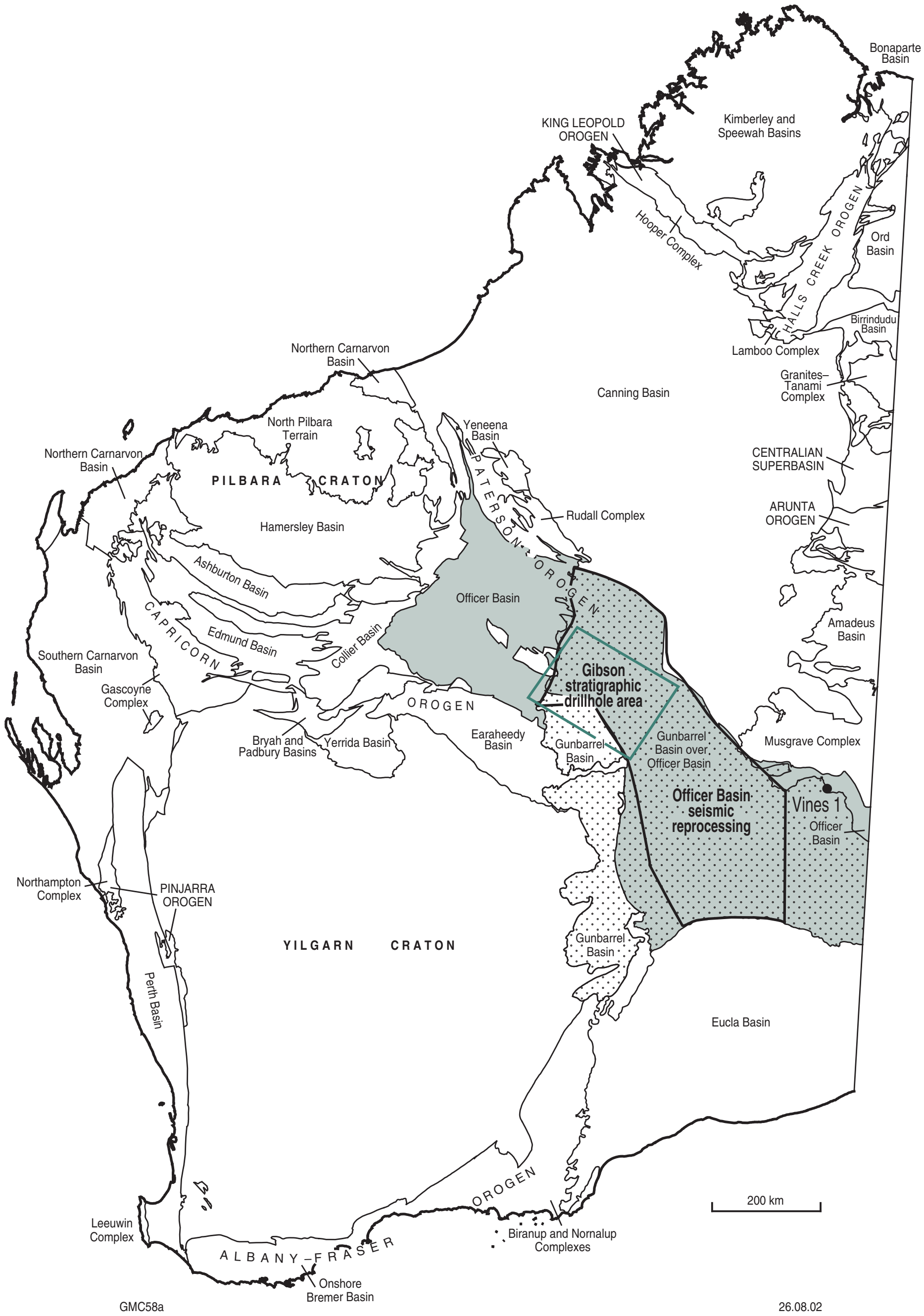


Figure 1. Location of the Interior basins petroleum initiatives project

Future work

Drilling and coring of a stratigraphic well in the Gibson area of the Officer Basin is planned for mid-2003. The basic data, core descriptions, and geophysical logs will be compiled for release as a Record in 2003–04.

An interpretation of the GA–GSWA seismic data will be included in a Report in progress on the Waigen area. A total of approximately 1750 km of reprocessed Officer Basin seismic reflection data will be released to the public domain. Leads and prospects in a currently unspecified area of the Officer Basin will be defined in a Record supporting a planned Specific Area Gazettal acreage release.

Additional planned publications include 'A review of the stratigraphy of the Officer Basin'; an extended paper on 'Hydrocarbons and petroleum systems of the Officer Basin, Western Australia'; and a number of external publications and presentations at the APPEA conference and the Western Australian Basins Symposium III conference.

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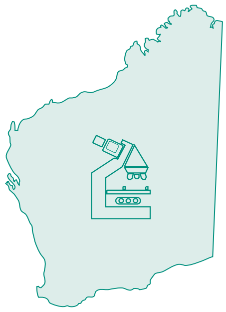
Biostratigraphy and palaeontological services



Objective: *To provide biostratigraphic, palaeoenvironmental, palaeobiological, and palaeontological 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 2001–02

Biostratigraphic and stratigraphic correlation and interpretation in the western Officer Basin (supporting the Interior basins petroleum initiative program) remains the major focus for GSWA palaeontological studies. A revision of lithostratigraphic nomenclature is nearing completion. Further studies of stromatolites from RUNTON and nearby areas confirm that carbonates are around 800–700 Ma old. Continuing palynological studies of Vines 1 drillcore identified the presence of a redeposited latest Neoproterozoic – earliest Cambrian component, indicating that the rocks are most probably Cambrian or younger.

Work continued on the 'terminal Neoproterozoic (Ediacarian) palynomorphs in Australia' monograph. In particular, more than one hundred photographic plates were digitized. Results will be published as an Australasian Association of Palaeontologists Memoir. As part of the National Geoscience Mapping Accord, data from the project will be incorporated in the GA databases managed by the Virtual Centre for Economic Micropalaeontology and Palynology (VCEMP), and will be used to validate key zones used in resource and exploration studies.

Cataloguing is now complete of the stromatolite collection, a significant component of the GSWA fossil collection, but the task of checking the Phanerozoic macrofossils in the collection is still to be completed before the collection is moved to the new Perth core storage facility under construction at Carlisle. A start was made by discarding poorly located, poorly preserved bulk material, some of which was donated to other institutions.

The Biostratigraphy and palaeontological services section continues to receive numerous requests for information about visiting fossil sites, setting up research projects, or using data from the 'ancientfossils' web pages in text books or teaching packages. Several initiatives have been undertaken to foster interest in the State's fossils and their uses. A guide providing information about visiting geoscientific sites in Western Australia has been prepared and it will now be developed as a web page. A suitable Pilbara site has been identified that will enable the public to view 3.5 billion-year-old fossils, and discussions are currently being held with stakeholders to allow public access.

Output from the section was either as publications, or in the form of data used by other geologists in preparing their products. Five conference presentations (on various aspects of the possible causes of a late Neoproterozoic acritarch radiation) contained contributions from the section. Six papers on broad aspects of Neoproterozoic correlation were published These were:

- A palaeomagnetic study of Empress 1A (in Precambrian Research);
- 'Cherts in a hot spring environment in the Bartle Member of the Killara Formation' (in Precambrian Research);
- Biotic changes following the 'Snowball Earth' (in GSWA Record 2002/5);
- New occurrences of 'strings of beads fossils (in GSWA Annual Review 2000–01);
- Palynology of Vines 1 (appendix in Record 2000/18, Vines 1 well completion report);
- Record 2002/11: 'Visiting geological sites in Western Australia — a guide to planning, collecting, and procedures'.

A further four papers and two abstracts are in press, and six more papers are at an advanced stage of preparation.

Future work

Work will continue on the palynology of several Officer Basin drillholes, with the aim of refining correlations. Stromatolite studies will be directed toward the preparation of at least two publications. Collaborative projects on the 'string of beads' fossils in the Collier Group will continue, particularly as they appear to be an important biomarker horizon of significance for mapping. The rehousing of the palaeontology collection and updating of the database will continue throughout 2002–03.

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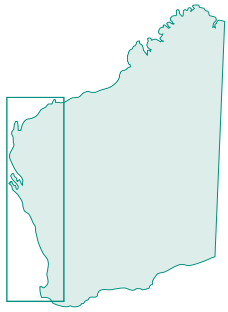
Western margin petroleum initiatives project



Objective: *To encourage and focus petroleum exploration within the onshore Carnarvon and Perth Basins with the production of original geoscientific reports on the hydrocarbon potential of those areas by integrating newly acquired GSWA data and industry open-file data.*

Highlights and activities 2001–02

The main activities during the year were the preparation of reports and external papers on the Southern Carnarvon Basin, with the completion of three basic well completion reports drilled on the Gascoyne Platform in 2001 as a joint GSWA–UWA project on the Cretaceous. Interpretive reports for these stratigraphic wells (Fig. 2) are underway with the cooperation of David Haig (UWA), who will oversee micropalaeontological studies of this material.

Work is nearing completion on a compilation of leads and prospects of the northern Perth Basin and the structure of the offshore Gascoyne Platform – Edel Terrace. Geohistory modelling of the Southern Carnarvon Basin currently underway will be incorporated into a summary of the evolution and petroleum potential of the basin synthesizing previously published GSWA reports.

Papers published or in press this year were on Carboniferous–Permian sedimentation in the Carnarvon Basin (Sedimentary Geology) and Statewide (Palaeogeography, Palaeoclimatology, Palaeoecology); anhydritization after dolomite of Silurian carbonates (Sedimentary Geology); the Peedamullah Shelf and the Southern Carnarvon Basin for the third Sedimentary Basins of Western Australia Symposium (WABS III); and a reply to comments on the age of the Woodleigh structure (Earth and Planetary Science Letters).

Promotional booths containing displays of products from the Western margin and Interior basins project teams were prepared for the 2002 AAPG Conference (Houston),

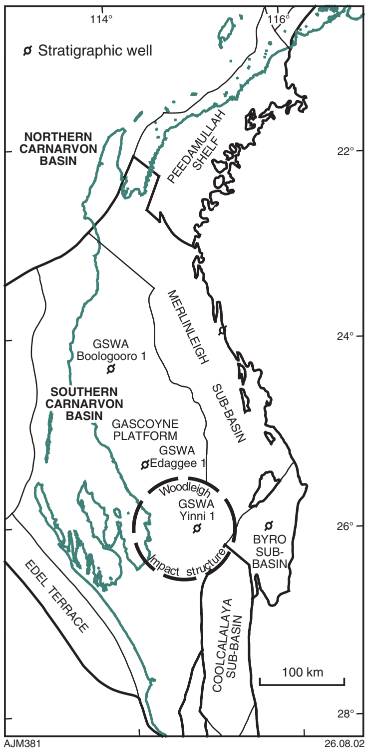


Figure 2. The northern part of the Western margin petroleum initiatives project area, showing the location of the three drillholes drilled in 2001

2002 APPEA Conference (Adelaide), and the GSWA 2002 open day.

2001–02 publications and products

- Record 2001/6: 'Woodleigh 1, 2, and 2A well completion report, Woodleigh impact structure, Southern Carnarvon Basin, Western Australia';
- Record 2002/6: 'GSWA Yinni 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia';
- Record 2002/7: 'GSWA Boologooro 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia';
- Record 2002/8: 'GSWA Edaggee 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia';
- 'Summary of petroleum prospectivity, onshore Western Australia 2001: Canning, Officer, Perth, Southern Carnarvon, and Bonaparte Basins';
- A paper on Silurian source rocks (in the GSWA Annual Review 2000–01).

Future work

Due for completion in 2002–03 are three Records for the Boologooro 1, Edaggee 1, and Yinni 1 interpretive well completion reports, and Reports on the prospects and leads in the northern onshore Perth Basin, and the offshore Gascoyne Platform – Edel Terrace. A geophysical interpretation of the Bernier Platform has commenced, to be incorporated in part into the offshore Gascoyne study, as well as a summary of the evolution and petroleum potential of the Southern Carnarvon Basin incorporating all work carried out by the team in the last six years.

The only new analyses planned for 2002–03 will be analyses of existing core required for the summary of the Southern Carnarvon Basin.

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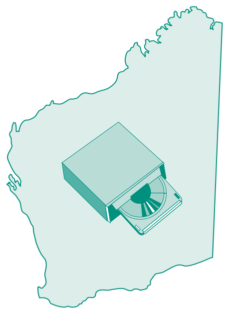
Mineralization and exploration assessment

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 data packages comprising hardcopy reports and maps, together with GIS-compatible databases on CD-ROMs.*



Highlights and activities 2001–02

During the year, one data package on the east Pilbara was released. Compilation of databases and digitizing of spatial data for mineral occurrences and mineral exploration activities were completed for the north Kimberley, west Kimberley, and Arunta–Musgrave areas, and writing of reports for these areas commenced. Database compilation and digitizing also commenced on two new project areas: Canning and Paterson. Updated CD-ROMs using data from the latest WAMEX releases since 1998 were completed for two earlier projects (Bangemall and southwest Western Australia) and two CD updates were in progress (north Eastern Goldfields and west Pilbara; Fig. 3).

Each data package normally contains a Report that synthesizes information on the mineral prospectivity of an area, a CD-ROM, and a 1:500 000-scale map that shows mineral occurrences, mineralization styles, commodity groups, and geology. For three planned project areas where there is limited open-file data (i.e. Arunta–Musgrave, Canning, and Officer–Eucla) each package will consist of a Record and a CD-ROM.

The CD-ROM for each package contains the following datasets available in Arc Explorer 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; aeromagnetic data; radiometric data; gravity data; and topographic and cultural features.

A 1:500 000-scale map showing mineralization and geology of the entire Pilbara Craton is in preparation for release in 2002. This product is a modified version of the poster display that was shown at the 4th International Archaean Symposium held in September 2001.

2001–02 publications and products

- Mineral Resources Bulletin 20: ‘Bentonite, attapulgite, and common clays in Western Australia’;
- Report 81: ‘Mineral occurrences and exploration potential of the east Pilbara’;
- Report 64: ‘Mineral occurrences and exploration potential of the Bangemall Basin — 2002 update’ (digital dataset only);
- Report 65: ‘Mineral occurrences and exploration potential of southwest Western Australia — 2001 update’ (digital dataset only);
- Record 2002/3: ‘Geology and mineral resources of the Southern Cross – Esperance Region of Western Australia’ (includes plate at 1:500 000 scale);
- Record 2002/12: ‘Industrial minerals in Western Australia: the situation in 2002’ (includes plate at 1:5 000 000 scale);
- ‘Overview of the mineral sector in Western Australia in 2000–01’;
- Iron ore deposits of the Pilbara region (1:500 000; including digital dataset);
- Mines and mineral deposits of Western Australia: digital extract from MINEDEX, July 2001.

Future work

Two data packages for the north Kimberley and Arunta–Musgrave areas are in preparation for release in late 2002. Updates of CD-ROMs for the north Eastern Goldfields and west Pilbara are also in preparation for release in late 2002. Two data packages are planned for release in 2003 on the west Kimberley area and the Canning area. Database compilation and digitizing will continue for the Paterson area, and will commence for the Earaheedy, Gascoyne, and Peak Hill areas (Fig. 3).

An update of mineral occurrences and mineral exploration activities will commence for the east Kimberley, using data from the latest WAMEX releases since 2000. The new digital data are planned for release on an updated CD-ROM in mid-2003.

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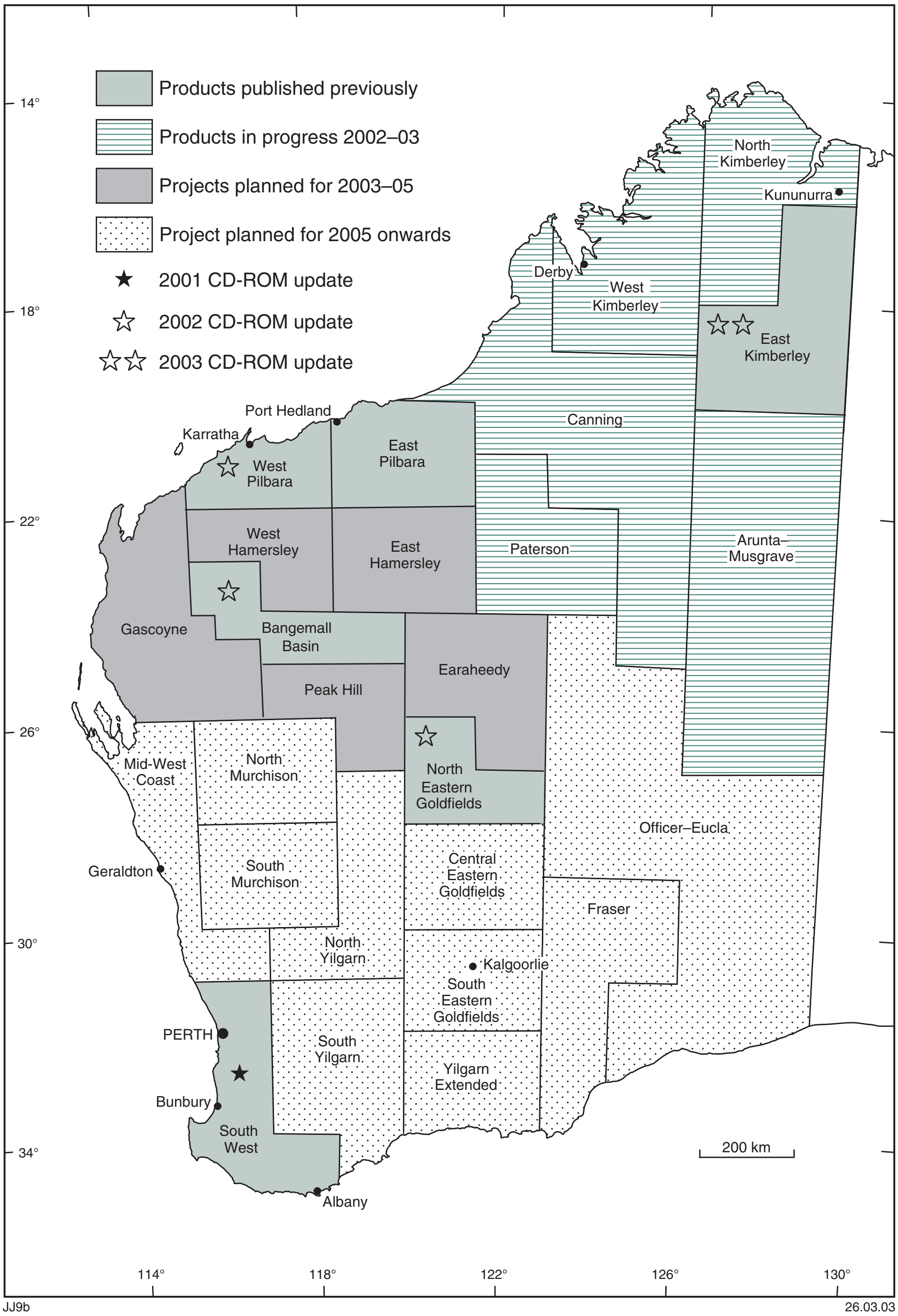

Figure 3. Progress of regional mineralization mapping projects

Resource mapping, assessment, and advice

Objectives: *To undertake detailed geological mapping and resource delineation in areas of the State that are likely to see significant development, and in which landuse planning would benefit from the availability of digital and hardcopy geoscience datasets. To provide high-quality and timely information and advice to Government, industry, and the general public on the regolith, landforms, mineral occurrences and resources, solid geology, and geohazards, both onshore and in shallow nearshore areas.*

Highlights and activities 2001–02

The regolith–landform mapping system — involving the systematic collection of surface and near-surface material properties, and landform properties and patterns, combined with an appraisal of potential for extracting basic raw materials — continues to form the basis of published maps, reports and assessments.

The results of field activities from previous years in the KARRIDALE – TOOKER – LEEUWIN area were published and field mapping was largely completed for the KALGOORLIE and BOULDER 1:50 000 sheets (Fig. 4).

During the course of the year, five geoscientists responsible for resource assessments and community liaison for planning and development projects were transferred to GSWA from the Mineral Titles Division and integrated with the urban and development areas geological mapping group. As an indication of the workload that was transferred with the new staff, a total of 1251 resource assessments were made by them during the year in response to ad hoc inquiries from planning and development agencies.

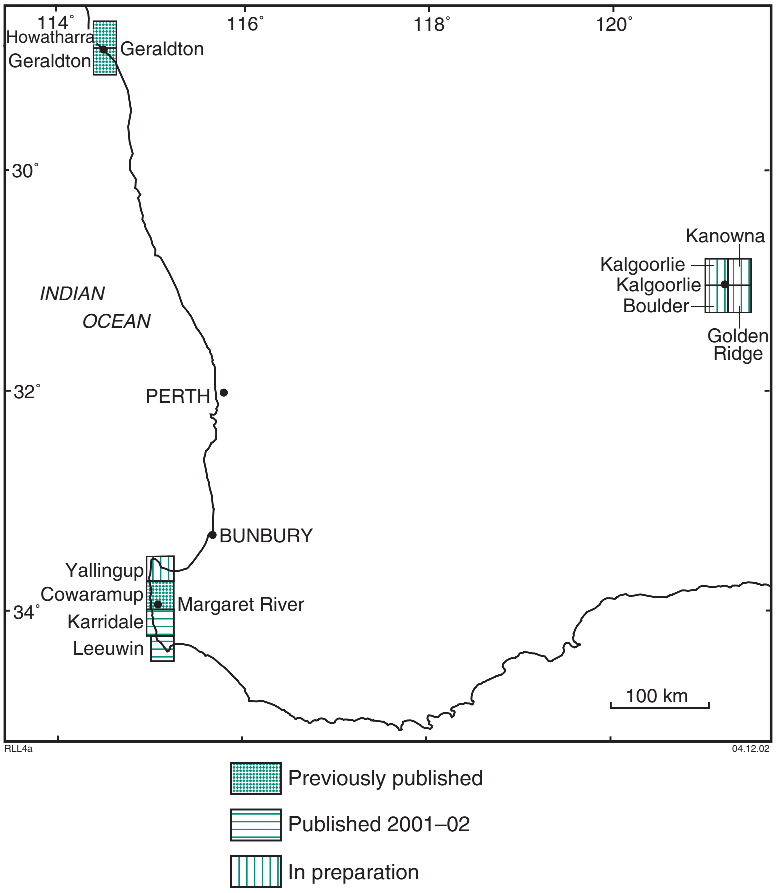

Figure 4. Progress of urban and development areas geological mapping

The additional workload and responsibilities resulted in a change of focus to resource mapping and assessment in order to respond to direct requests from landuse planning agencies and authorities; a change of title for the new group; and a reordering of priorities. Consequently, compilation, and hence the planned release, of the KALGOORLIE and BOULDER 1:50 000 sheets was deferred while new systems and procedures were implemented, and the planned field activities for the KANOWNA and GOLDEN RIDGE 1:50 000 sheets were put on hold.

2001–02 publications and products

- Record 2002/10: 'Regolith–landform resources of the Karridale–Tooker and Leeuwin 1:50 000 sheets' (including map and CD-ROM).

Future work

The KALGOORLIE–BOULDER regolith–landform resources maps, report and CD-ROM will continue to be worked on in 2002–03, but with an increased emphasis on mineral resource data. However, this will depend on the volume of assessment work that is requested, as many of these requests are statutory in nature and must be given priority.

If staff resources are sufficient, digital remastering and revisionary fieldwork will be completed on YALLINGUP in early 2003, leading to completion of a Cape-to-Cape dataset for this part of the South West Region.

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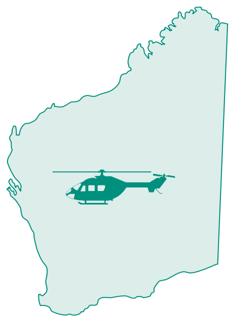
Subprogram 3103
REGIONAL GEOSCIENCE MAPPING

Regolith mapping and geochemistry



Objectives: *To determine the distribution and composition of surface material (regolith) over Western Australia, and present these data as digital datafiles and maps to the mineral exploration industry. To acquire, collate, and disseminate geochemical data in a central repository, and make these data available for projects aimed at enhancing the prospectivity of the State.*

Highlights and activities 2001–02

Digital data, maps, and Explanatory Notes were published for the NICHOLLS 1:100 000 map sheet (Fig. 5), and gravity data were acquired at selected sampling sites. The regolith chemistry for NICHOLLS is the first to compare total and partial digest chemistry, an initiative aimed at facilitating exploration in areas of transported overburden. These data have extended the area of potential mineralization, as well as identifying newly prospective areas. A regolith map at 1:250 000 scale was prepared for WILUNA. Compilation of a regolith map for the southern part of Western Australia (south of 26°S) from existing geological and regolith maps was completed. The division of regolith is based on seven primary divisions outlined in the GSWA regolith classification scheme. This regolith coverage has been generalized using a gridding process, thus reducing the number of polygons and their complexity for viewing at different scales.

In conjunction with the Earaheedy mapping team, a program was commenced to examine the chemistry and mineralization implications of Mesoproterozoic mafic igneous rocks that make up a large igneous province (LIP) in central western Australia. A presentation about the implications for mineralization of a LIP in the Proterozoic of Western Australia was given at the GSWA open day in March 2002. Implementation of DataShed software as the database to house geochemical data, including that generated by GSWA and open-file company data, was commenced.

Collaborative work began with the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME) on U–Th dating of regolith using opaline silica, and production of a geochemical map of the Yilgarn Craton based on collection and analysis of ferruginous duricrust.

2001–02 publications and products

- Explanatory Notes, maps, and digital data for the NICHOLLS 1:100 000 map sheet.

Future work

During 2002–03, GSWA will complete the commissioning of the DataShed geochemical database, and progressively migrate both in-house and open-file geochemical data into this database. The regolith map for the remainder of the State (north of 26°S) will be compiled from existing geological and regolith maps. As a member of CRC LEME, GSWA will continue the collection and subsequent analysis of regolith samples over parts of the Yilgarn Craton for the Yilgarn geochemical map project.

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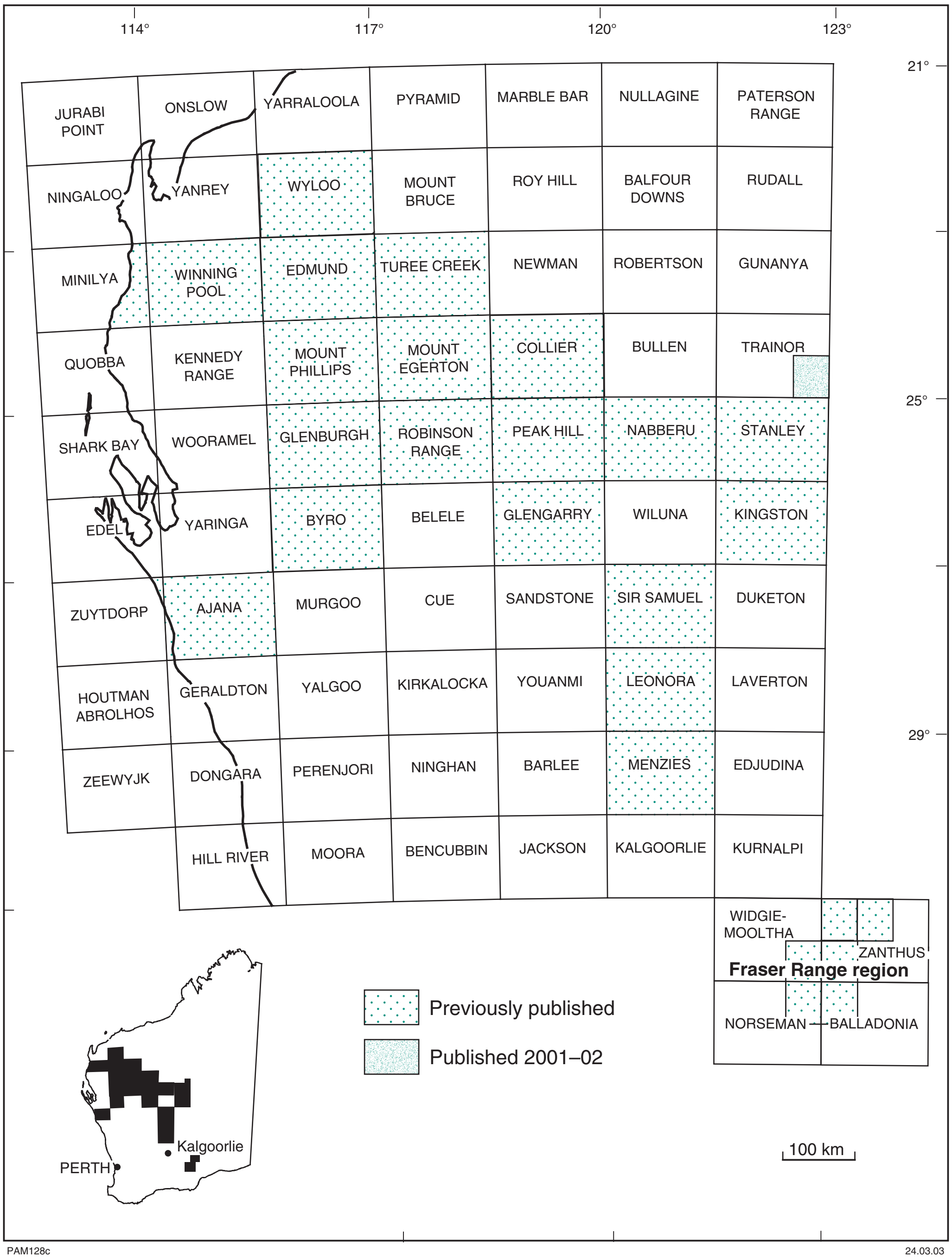
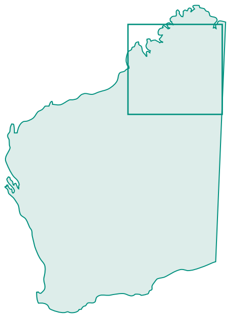


Figure 5. Progress of the regional regolith and geochemical mapping program

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, palaeontology, remote sensing, and metallogeny.*

Highlights and activities 2001–02

During 2001–02, work was commenced on writing Explanatory Notes for the DIXON 1:100 000 map sheet (Fig. 6). Work continued on a paper intended for the Australian Journal of Earth Sciences that presents SHRIMP U–Pb zircon ages obtained in collaboration with R. W. Page (then of AGSO) for the Valentine Siltstone (1834 ± 3 Ma) and the Hart Dolerite (1783 ± 3 Ma). These ages place constraints on the time of deposition of the Palaeoproterozoic Speewah and Kimberley Groups.

In May 2002, S. Sheppard presented two invited papers at the John Lewry Symposium on 'Collision tectonics in the continental interior of Canada' held as part of the Geological Association of Canada – Mineralogical Association of Canada joint meeting at the University of Saskatchewan. One paper by S. Sheppard and I. M. Tyler on 'Tectonic processes in the Palaeoproterozoic of Australia' examined differences in tectonic style of Palaeoproterozoic orogenic belts (including the King Leopold and Halls Creek Orogens) between Canada and Western Australia, and the nature of Palaeoproterozoic plate tectonics. The second paper by I. M. Tyler, S. Sheppard, and K. M. Ansdell (University of Saskatchewan) on 'Palaeoproterozoic orogenesis in the Kimberley region of northern Australia: a connection to Laurentia?' examined correlations between the Halls Creek Orogen and the Trans-Hudson Orogen.

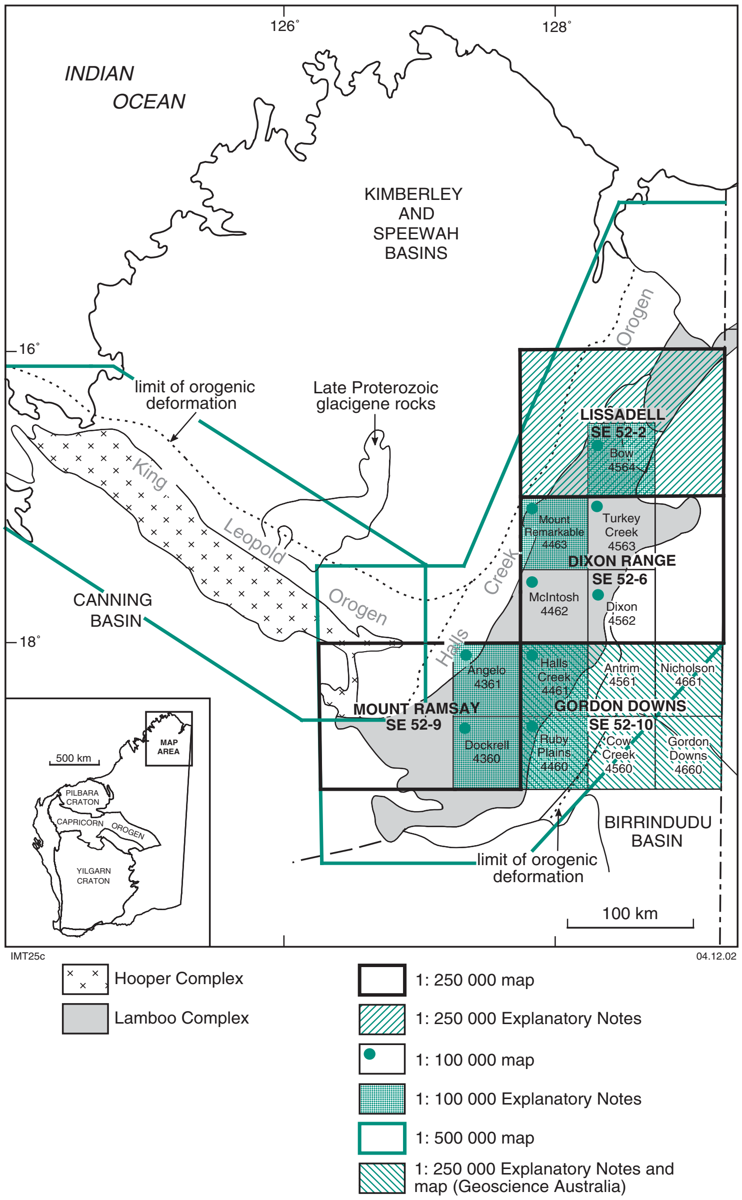


Figure 6. Recently published geological maps across the King Leopold and Halls Creek Orogens

Future work

During 2002–03, work will continue on the first draft of Bulletin 143 on the geology of the King Leopold and Halls Creek Orogens. Writing of Explanatory Notes for TURKEY CREEK and MCINTOSH 1:100 000 map sheets (Fig. 6) will commence.

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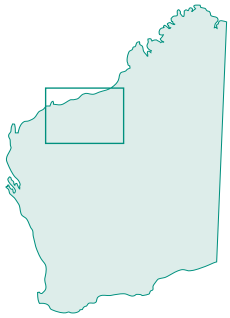
Pilbara Craton project



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 project commenced in 1995, and will be completed in 2004. The project is a National Geoscience Mapping Accord (NGMA) project with GA. By 2004, the project will have resulted in the detailed remapping of a 70 000 km^2 area, publication of 31 new 1:100 000-scale maps, new editions of seven 1:250 000-scale maps, and various non-series maps at 1:50 000 and 1:250 000 scales (Fig. 7). An additional four 1:100 000-scale maps (ROCKLEA, ISABELLA, BRAESIDE, and PEARANA) and two 1:250 000-scale maps (MOUNT BRUCE and ROY HILL) were mapped as parts of earlier projects immediately prior to commencement of the project. Explanatory Notes that describe all aspects of the geology of individual sheets accompany all the published maps. GSWA Reports, papers in international journals, and contributions to a number of geological conferences have presented both regional syntheses and the results of specialized research in this area.

Highlights and activities 2001–02

Geological mapping was completed on the HOOLEY, EASTERN CREEK, MOUNT EDGAR, and CARLINDIE 1:100 000 map sheets, continued on the MARBLE BAR and NULLAGINE 1:250 000 sheets, and commenced on the COONGAN, YILGALONG, NOREENA DOWNS, WARRIE, and MOUNT MARSH 1:100 000 sheets. Mapping from the 1:100 000 program, combined with interpretation of data from remote sensing, was used to compile the YARRIE and PYRAMID 1:250 000 sheets. A complete coverage of all granite–greenstones in the northern part of the Pilbara Craton was made possible by a decision to add the NOREENA DOWNS, WARRIE, and MOUNT MARSH 1:100 000 maps to the mapping program.

Results of the project were presented at the 4th International Archaean Symposium (4IAS), Perth, in September 2001, and included field excursions covering the geology of the East Pilbara Granite-Greenstone Terrane (GSWA), and metallogenesis of the north Pilbara granite–greenstones (GA). Three field guides (two from GSWA, and one from GA) on the northern Pilbara Craton, which included regional geological reviews, were published for the 4IAS.

The 4IAS provided an ideal forum for the presentation of new geological data and interpretations to an international audience of geoscientists specializing in Archaean geology. The vast amount of new geoscientific data obtained through the NGMA Pilbara project has confirmed that the northern part of the Pilbara Craton is the world's best exposed and least metamorphosed assemblage of diverse Palaeoarchaean and Mesoarchaean granite–greenstone terranes. The 4IAS revealed an increasing international recognition that the Pilbara provides a unique field laboratory to study subjects such as Earth's early tectonic processes, Archaean igneous geochemistry, and the origins of life.

GSWA's Pilbara team provided oral and poster presentations on a range of issues including granitoid geochemistry and petrogenesis; magmatism in the Mallina Basin; the tectonic evolution of the West Pilbara Granite-Greenstone Terrane (WPGGT); and tectonic processes in the East Pilbara Granite–Greenstone Terrane (EPGGT). Central to these presentations was a new tectonic interpretation of the northern Pilbara Craton based on the 1:100 000-scale mapping and accompanying SHRIMP U–Pb zircon geochronology. This interpretation, which recognizes three distinct granite-greenstone terranes separated by two dominantly clastic sedimentary basins, was described in papers submitted to Economic Geology and Precambrian Research.

New SHRIMP geochronology, combined with new Sm–Nd isotopic

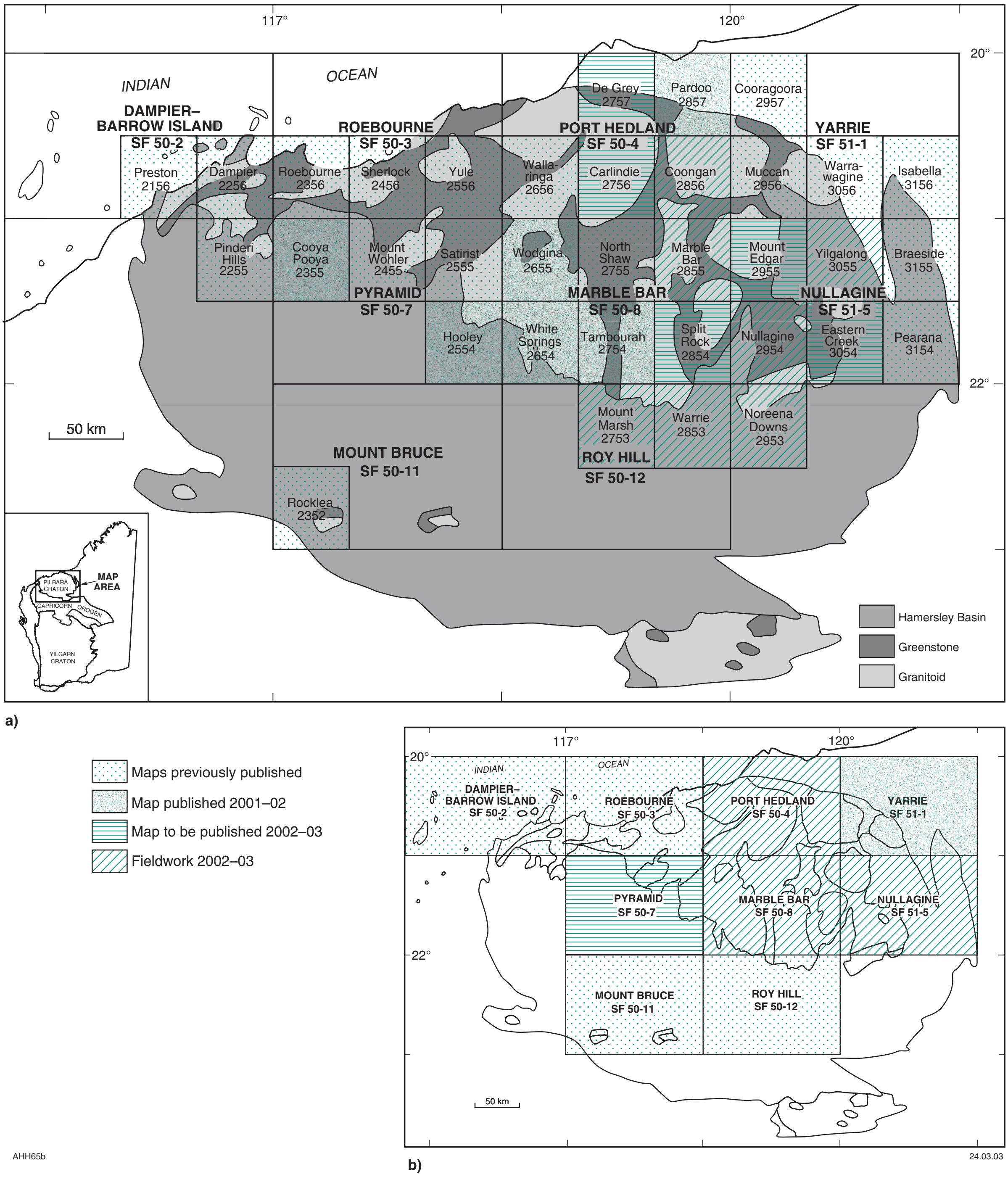


Figure 7. Progress of recent regional mapping in the Pilbara Craton: a) 1:100 000 sheet areas; b) 1:250 000 sheet areas

data, has supported the interpretation that the c. 3650–2850 Ma EPGGT is separated from the c. 3270–2920 Ma WPGGT by a belt of Archaean crust (Central Pilbara Tectonic Zone, including the Mallina and Whim Creek Basins) that is entirely younger than c. 3200 Ma. The younger crust is interpreted to have formed in a northeast-trending rift zone after plume-related separation of the EPGGT and WPGGT between c. 3280 and 3240 Ma. Plate-tectonic processes similar to those in the Proterozoic and Phanerozoic were operating in the WPGGT as early as 3160 Ma, but did not effect the thick continental crust of the EPGGT. The evolution of the EPGGT mainly involved plume-related magmatism, and phases of diapiric deformation driven by density inversion and isostatic adjustments. This style of deformation, which is not evident in the other four tectonic divisions of the north Pilbara granite–greenstones, produced the characteristic large dome and synform structures of the EPGGT.

2001–02 publications and products

- Roebourne 1:100 000 Explanatory Notes;
- Wallaringa 1:100 000 Explanatory Notes;
- Roebourne 1:250 000 Explanatory Notes;
- Wodgina 1:100 000 map sheet;
- Tambourah 1:100 000 map sheet;
- White Springs 1:100 000 map sheet;
- Hooley 1:100 000 map sheet;
- Cooya Pooya 1:100 000 map sheet;
- Pardoo 1:100 000 preliminary release map sheet;
- Yarrie 1:250 000 map sheet;
- Record 2001/9: 'Archaean geology of the East Pilbara Granite–Greenstone Terrane, Western Australia — a field guide';
- Record 2001/16: 'Evolution of the West Pilbara Granite–Greenstone Terrane and Mallina Basin, Western Australia — a field guide'.

Future work

The 2002–03 year will see the publication of the Eastern Creek, Mount Edgar, Split Rock, De Grey, and Carlindie 1:100 000 maps, the Pyramid 1:250 000 map, the North Shaw – Tambourah 1:50 000 map, and the West Pilbara Granite–Greenstone Terrane 1:250 000 map. Explanatory Notes for the Tambourah, Pinderi Hills, Split Rock, Eastern Creek, Preston, Wodgina, and White Springs 1:100 000 maps, and the Yarrie and Dampier – Barrow Island 1:250 000 maps will be completed. Mapping will be completed for the Yilgalong, Nullagine, Marble Bar, Noreena Downs, Warrie, and Mount Marsh 1:100 000 maps, and on the Marble Bar and Nullagine 1:250 000 sheet areas. This will complete all geological mapping for the project.

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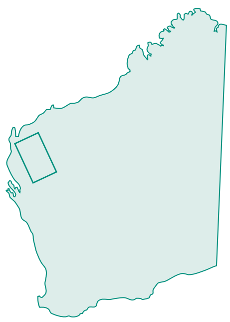
Southern Gascoyne Complex project

Objective: *To increase geological knowledge of the southern Gascoyne 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, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*



Highlights and activities 2001–02

Completion of geological mapping on the Glenburgh 1:250 000 sheet area (Fig. 8) during the 1999 field season ended the current program of field activities in the southern Gascoyne Complex. In 2001, two Honours students (based at Curtin University of Technology) from the Tectonics Special Research Centre submitted their theses on a part of the Mount Phillips 1:100 000 sheet area. During 2001, most of the fieldwork for a PhD study at Curtin University of Technology by S. A. Occhipinti entitled 'The tectonothermal evolution of the southern Capricorn Orogen' on the Glenburgh 1:250 000 sheet area was completed.

The Honours theses by C. A. Varvell on 'Age, structure and metamorphism of a section of the Morrissey Metamorphic Suite, central Gascoyne Complex, Western Australia' and by K. E. Culver on 'Structure, metamorphism and geochronology of the northern margin of the Gurun Gutta Granite, central Gascoyne Complex, Western Australia' have important implications for the tectonic evolution of the Gascoyne Complex. SHRIMP U–Pb dating of detrital zircons from a semi-pelitic schist indicates a maximum depositional age for the precursor sediment of 1840 ± 4 Ma (Varvell). This is much younger than the depositional ages of metasedimentary rocks farther south that were previously also included in the Morrissey Metamorphic Suite. Metamorphic studies indicate pressures of 7–10 kb, and imply significant crustal thickening during the 1830–1780 Ma Capricorn Orogeny. A SHRIMP U–Pb date of

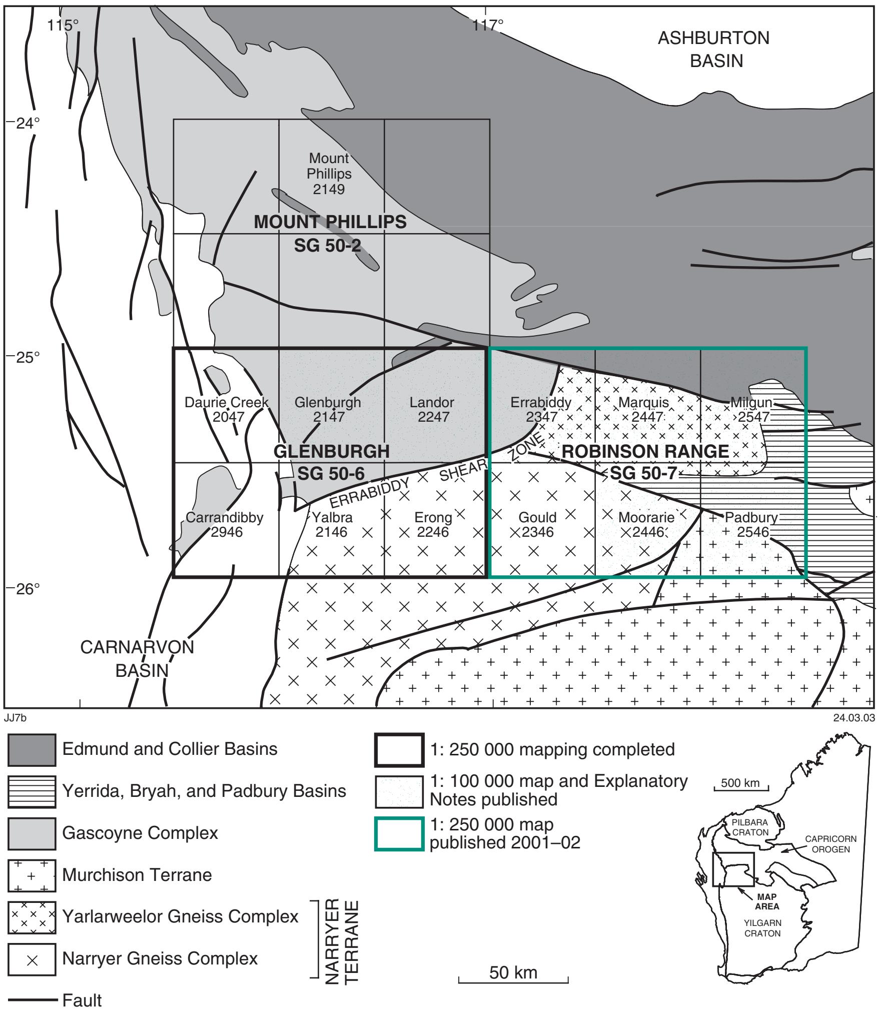


Figure 8. Progress of recent geological mapping for the Southern Gascoyne Complex project

1652 ± 5 Ma by Culver for a granite pluton confirms the widespread nature of magmatism in the Capricorn Orogen between 1650 and 1620 Ma.

A 2nd edition Robinson Range 1:250 000 map sheet was released, and writing of the accompanying Explanatory Notes has largely been completed. In September 2001, GSWA staff led an excursion to the Narryer Terrane and southern Gascoyne Complex, as part of the 4th International Archaean Symposium held in Perth. S.A. Occhipinti and S. Sheppard also presented a poster entitled 'Stuck between two cratons — latest Archaean crust in the Gascoyne Complex, Western Australia' at the symposium. GSWA staff have also prepared several papers for publication in a forthcoming special issue of Precambrian Research on the Capricorn Orogen. A paper on the relationship between granites of the Yarlarweelor Gneiss Complex and regional tectonism was also prepared for another external journal.

2001–02 publications and products

- Robinson Range 1:250 000 map sheet;
- Record 2001/8: 'Archaean and Palaeoproterozoic geology of the Narryer Terrane (Yilgarn Craton) and the southern Gascoyne Complex (Capricorn Orogen), Western Australia — a field guide'.

Future work

Explanatory Notes for the 2nd edition Robinson Range 1:250 000 map sheet will be published during 2002–03. Compilation for a 2nd edition Glenburgh 1:250 000 map sheet will also commence during this period.

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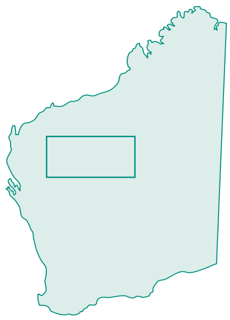
Bangemall Supergroup project



Objective: *To increase the knowledge of the 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.*

The Mesoproterozoic Bangemall Supergroup is a major geological unit that contains Western Australia's largest stratabound Pb–Cu–Ba deposit. This, combined with the unit's age and geological setting, makes it one of the most prospective areas in Australia for large, concealed, sediment-hosted base-metal orebodies. The Bangemall Supergroup also has a history of minor gold and phosphate production.

Highlights and activities 2001–02

Fieldwork carried out around the northwestern outcrop of the Bangemall Supergroup during 2001–02 has involved detailed mapping of the Capricorn Group and Gascoyne Complex rocks on the CAPRICORN and MAROONAH 1:100 000 map sheet areas (Fig. 9). This work complements recent mapping of the overlying Mesoproterozoic Bangemall Supergroup rocks in the area.

On MAROONAH, the Gascoyne Complex consists largely of medium-grade foliated and gneissic granites with screens and xenoliths of siliciclastic and minor calc-silicate rock. Pervasive epidote alteration is a conspicuous feature of some granitic and siliciclastic sedimentary rocks. Large plutons of massive biotite- and muscovite-bearing granites were emplaced following low- to medium-grade metamorphism and folding. The geological history of MAROONAH cannot be readily reconciled with that on the EDMUND 1:100 000 sheet area immediately to the southeast. This observation suggests that the two areas may have been juxtaposed late in the evolution of the Gascoyne Complex.

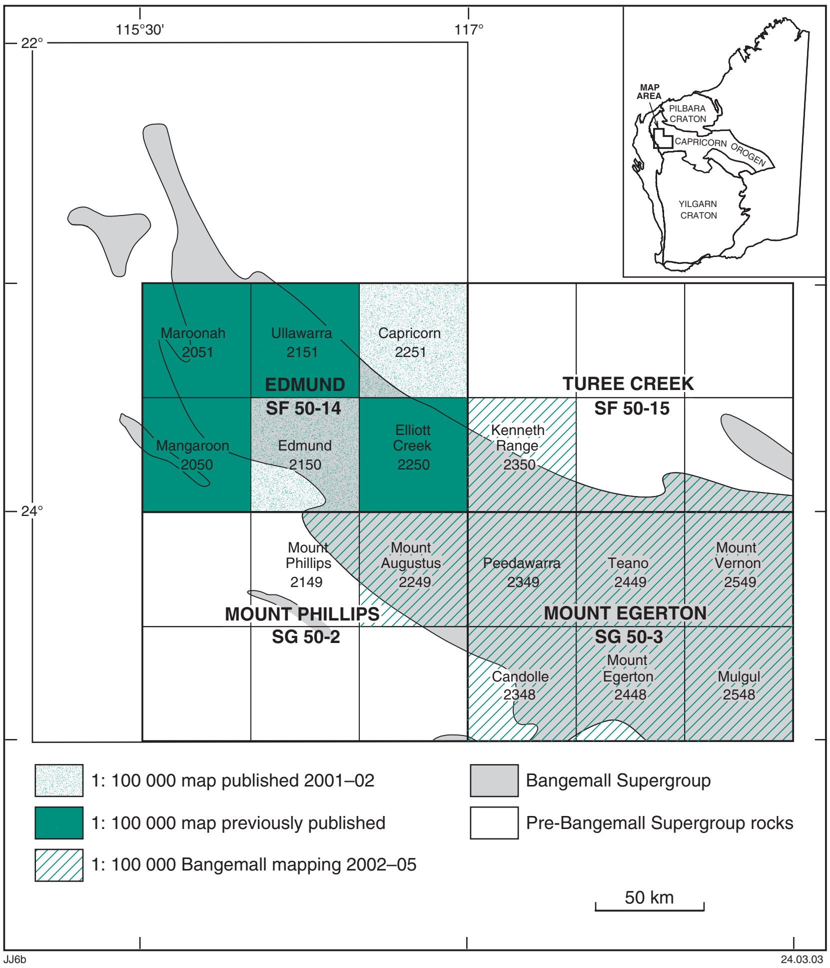


Figure 9. Progress of recent geological mapping for the Bangemall Supergroup project

On CAPRICORN, the Capricorn Formation has been raised to group status, with a two-fold subdivision into an older Bywash Formation and a younger Mooline Formation. Recent mapping has also confirmed the presence of an unconformity between the Bywash Formation and the underlying Ashburton Formation that includes a c. 1806 Ma felsic volcanic unit. Both the Bywash and Mooline Formations are characterized by marked thickness and facies variations across the map sheet.

Throughout most of CAPRICORN, the Bywash Formation varies in thickness from approximately 200 to 450 m. In the southeast, the base of the formation is marked by a thin, cross-stratified quartz sandstone. This is overlain by a mixed assemblage of deltaic to shallow marine deposits consisting of cross-stratified fine- to very coarse-grained lithic sandstone interbedded with quartzitic dolarenite and dolomitic siltstone, and thin beds of felsic volcaniclasic rock. Palaeocurrent data from medium- to large-scale trough cross-strata in the sandstone units are broadly from south to north. The top of the Bywash Formation is marked by a thin felsic volcaniclastic unit, the Koonong Member.

The overlying Mooline Formation ranges in thickness from about 900 m in southeastern CAPRICORN to about 2500 m in the northwest. It consists of thick units of delta-top trough cross-stratified quartz sandstone and delta-front ripple-laminated sandstone alternating with marine shelf deposits including siltstone, lithic quartz sandstone–dolostone, and fine-grained felsic volcaniclastic sandstone. In southeastern CAPRICORN, upper parts of the Mooline Formation contain channelized pebble- to cobble-conglomerate bodies. Large-scale trough cross-strata in the underlying sandstone bodies suggest a broadly south to north palaeoflow.

Office-based activities have included the compilation of geological data for EDMUND, CAPRICORN, and MAROONAH, and analysis of field data.

2001–02 publications and products

- EDMUND 1:100 000 preliminary release map sheet;
- CAPRICORN 1:100 000 preliminary release map sheet;
- Record 2002/4: 'Age and palaeomagnetism of dolerite sills intruded into the Bangemall Supergroup on the Edmund 1:250 000 map sheet, Western Australia';
- Record 2002/15: 'Revised lithostratigraphy of the Mesoproterozoic Bangemall Supergroup on the Edmund and Turee Creek 1:250 000 sheets, Western Australia'.

Future work

Work planned to be completed during 2002–03 includes the mapping and compilation of Bangemall Supergroup and Wyloo Group rocks on KENNETH RANGE and MOUNT AUGUSTUS, and Gascoyne Complex rocks on MANGAROON. The major aims of this work are to further test and implement the revised stratigraphy for the Bangemall Supergroup on KENNETH RANGE and MOUNT AUGUSTUS; to identify and sample suitable targets for U–Pb zircon geochronology, provenance studies, and geochemistry; and to better understand the relationship between the different Gascoyne Complex rock units on the EDMUND 1:250 000 map sheet.

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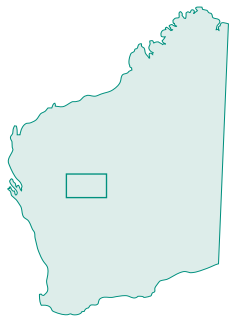
Earaheedy Basin project



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 that integrate field and laboratory studies including mapping, petrology, geochemistry, geochronology, remote sensing, and metallogeny.*

Work in the Earaheedy Basin commenced in 1997 and is now nearing conclusion. Since 1997, ten 1:100 000-scale geological maps have been published (Fig. 10) and four sets of Explanatory Notes. In addition, a number of papers have been presented at national and international conferences.

The Earaheedy Basin contains the Earaheedy Group and lies at the easternmost end of the Capricorn Orogen. Basement to the exposed Earaheedy Basin is the Archaean Yilgarn Craton and, to the west, the Yerrida Basin. The regional structure is an asymmetric east-plunging syncline with a vertical to locally overturned northern limb, due to compressive movements from the northeast that created a zone of intense deformation along the exposed northern margin of the Earaheedy Basin. This zone of deformation, named the Stanley Fold Belt, is characterized by reverse faults and shear zones that

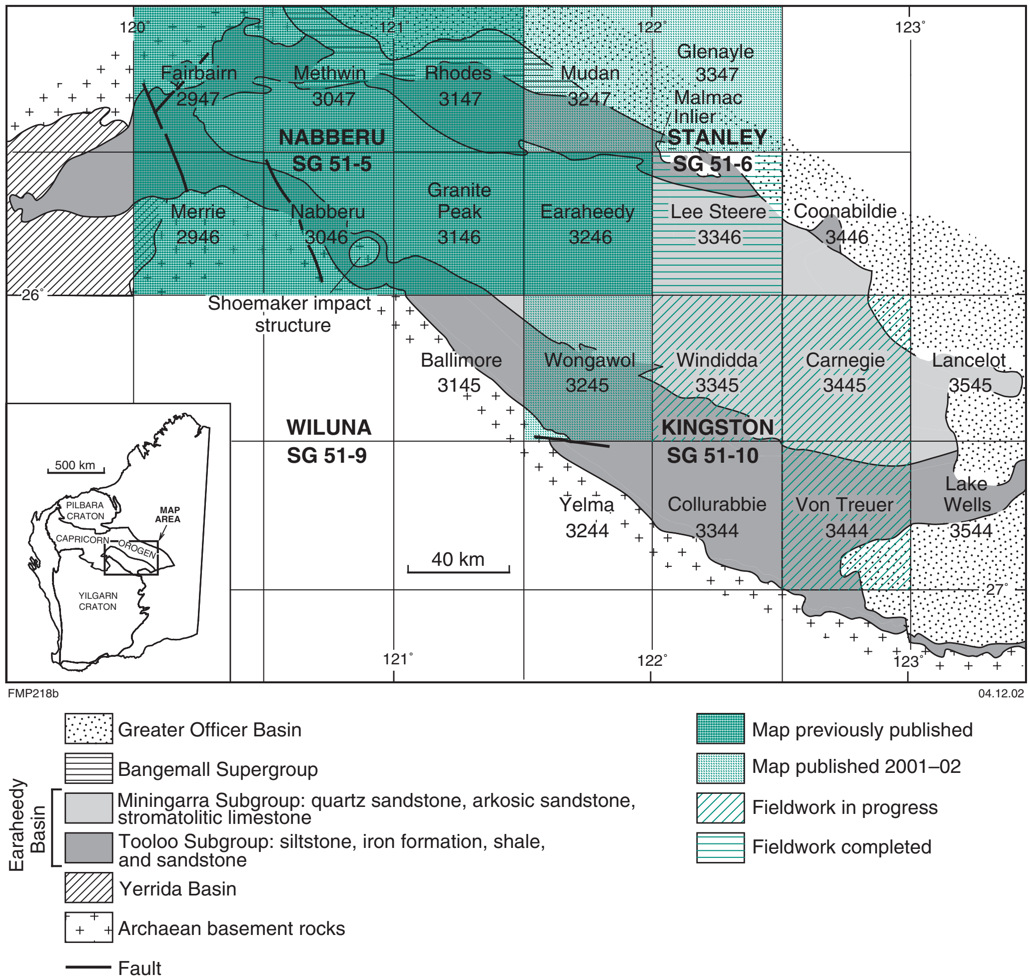


Figure 10. Progress of 1:100 000-scale geological mapping for the Earaheedy Basin project

consistently dip steeply to the north, the development of slaty cleavage and phyllitic rocks, and the presence of metamorphic minerals (e.g. muscovite, sericite, and chlorite). The intensity of deformation gradually decreases southward, but abruptly decreases to the north.

The Palaeoproterozoic Earaheedy Basin contains the Earaheedy Group, a 5 km-thick succession of shallow-marine clastic and chemical sedimentary rocks that is divided into two subgroups. The Tooloo Subgroup consists of the Yelma (base), Frere, and Windidda Formations (top). The overlying Miningarra Subgroup consists of the Chiall Formation (base), Wongawol Formation, Kulele Limestone, and Mulgarra Sandstone (top). The boundary between the Tooloo and Miningarra Subgroups (base of the Chiall Formation) reflects a change in depositional setting from a chemical, clastic-starved regime to one of abundant clastic supply.

The age of the Earaheedy Group is stratigraphically constrained by the age of the underlying Mooloogool Group (c. 1.84 Ga Maraloou Formation), and by the Malmac (2.6 Ga) and Imbin (1.99 Ga) Inliers. SHRIMP U–Pb dating of detrital zircons from the Yelma Formation provides a maximum depositional age of 2.03 Ga,whereas Pb–Pb isochron ages on galena hosted by the Sweetwaters Well Member provide additional minimum age constraints of 1.77 – 1.74 Ga. The range in detrital zircon ages suggests both Archaean and Palaeoproterozoic sources for the Earaheedy Group. Archaean ages are consistent with the Yilgarn Craton as a source. The youngest age of detrital zircons in the lower Tooloo Subgroup suggests a 2.0 – 1.8 Ga source. The only possible source of these Palaeoproterozoic zircons in the immediate region (barring unknown continental fragments elsewhere) is the southern Gascoyne Complex in the west. The source of iron for the granular iron-formations in the Frere Formation is a key element in the understanding of the basin, as is the lack of evidence of contemporaneous volcanism and major deformation. During deposition of the Tooloo Subgroup, no oceanic environment is known to have been present in the west. From known rock distributions, oceans must have been to the north and/or northeast, separating the North Australian and West Australian cratons.

The Miningarra Subgroup heralded a new phase of sedimentation, still in a passive margin setting, with a dominant clastic sediment input from areas of orogenic uplift in the west and/or northwest (i.e. Pilbara–Yilgarn collision and the Capricorn

Orogeny). This is supported by the presence of sedimentary breccias, suggestive of liquefaction in situ and interpreted as seismites, and ball-and-pillow (hydroplastic) loading structures throughout the Mingarra Subgroup, which are indicative of far-field seismic and tectonic activity. The rapid influx of siliciclastics into the basin overwhelmed the chemical deposition of iron oxides (granular iron-formation) and favoured instead the deposition of glauconitic sandstones. The Kulele Limestone, deposited in a subtidal stromatolitic carbonate environment, reflects a decrease in terrigenous supply caused either by climatic or tectonic changes. The Mulgarra Sandstone shows a return to the shelfal depositional setting of the Wongawol and Chiall Formations. A carbonate interval at the topmost Mulgarra Sandstone may have heralded a return to carbonate deposition, now only barely preserved because of later erosion.

Based on the above, and given the age constraints, the deposition of the Earaheedy Group was essentially synchronous with the Capricorn Orogeny.

Highlights and activities 2001–02

During the year, mapping continued in the northern parts of the basin (LEE STEERE and WINDIDDA), but was considerably slowed down by inclement weather. This mapping encompassed tectonic units such as the Glenayle and Prenti Dolerites, which intrude c. 1200 Ma sedimentary rocks of the Collier Basin and correlative units, as well as the Earaheedy Group. This work led to the recognition that these mafic rocks belong to a much wider unit, in which coeval and compositionally similar rocks can be traced as far as the western parts of the Edmund Basin and the Musgrave Complex in the east, along a tract of more than 1000 km strike, thereby constituting a large igneous province (LIP). Recent dating by SHRIMP (U–Pb; baddelyite) and K–Ar suggests that the LIP was emplaced at c. 1070 Ma. This is a global thermal event that affected the North American continent and the southern African subcontinent. The implications of this discovery are very important from the economic point of view, and are still under investigation in cooperation with researchers from UWA and Curtin University.

Four papers were accepted for publication, one by Geochemistry — Exploration, Environment, Analysis and three by Precambrian Research.

2001–02 publications and products

- Report 82: 'Geology of the Shoemaker impact structure, Western Australia';
- MEREWETHER 1:100 000 Explanatory Notes;
- METHWIN 1:100 000 Explanatory Notes;
- GLENAYLE 1:100 000 map sheet;
- WONGAWOL 1:100 000 map sheet;
- MUDAN 1:100 000 map sheet.

Future work

Work planned for 2002–03 includes the continuation of field mapping for WINDIDDA, VON TRUER, and CARNEGIE. A second edition 1:250 000-scale map of NABBERU is being completed. New compilations will include LEE STEERE and WINDIDDA. Two Records will be published by co-workers from UWA on the palaeomagnetism of the Glenayle Dolerite and the geophysics of the Shoemaker impact structure.

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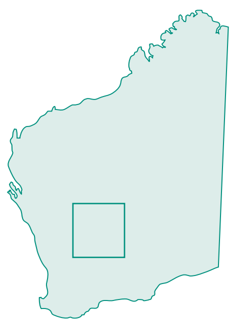
East Yilgarn project

Objective: *To increase geoscientific knowledge of the granite–greenstone terranes of the east Yilgarn Craton by the collection, synthesis, and dissemination of geological information, particularly through the production of GIS-based seamless geological databases, geological maps, and supporting publications that integrate field and laboratory studies, including mapping, petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*



The East Yilgarn project covers the highly mineralized Eastern Goldfields Granite–Greenstone Terrane and the southern part of the Southern Cross Granite–Greenstone Terrane that together comprise the eastern part of the Archaean Yilgarn Craton. The project embodies the Kalgoorlie regional office, the J. H. (Joe) Lord Core Library, and the Eastern Goldfields.

Highlights and activities 2001–02

The third phase of the GIS-based seamless East Yilgarn digital geoscience database was released. This phase covers the Leonora to Laverton region and includes the following eighteen 1:100 000 map sheets: MUNJEROO, WILDARA, WEEBO, NAMBI, MOUNT VARDEN, MCMILLAN, MOUNT ALEXANDER, WILBAH, LEONORA, MINERIE, LAVERTON, BURTVILLE, MOUNT MASON, BALLARD, MELITA, YERILLA, LAKE CAREY, and MOUNT CELIA (Fig. 11). With completion of the Eastern Goldfields portion of the digital database, the East Yilgarn seamless digital database now incorporates fifty-six 1:100 000 geological outcrop maps that stretch from Wiluna in the north to Norseman in the south. The themes included in this extensive database are 1:100 000 outcrop geology and structures, mineral location and resource data (MINEDEX), tenement and geographic information (TENGRAPH), Landsat images, aeromagnetic coverage, and 1:250 000 or 1:500 000 interpretative geology. The data is supplied in a number of computer software formats including ArcInfo, ArcView, and MapInfo. To generate the seamless coverage, a uniform rock code scheme was developed, and field mapping was carried out where required along adjoining edges of adjacent 1:100 000 map sheets.

This seamless digital geoscientific coverage of the Eastern Goldfields is currently being extended by new mapping at 1:100 000 scale of the eastern and southeastern margins of the Yilgarn Craton. These are underexplored and poorly understood areas of the Yilgarn Craton not previously mapped at this scale.

The J. H. (Joe) Lord Core Library that is part of the regional office facility in Kalgoorlie–Boulder has continued to assist the mining and exploration industry through the acquisition, storage, and display of drillcore.

The Kalgoorlie regional office of the Geological Survey provides advice to the general public, mining companies, and others on the geology of the east Yilgarn. The Kalgoorlie office continues to be the operational base for field geological staff involved in the Eastern Goldfields regional mapping projects, the development of an inventory of abandoned mine sites in the Kalgoorlie region, and the Development areas resource mapping team working on the KALGOORLIE and BOULDER 1:50 000 sheets.

In October 2001, a combined GSWA and GA open day was again held in Kalgoorlie. Following on from previous years, recent activities of GSWA and GA in the Yilgarn Craton were depicted through posters, displays, and a series of talks. A poster on the East Yilgarn Geoscience Database was displayed at the 4th International Archaean Symposium held in September 2001.

2001–02 publications and products

- MOUNT BELCHES 1:100 000 Explanatory Notes;
- East Yilgarn Geoscience Database: Leonora–Laverton region, Eastern Goldfields Granite–Greenstone Terrane (1:100 000);
- Record 2002/13: 'Compilation of whole-rock geochemical data for the Gordon area, Eastern Goldfields, Western Australia';
- Record 2002/14: 'Selection criteria for mineral drillcore in the Western Australian core libraries'.

Future work

In 2002–03, the Report for the Leonora–Laverton 1:100 000 digital geological data package of the East Yilgarn Geoscience Database will be published, as will the YARDILLA 1:100 000 sheet.

In 2002–03, a GSWA Record and dataset on metamorphism in the Kalgoorlie region, a mineral occurrence dataset for the WOOLGANGIE and YILMIA 1:100 000 map sheets, and a Report on gold mineralization in the Edjudina–Kurnalpi–Kanowna area will be released. In addition, a dataset on the regolith of the Eastern Goldfields will be completed.

Field mapping will commence on the YARDINA, ERAYINIA, JOHNSTON, and TAY 1:100 000 map sheets in 2002–03.

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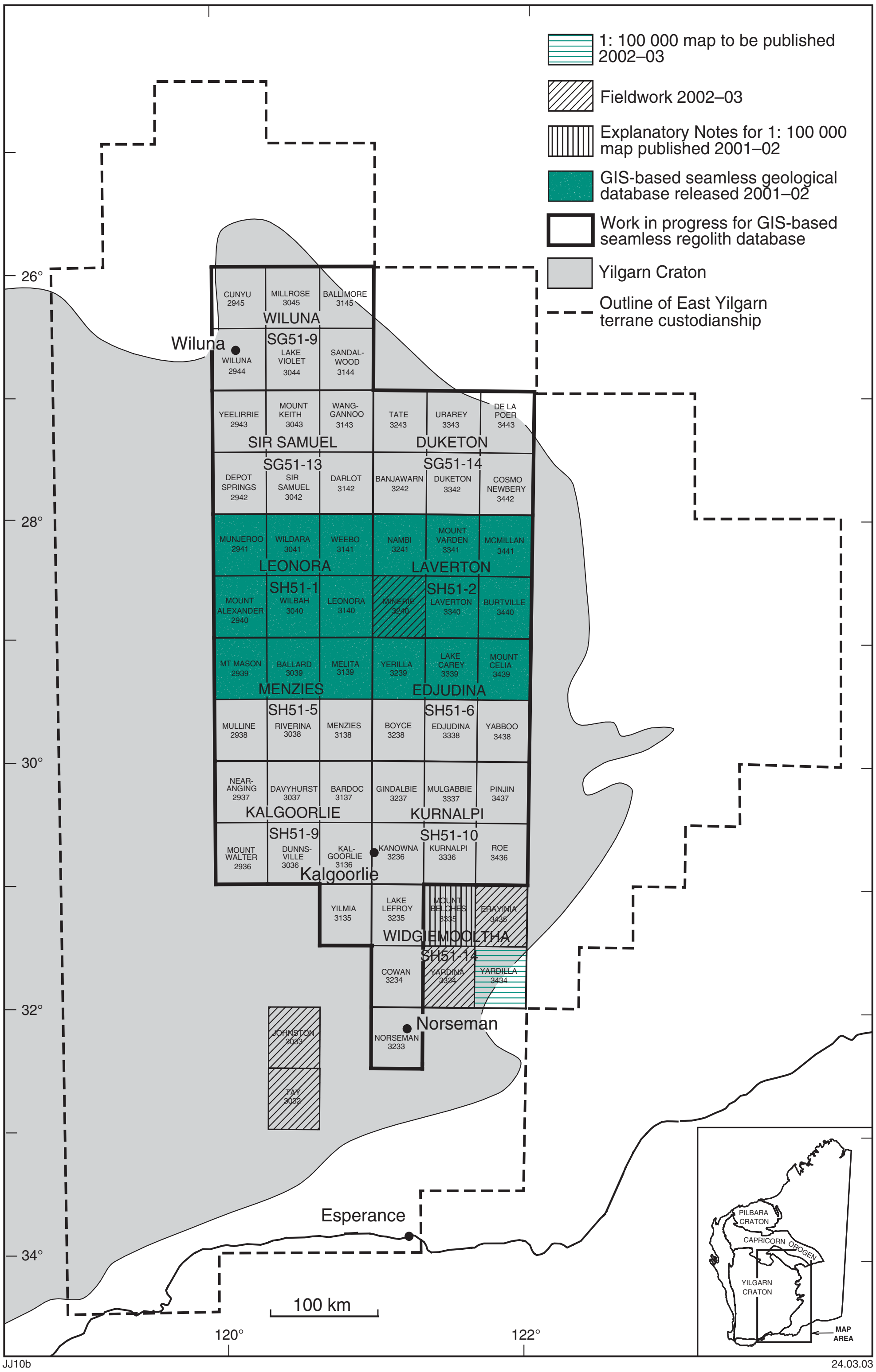
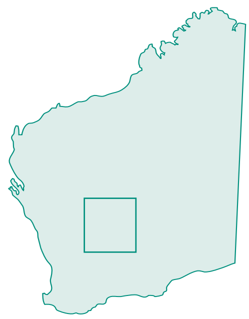


Figure 11. Progress of recent geological mapping in the east Yilgarn region and progress towards the GIS-based seamless digital database

Central Yilgarn (Southern Cross) 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 began in the Marda–Diemals area, the geographic centre of the Yilgarn Craton, in late 1997 and eight 1:100 000 sheets have been published to date (Fig. 12).

Highlights and activities 2001–02

In 2001–02, fieldwork and compilation of the Atley 1:100 000 and Menzies 1:250 000 sheets was completed, and field mapping commenced on the Lake Mason and Sandstone 1:100 000 sheets.

Also during 2001–02, there was a field excursion to the central Yilgarn in association with the 4th International Archaean Symposium in September 2001. This involved publication of a comprehensive excursion guide. A poster detailing the geology and structural evolution of the central Yilgarn was presented at the symposium. A paper detailing the stratigraphic correlations in the Marda–Diemals greenstone belt has been submitted for external publication. Another paper, describing results of geochronological studies of detrital zircons in quartzites in the central Yilgarn, was prepared for external publication. Fifteen new SHRIMP U–Pb isotopic ages were acquired and published.

Recent mapping has allowed stratigraphy to be established for greenstone belts away from the Marda–Diemals greenstone belt. However, no simple regional stratigraphic model for the lower (mafic–ultramafic–metasedimentary) greenstone succession has become apparent. Although containing broadly similar assemblages, the greenstone belts have different arrangements of greenstone packages that cannot be easily correlated. A lack of suitable material for SHRIMP U–Pb zircon geochronology means that absolute ages of greenstones in the lower succession are unknown, so it is difficult to test proposed stratigraphic correlations.

The 2.73 Ga upper greenstone succession in the Marda–Diemals greenstone belt (felsic volcanic rocks of the Marda Complex and metasedimentary rocks of the Diemals Formation) differs in age from other felsic successions in the region and appears to represent an isolated volcanic centre.

2001–02 publications and products

- Jackson 1:100 000 Explanatory Notes;
- Record 2001/14: 'Archaean granite–greenstones of the central Yilgarn Craton, Western Australia — a field guide';
- Marmion 1:100 000 map sheet;
- Everett Creek 1:100 000 map sheet;
- Richardson 1:100 000 map sheet.

Future work

Fieldwork on the Lake Mason 1:100 000 sheet will be completed in 2002–03, and that sheet will be compiled and published. Fieldwork will continue on the Sandstone 1:100 000 sheet, and work on the Rays Rocks, Montagu, and Youno Downs 1:100 000 sheets will commence. Work will continue on a study of regional-scale shear zones. Explanatory Notes will be published for the Barlee and Bungalbin 1:100 000 sheets, and Explanatory Notes will be prepared for the Everett Creek, Marmion, and Richardson 1:100 000 sheets, and for the Menzies 1:250 000 sheet.

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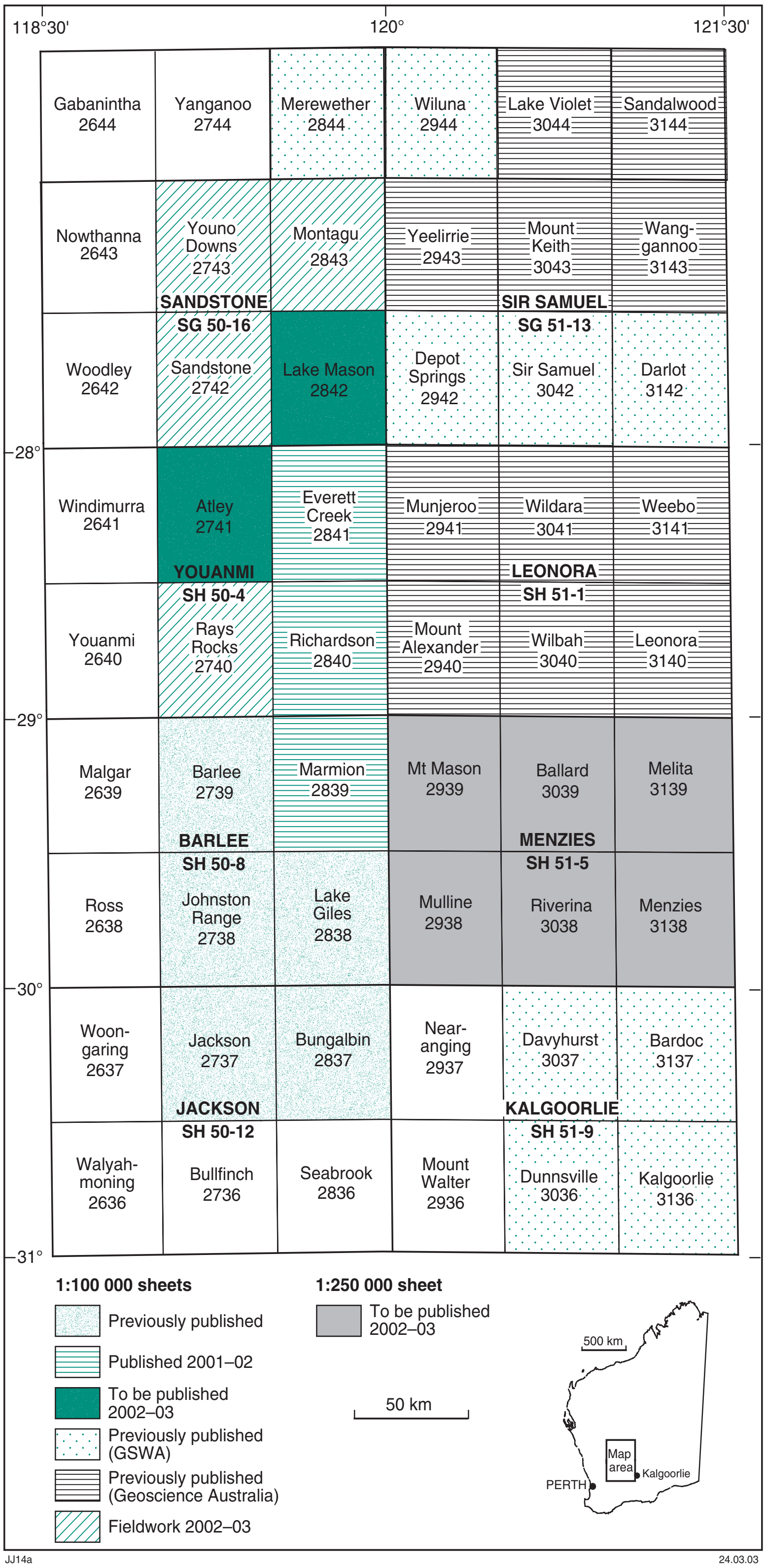
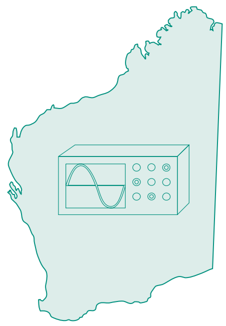


Figure 12. Progress of recent geological mapping for the Central Yilgarn (Southern Cross) project

Subprogram 3104
SCIENTIFIC, TECHNICAL, AND FIELD SUPPORT

Geoscientific specialist support

Geochronology



Objective: *To increase the knowledge of the geology of Western Australia by the collection, interpretation, and synthesis of geological, geochronological, and geophysical information for dissemination and to support the regional mapping projects.*

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

Highlights and activities 2001–02

Over 60 samples from throughout Western Australia were dated by the SHRIMP U–Pb zircon and monazite techniques, with typical precision of ± 6 Ma, for incorporation into GSWA geological maps and projects. An additional 15 samples from the Pilbara Craton, the Gascoyne and Leeuwin Complexes, and the Officer, Collier, Gunbarrel, and Yerrida Basins were dated by the K–Ar and Ar–Ar techniques. GSWA Record 2002/2 documents all results from the geochronology work undertaken during calendar 2001.

One highlight of year 2001 was the identification of a 4364 ± 8 Ma detrital zircon within a quartzite from the basal greenstones of the Maynard Hills greenstone belt of the Southern Cross Granite–Greenstone Terrane, central Yilgarn. This zircon crystallized only 200 million years after the formation of the Earth and is the second oldest terrestrial sample yet identified. The age profiles of the detrital zircon populations within the basal quartzites of the Southern Cross Granite–Greenstone Terrane closely match those of the Narryer Terrane some 400 km to the northwest. These new findings have important implications for models of the development of the Yilgarn Craton.

During the year, assessment of the Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICPMS) technique for Hf isotopic and reconnaissance U–Pb provenance investigations continued. New photomicrography equipment is currently being assessed that may enable the publication on CD of digital images of the minerals analysed for geochronology. These could then be released with the annual GSWA geochronology Record.

2001–02 publications and products

- Record 2001/2: 'Compilation of geochronology data, 2000';
- Record 2002/2: 'Compilation of geochronology data, 2001'.

Future work

Further geochronology work in the Eastern Goldfields, Pilbara, Southern Cross, and Bangemall regions is in progress for 2002–03.

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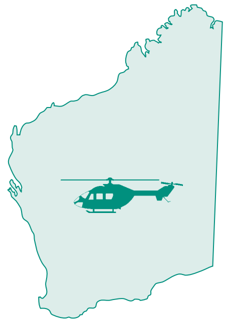
Geophysics



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

Regional airborne geophysics

In June 2002, GSWA and GA contracted UTS Geophysics to acquire approximately 68 000 line km of new magnetic and radiometric data in the west Tanami area. The new data, when merged with previously flown private company data and existing GA data, will provide complete coverage of the Gordon Downs, Billiluna and northern half of the Lucas 1:250 000 sheets at survey line spacings from 200 to 400 m.

Fugro Airborne Surveys was also contracted to acquire 45 000 line km of magnetic and radiometric data in a survey in the west Musgrave area that was planned to commence at the same time. The survey was delayed while access issues were resolved; however, acquisition is expected to start in July 2002. With the incorporation of private company data, this survey will provide coverage over the southern part of the Scott and northern part of the Cooper 1:250 000 sheets.

The located and gridded data from both areas will be available for public access, together with magnetic and radiometric images, in late 2002 or early 2003.

Airborne geophysical survey register and data repository

During 2001–02, 61 new airborne survey datasets, containing approximately 256 000 line km of magnetic, radiometric, digital elevation, and electromagnetic data, were received for inclusion in the MPR Airborne Geophysical Information eXchange (MAGIX) data repository. About 2.7 million line km of private data from almost 500 surveys are now held in the repository.

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

Regional gravity surveys

GSWA carried out the Morton Craig semi-detailed gravity survey in the southwestern Officer Basin. A total of 452 stations were recorded on a regular 1 × 2 km grid.

Seven regional gravity traverses were carried out across the major greenstone belts in the eastern and western Pilbara. A total of 789 stations with variable 250–1000 m spacing were collected to assist in evaluation of the 3D geometry of the greenstones.

2001–02 publications and products

- Record 2001/19: 'Gravity data — Byro 1:250 000 sheet, Western Australia';
- South Dongara Bouguer gravity image (1:100 000);
- South Dongara residual of the Bouguer gravity image (1:100 000);
- Morton Craig gravity dataset;
- Pilbara gravity traverses dataset.

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Logistics support and core libraries

Objectives:

- *To manage core library facilities in both Perth and Kalgoorlie to service the needs of industry and GSWA*
- *To manage field support services, including transport and other equipment, and field assistants, and provide a communications link 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

The Kalgoorlie J. H. (Joe) Lord Core Library and Operational Base was completed in June 2000 and is now fully operational, providing a mineral-core archive and research centre for the Eastern Goldfields. The 2800-pallet facility currently holds more than 900 pallets of mineral core.

Construction of a new, 8600-pallet capacity, core storage facility building adjacent to the GSWA operations base at Carlisle commenced in May 2002 and is scheduled for completion in mid-November 2002. The new Perth Core Library will hold mineral and petroleum core and cuttings, geochemical samples including rock pulps, and GSWA rock collections, and will provide industry with the most advanced system of drillcore storage in Australia.

During the year, 182 visitors to the new Kalgoorlie facility and to the existing Perth facilities at Dianella, and Star Street, Carlisle spent 979 hours viewing core and cuttings, and took 1855 samples for further analysis. More than 400 pallets of mineral exploration core and 28 pallets of petroleum core and cuttings were accessioned into the collection.

Field support

The GSWA specialized 4WD fleet is managed from the division's Carlisle depot. During the year, 175 vehicle dispatches occurred (fully serviced and equipped vehicles leaving the depot for the field), resulting in a total of 3137 vehicle-field days supported by daily radio communication schedules and servicing of ad hoc requests from field parties. A maintenance and preparation schedule was introduced that resulted in a one-day response time after requests for vehicles. Different vehicles are being trialled for their suitability and efficiency.

Base-level field staff requirements have been maintained and provision of additional field assistants by an employment agency continues to allow flexibility in meeting short-term needs.

Continuous improvement of work practices in regard to field safety remains a high priority. Communication procedures have been improved with the introduction of satellite telephones; however, the high-frequency radio communications base at the Carlisle depot continues to be the focus point for monitoring safe operations in the field. A new initiative was the pilot installation of a field-safety computer system ('SafetyNet'), offering the potential to incorporate an automatic vehicle-tracking system, and communicate field movements through a web interface.

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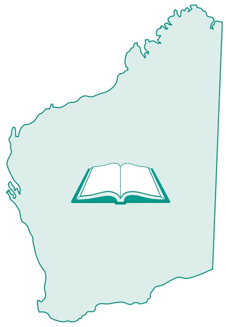
Subprogram 3105
GEOSCIENCE INFORMATION PRODUCTS

Publications and promotion

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*



2001–02 publications and products

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

Geological and geophysical maps

In 2001–02, the group published 28 maps and images at various scales (Appendix, p. 124), including:

- Two 1:50 000 regolith–landform maps
- Fourteen 1:100 000 geological series maps
- Two 1:250 000 geological series maps
- Two regolith geochemistry maps
- Six project maps at various scales
- Two gravity images.

Geoscientific digital data packages

Nineteen geoscientific digital data packages were released in 2001–02 (Appendix, p. 124), including:

- One Eastern Yilgarn Geoscience Database package
- One regolith–landform data package
- One regolith geochemistry data package
- One mineral resources data package
- One annual update for the Pilbara iron ore resources package
- One mineral occurrences and exploration potential data package
- Updates of two mineral occurrences and exploration potential data packages
- One seismic reflection data package for the northern Yilgarn seismic survey
- Five well completion report data packages
- One acreage release data package.

Geoscientific reports

During 2001–02, a total of 49 manuscripts were edited, illustrated, and published (Appendix, p. 124), including:

- Eight Explanatory Notes for series maps
- Thirty-one Records and Reports, including ten volumes for the 4th International Archaean Symposium
- One Mineral Resources Bulletin
- Nine miscellaneous publications, including the GSWA Annual Review 2000–01.

Other activities

Promotional activities

During the year, advertisements and short articles publicizing the release of GSWA published products were placed in a number of newspapers, industry magazines, and journals.

Media releases describing GSWA products, services, and new publications were prepared and issued during the year, in cooperation with the Corporate Communications Branch of MPR.

Publication of Fieldnotes (the GSWA quarterly newsletter first published in January 1996) continued during 2001–02 and provided a medium for informing our customers about our activities, and promoting newly released maps, publications, and datasets.

Displays of ongoing and completed geoscientific work by GSWA were presented at the following industry events:

- Diggers and Dealers Conference (Kalgoorlie, July)
- New Generation Gold 2001 (Perth, November)
- ASEG 2001 (Brisbane, August)
- 4th International Archaean Symposium (Perth, September)
- Good Oil Conference (Fremantle, September)
- Mining 2001 Resources Convention (Melbourne, November)
- Prospectors and Developers Association of Canada Conference (Toronto, March)
- MINEX 2001 (Perth, March)
- North American Prospectors Expo (Houston, January)
- Australian Petroleum Production and Exploration Association (APPEA) Conference (Adelaide, April)
- Applied Structural Geology Conference (Kalgoorlie, September)
- American Association of Petroleum Geologists Conference 2002 (Houston, March)
- Australian Platinum Conference (Perth, June).

In addition to the above, MPR/GSWA held three events to promote communication with our customers. These were:

- Petroleum Open Day — recent work by the Department and issues of interest to petroleum explorers (Perth, October)
- Open day and display of recent work in the Eastern Goldfields (Kalgoorlie, October, in association with Geoscience Australia)
- GSWA 2002 — GSWA Online (Perth, April).

Of these events, GSWA 2001 was a highlight, with the promotion of GSWA's online databases and other services, including the GeoVIEW.WA web mapping application.

The promotion of Western Australia's prospectivity overseas continued in 2001–02. GSWA was present with display material at PDAC 2002 in Toronto, the North American Prospectors Expo in Houston, and at the AAPG conference also in Houston.

GeoVIEW.WA

GeoVIEW.WA harnesses leading-edge geographic-information system and web-based technologies to create an easy-to-use interface that allows customers, including exploration geologists, prospectors, and the community, to create a customized view of geoscientific data on their PC.

As part of ongoing enhancements to GeoVIEW.WA, GSWA developed a mapping-tool application that enables its customers to make better use of the information available to them. Through the mapping tool, customers will be able to produce a hardcopy of the map they have prepared within the GeoVIEW.WA web interface. The mapping tool allows users to print a 'quality' map version of the screen view of the data from the web-based interface incorporating GSWA's geoscientific map standards.

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Subprogram 3106 GEOSCIENTIFIC AND EXPLORATION INFORMATION

Statutory exploration information group — Minerals section

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

Highlights and activities 2001–02

During 2001–02, images of the PDF files of mineral exploration reports were made available for viewing on the web. The files are attached to individual records of reports on the WAMEX database and can be viewed using Citrix software. All reports released to open file as scanned reports are available for viewing in this manner. In addition, the Department has commenced a program of scanning reports previously released to open file in microfiche format. Over 5000 reports are now available online.

Work commenced on a review of the WAMEX database, with documentation of user needs and functionality requirements.

Mineral exploration reports

During the year, 2148 mineral exploration reports (3288 volumes) were received, representing industry activity on 8964 tenements. The total number of volumes held is now 76 681. Gold is still the most commonly sought commodity, with over 75% of reports submitted relating to exploration programs for gold. Submission of data in digital form continues to increase, with about 70% of all reports submitted during the year containing some digital data.

Reporting standards

This year has been the sixth full year of required compliance with the 'Guidelines for mineral exploration reports on mining tenements' and the second year in which companies were permitted to submit data in digital format according to the Department's requirements. The quality-control checking by Departmental staff found that the content of the hard-copy reporting has been improving, with only 18% of reports not complying with the 'Guidelines for mineral exploration reports on mining tenements'. The submission of digital data is voluntary; however about 70% of reports contain some digital data and about 40% of all reports submitted are totally digital.

The 'Requirements for the submission of mineral exploration data in digital format', that 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.

WAMEX database development

During the development of processes and data management systems for the core library, it was recognized that a review of the management and delivery of mineral exploration data was needed. This review has commenced with identification and documentation of user needs and system functionality.

Data release

During the year, 1306 reports were released to open file, bringing the total number of open-file mineral reports to 30 789.

Future work

- Review of the current WAMEX database and core library database, followed by the design and development of a new system
- Continuing implementation and refinement of the 'Requirements for the submission of mineral exploration data in digital format'
- Continuation of scanning to PDF files (rather than microfiching) of

mineral exploration reports prior to release to open file, and scanning of reports previously released to open file in microfiche format

- Provision of both scanned and generated files of mineral exploration data via the web-based WAMEX interface
- Progressive capture of metadata for digital files submitted prior to the release of the 'Requirements for the submission of mineral exploration data in digital format'
- Progressive acquisition in digital format of legacy tabular data previously submitted in hardcopy reports.

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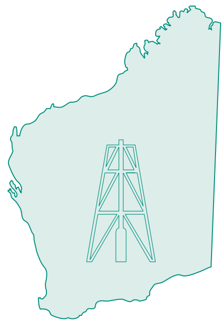
Statutory exploration information group — Petroleum section



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 2001–02

The program of scanning well completion reports from hardcopy to PDF and TIFF file formats continued, focusing on the Officer, Perth, eastern Canning, Browse, and western Canning Basins and loading them onto the WAPIMS system for online web viewing.

As part of the WAPIMS database program, well log curves for 150 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 Officer Basin and northern Perth Basin from nine track reels to 3590 cartridges (approximately 2200 tapes) was undertaken to reduce the number of 'old' tapes in the archive and move these valuable data to new and more reliable media.

The Petroleum data management project (WAPIMS) was successfully undertaken and became public in February 2002. Data is constantly being added to this system and both the Geological Survey and Petroleum Division now access and update the same data.

Due to industry and Government concerns on the reliability of submitted data, both well logs and post-stack seismic data received from industry are now quality checked by two specialist companies for completeness and format prior to acceptance by MPR.

A review of processes and performance measures within the section showed the extent of backlogs in the monitoring, accessioning, and capture areas. Of particular concern is the backlog in data not submitted by industry, an issue that is currently being addressed by the section.

WAPIMS database development

Following the successful completion of a pilot project for a greatly enhanced Western Australian petroleum information management system (WAPIMS), the Department decided to implement the Finder data management system in late 2000–01. This implementation process commenced during the year, with all petroleum exploration and production data from both GSWA and the Petroleum Division loaded into the system. The new database became public in February 2002 and is accessible through the MPR website in both text- and map-based formats. Electronic document management and the ability for the public to view these documents via the website were also implemented. During the development of the petroleum data management system, a database for the management of the core library was developed for petroleum and mineral core; this is in its early stages of testing.

Data release

During 2001–02, 145 edited datasets, 104 unedited datasets, 115 sets of well logs, and 29 sets of seismic sections were released. Industry requests were at a level similar to 2000–01, with 67 requests for loans of seismic and well, digital field, and processed data resulting in a total of 2550 tapes being supplied. In addition, 57 requests for sample drillcore or cuttings and 2 requests for palaeontological data were processed.

Future work

- Continuation of scanning well completion reports to PDF files for release via the web
- A project to transcribe old seismic field data to new media has commenced to ensure that the data are preserved and to reduce the cost of storage of the old, bulky media.

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Subprogram 3107
INVENTORY OF ABANDONED MINE SITES

Inventory of abandoned mine sites

Objective: *To locate 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 the necessary remedial action and rehabilitation of high-risk abandoned mine sites.*

Highlights and activities 2001–02

The inventory project, which commenced in 1999–2000, has the objective of locating mining-related features within historic mine sites in the State and documenting factors relevant to their safety, environmental hazard, and heritage value. This will provide a sound basis for providing advice on remedial action, rehabilitation, or conservation of historic mine sites.

The field database on a mobile computer is linked to satellite navigation equipment capable of locating mine sites to around 5 m accuracy. The rate of collection of data continues to be high, with 24 816 mine-site features added to the inventory during 2001–02. The three-year total of points in the inventory stood at 57 581 at 30 June 2002. The total also includes some potential hazards completely or partially rehabilitated by mining tenement holders, with location data supplied to the Department by companies.

Priority for field inspection is being given to those sites in close proximity to towns and major roads; that is, within 10 km of towns and within 1 km of main roads. About 45% of all abandoned mine sites are in this high-priority category. At 30 June 2002, approximately 55% of known high-priority production sites had been inspected during the first three years of the program.

Fieldwork during 2001–02 was conducted at high-priority sites around Kalgoorlie, including surveying all sites for the four 1:50 000 map sheets areas centered on Kalgoorlie; that is, KALGOORLIE (3162-II), BOULDER (3135-I), GOLDEN RIDGE (3235-IV), and KANOWNA (3236-III). Fieldwork will continue in the Kalgoorlie and Coolgardie areas into 2002–03.

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Appendices

List of acronyms and abbreviations 123

Planned achievements and publications released 124

External papers published by GSWA staff in 2001–02 129

Geological Survey Liaison Committee 132

List of acronyms and abbreviations

AAPG	American Association of Petroleum Geologists
ABS	Australian Bureau of Statistics
AESIS	Australian Earth Science Information System
AGSEAN	Australian Geologist Skills and Employment Advancement Network
AGSO	Geoscience Australia, formerly Australian Geological Survey Organisation
AMEC	Association of Mining and Exploration Companies (Inc.)
AMIRA	Australian Mineral Industries Research Association Limited
ANZMEC	Australian and New Zealand Minerals and Energy Council
ANU	Australian National University
APPEA	Australian Petroleum Production and Exploration Association Limited
ASEG	Australian Association of Exploration Geophysicists
ASX	Australian Stock Exchange
AusIMM	Australasian Institute of Mining and Metallurgy
AVIMS	ArcView Internet Map Server
BMR	Bureau of Mineral Resources
BRS	Bureau of Resource Sciences
CSIRO	Commonwealth Scientific Industrial Research Organisation
DOLA	Department of Land Administration
EXACT	Western Australian mineral exploration activities database
GA	Geoscience Australia, formerly Australian Geological Survey Organisation
GeoVIEW.WA†	GSWA's integrated geoscience information system
GIS	Geographic Information System
GPS	Global Positioning System
GSLC	Geological Survey Liaison Committee
GSWA	Geological Survey of Western Australia
JORC	Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists, and Minerals Council of Australia
Landsat TM	Landsat Thematic Mapper
LME	London Metals Exchange
MAGIX	Mineral Airborne Geophysics Information eXchange
MERIWA	Minerals and Energy Research Institute of Western Australia
MINEDEX	MPR’s mines and mineral deposits information database
MINESTAT	Mineral production module of MINEDEX
MPR	Department of Mineral and Petroleum Resources
NASA	National Aeronautics and Space Administration
NGMA	National Geoscience Mapping Accord
OLIB	Oracle Libraries database
PALAEOBASE	GSWA’s palaeontological database
PDAC	Prospectors and Developers Association of Canada
PESA	Petroleum Exploration Society of Australia
REGOCHEM	GSWA’s regolith and geochemistry database
SHRIMP	Sensitive high-resolution ion microprobe
TENGRAPH*	MPR’s electronic tenement-graphics system
UWA	University of Western Australia
VCEMP	Virtual Centre for Economic Micropalaeontology and Palynology
WACHEM	Western Australian inorganic geochemistry database
WACHRON	Western Australian geochronology database
WAMEX*	Western Australian mineral exploration database
WAMIN	Western Australian mineral occurrence database
WAMPRI	Western Australian Minerals and Petroleum Research Institute
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: * WAMEX, WAPEX, and TENGRAPH are registered Trade Marks for MPR; † pending

Planned achievements and publications released

Major planned achievements for 2001–02

The GSWA program for 2001–02 was an ambitious project-based program of work designed to promote Western Australia's exploration potential. The programmed planned achievements for 2001–02 were:

- release of 33 geoscientific maps at various scales;
- publication of 48 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of 15 digital geoscience datasets;
- continued and enhanced provision of geoscientific data and exploration information to industry and the public through our library services and the mineral (WAMEX) and petroleum (WAPIMS) exploration databases.

During 2001–02, changing priorities resulted in the completion of a slightly different mix of published output for the year than was originally planned. Twenty-eight maps and 49 books were published, and 19 digital datasets were released, which again reflected the changing technology and a greater volume of geoscience data being provided in digital form. In particular, provision of data in digital form, either on CD or via the internet, grew during the year, with the release of several GSWA publications as digital (PDF) files. In overall terms, GSWA publication milestones for 2001–02 were met. The total combined number of published products released was 99 and exceeded our stated target of 96.

Provision of statutory information services to industry via the WAMEX and WAPIMS database systems continued through the year. Work progressed on enhancements to both systems, which now allow the delivery of digital reports and data to customers via the worldwide web.

Products released in 2001–02 allowed the Geological Survey again (for the seventh successive year) to exceed its target productivity improvement of 5%. A real productivity gain of 5.12% was achieved in 2001–02.

Maps, books, and datasets released in 2001–02

Geological series maps

1:50 000 Regolith–landform resources maps

KARRIDALE–TOOKER by J. R. Marnham and G. J. Hall
LEEUWIN by J. R. Marnham and G. J. Hall

1:100 000 Geological Series

COOYA POOYA by A. H. Hickman
EVERETT CREEK by A. Riganti
GLENAYLE by F. Pirajno and R. M. Hocking
HOOLEY by R. H. Smithies
MARMION by S. F. Chen and J. E. Greenfield

MUDAN by F. Pirajno and R. M. Hocking
RICHARDSON by S. F. Chen and J. E. Greenfield
TAMBOURAH by M. J. Van Kranendonk and M. Pawley
WHITE SPRINGS by R. H. Smithies
WODGINA by R. S. Blewett, D. C. Champion, R. H. Smithies, M. J. Van Kranendonk, T. R. Farrell, and D. Thost
WONGAWOL by J. A. Jones

1:100 000 Geological Series preliminary release

CAPRICORN by A. M. Thorne, D. McB. Martin, and I. A. Copp
EDMUND by D. McB. Martin, A. M. Thorne, and S. A. Occhipinti
PARDOO by R. H. Smithies

1:250 000 Geological Series

YARRIE by I. R. Williams and A. F. Trendall
ROBINSON RANGE by S. A. Occhipinti, S. Sheppard, I. M. Tyler, C. P. Swager, and J. S. Myers

Regolith geochemistry maps

Regolith materials, Nicholls, W.A., by A. J. Sanders
Simplified geology and sample locations, Nicholls, W.A., by A. J. Sanders

1:500 000 maps

Mineralization and geology of the east Pilbara, by K. M. Ferguson, A. H. Hickman, E. P. W. Peiris, and F. Vanderhor

Geology and mineral resources of the Southern Cross – Esperance region, by F. Vanderhor (Record 2002/3 , Plate 1)

Iron ore deposits of the Pilbara region

Geological maps at other scales

Industrial mineral occurrences, by J. M. Fetherston (1:5 000 000)

Interpreted geology of the Shoemaker impact structure, by F. Pirajno (1:100 000)

Gibson area geophysical montage, western Officer Basin, Western Australia, by H. T. Moors and S. N. Apak

Geophysical images

South Dongara Bouguer gravity image (1:100 000)
South Dongara residual of the Bouguer gravity image (1:100 000)

Mineral Resources Bulletins

20 **Bentonite, attapulgite, and common clays in Western Australia,** by P. B. Abeysinghe

Reports

80 **Basin development and petroleum exploration potential of the Gibson area, western Officer Basin, Western Australia,** by H. T. Moors and S. N. Apak

81 **Mineral occurrences and exploration potential of the east Pilbara,** by K. M. Ferguson and I. Ruddock

82 **Geology of the Shoemaker impact structure, Western Australia,** by F. Pirajno, A. Y. Glikson, D. Phillips, and T. Uysal

Records

2001/1 **Geological Survey work program for 2001–02 and beyond**

2001/2 **Compilation of geochronology data, 2000**, by D. R. Nelson

2001/6 **Woodleigh 1, 2, and 2A well completion report, Woodleigh impact structure, Southern Carnarvon Basin, Western Australia**, by A. J. Mory, F. Pirajno, A. Y. Glikson, and J. Coker

2001/8 **Archaean and Palaeoproterozoic geology of the Narryer Terrane (Yilgarn Craton) and the southern Gascoyne Complex (Capricorn Orogen), Western Australia — a field guide**, by S. A. Occhipinti, S. Sheppard, J. S. Myers, I. M. Tyler, and D. R. Nelson

2001/9 **Archaean geology of the East Pilbara Granite–Greenstone Terrane, Western Australia — a field guide**, by M. J. Van Kranendonk, A. H. Hickman, I. R. Williams, and W. Nijman

2001/10 **Komatiites of the Norseman–Wiluna Greenstone Belt, Western Australia — a field guide**, by R. E. T Hill, S. J. Barnes, and S. E. Dowling

2001/11 **Metallogenesis of the North Pilbara granite–greenstones, Western Australia — a field guide**, by D. L. Huston, R. S. Blewett, M. Sweetapple, C. Brauhart, H. Cornelius, and P. L. F. Collins

2001/12 **Jimperding and Chittering metamorphic belts, Western Australia — a field guide**, by S. A. Wilde

2001/13 **Archaean volcanic and sedimentary environments of the Eastern Goldfields Province, Western Australia — a field guide**, by S. J. A. Brown, B. Krapez, S. W. Beresford, K. F. Cassidy, D. C. Champion, M. E. Barley, and R. A. F. Cas

2001/14 **Archaean granite–greenstones of the central Yilgarn Craton, Western Australia — a field guide**, by S. F. Chen and S. Wyche

2001/15 **Geology of the western Yigarn Craton and Leeuwin Complex, Western Australia — a field guide**, by S. A. Wilde and D. R. Nelson

2001/16 **Evolution of the West Pilbara Granite–Greenstone Terrane and Mallina Basin, Western Australia — a field guide**, by A. H. Hickman, R. H. Smithies, G. Pike, T. R. Farrell, and K. A. Beintema

2001/17 **World-class gold camps and deposits in the eastern Yilgarn Craton, Western Australia, with special emphasis on the Eastern Goldfields Province**, by S. G. Hagemann, P. Neumayr, and W. Witt

2001/18 **Vines 1 well completion report, Waigen area, Officer Basin, Western Australia**, by S. N. Apak, H. T. Moors, and M. K. Stevens

2001/19 **Gravity data — Byro 1:250 000 sheet, Western Australia**, by K. A. Blundell, S. Sheppard, and S. I. Shevchenko

2002/2 **Compilation of geochronology data, 2001**, by D. R. Nelson

2002/3 **Geology and mineral resources of the Southern Cross – Esperance Region of Western Australia**, by P. B. Abeysinghe, D. J. Flint, S. A. Luckett, S. A. McGuinness, J. Pagel, D. B. Townsend, and F. Vanderhor

2002/4 **Age and palaeomagnetism of dolerite sills intruded into the Bangemall Supergroup on the Edmund 1:250 000 map sheet, Western Australia**, by M. T. D. Wingate

2002/5 **GSWA 2002 extended abstracts: GSWA online**, by Geological Survey of Western Australia

2002/6 **GSWA Yinni 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia**, by A. J. Mory and M. Dixon

2002/7 **GSWA Boologooro 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia**, by A. J. Mory and M. Dixon

2002/8 **GSWA Edaggee 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia**, by A. J. Mory and M. Dixon

2002/10 **Regolith–landform resources of the Karridale–Tooker and Leeuwin 1:50 000 sheets**, by J. Marnham and G. Hall

2002/11 **Visiting geological sites in Western Australia — a guide to planning, collecting, and procedures**, by K. Grey

2002/12 **Industrial minerals in Western Australia: the situation in 2002**, by J. M. Fetherston

2002/13 **Compilation of whole-rock geochemical data for the Gordon area, Eastern Goldfields, Western Australia**, by F. I. Roberts and W. K. Witt

2002/14 **Selection criteria for mineral drillcore in the Western Australian core libraries**, by F. I. Roberts

2002/15 **Revised lithostratigraphy of the Mesoproterozoic Bangemall Supergroup on the Edmund and Turee Creek 1:250 000 sheets, Western Australia**, by D. McB. Martin and A. M. Thorne

Explanatory Notes

1:100 000 Geological Series

Geology of the Jackson 1:100 000 sheet, by A. Riganti and S. F. Chen

Geology of the Merewether 1:100 000 sheet, by D. D. Ferdinando

Geology of the Methwin 1:100 000 sheet, by R. M. Hocking and J. A. Jones

Geology of the Mount Belches 1:100 000 sheet, by M. G. M. Painter and P. B. Groenewald

Geology of the Roebourne 1:100 000 sheet, by A. H. Hickman

Geology of the Wallaringa 1:100 000 sheet, by R. H. Smithies, D. C. Champion, and R. S. Blewett

1:250 000 Geological Series

Roebourne 1:250 000 sheet, Western Australia, by A. H. Hickman and R. H. Smithies

Regolith Geochemistry Series

Geochemical mapping of the Nicholls 1:100 000 sheet, by A. J. Sanders

Miscellaneous

GSWA Annual Review 2000–01

Overview of the mineral sector in Western Australia in 2000–01, by D. J. Flint

Summary of petroleum prospectivity, onshore Western Australia 2001: Canning, Officer, Perth, Southern Carnarvon, and Bonaparte Basins

Fieldnotes v.20

Fieldnotes v.21

Fieldnotes v.22

Fieldnotes v.23

Supplement to Catalogue of GSWA maps and publications (September 2001)

Supplement to Catalogue of GSWA maps and publications (March 2002)

Digital products

East Canning Basin Specific Area Gazettal data package

East Yilgarn Geoscience Database: Leonora–Laverton region, Eastern Goldfields Granite–Greenstone Terrane (1:100 000)

Woodleigh 1, 2, and 2A well completion report, Woodleigh impact structure, Southern Carnarvon Basin, Western Australia (Record 2001/6)

Vines 1 well completion report, Waigen area, Officer Basin, Western Australia (Record 2001/18)

Compilation of geochronology data, 2001 (Record 2002/2)

Geology and mineralization of the Southern Cross – Esperance Region (Record 2002/3)

GSWA Yinni 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia (Record 2002/6)

GSWA Boologooro 1 well completion report (basic data), Gascoyne Platform, Western Australia (Record 2002/7)

GSWA Edaggee 1 well completion report (basic data), Gascoyne Platform, Southern Carnarvon Basin, Western Australia (Record 2002/8)

Compilation of whole-rock geochemical data for the Gordon area, Eastern Goldfields (Record 2002/13)

Iron ore deposits of the Pilbara region — 1:500 000 digital data package

Mineral occurrences and exploration potential of southwest Western Australia — 2001 update

Mineral occurrences and exploration potential of the Bangemall Basin — 2002 update

Mineral occurrences and exploration potential of the East Pilbara (Report 81)

Mines and mineral deposits of Western Australia: digital extract from MINEDEX, July 2001

Geochemical mapping of the Nicholls 1:100 000 sheet

Publications, maps, and datasets for explorers — mini CD

Regolith–landform resources of the Karridale–Tooker and Leeuwin 1:50 000 sheets (Record 2002/10)

GA–GSWA–pmd*CRC seismic reflection data, northern Yilgarn seismic survey

Major planned achievements for 2002–03

The GSWA will continue to pursue a project-based program of work and maintain a vigorous level of output to match funding received. Planned achievements for 2002–03 include:

- release of 30 geological maps at various scales;
- publication of 50 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of 19 digital data packages.

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.

External papers published by GSWA staff in 2001–02

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GREY, K., WALTER, M. R., and CALVER, C. R., 2002, Plankton and isotope changes at the late Neoproterozoic Acraman Impact ejecta layer: impacts and the origin, evolution, and extinction of life: Rubey Colloqiuim, University of California, Los Angeles, USA, February 2002, p. 23–24.

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Note: GSWA authors are in italics

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The Geological Survey Liaison Committee (GSLC) meets twice a year to review progress and advise on future work programs for the Geological Survey. The three Technical Subcommittees provide comment and advice in each of the special areas for consideration by the GSLC.

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