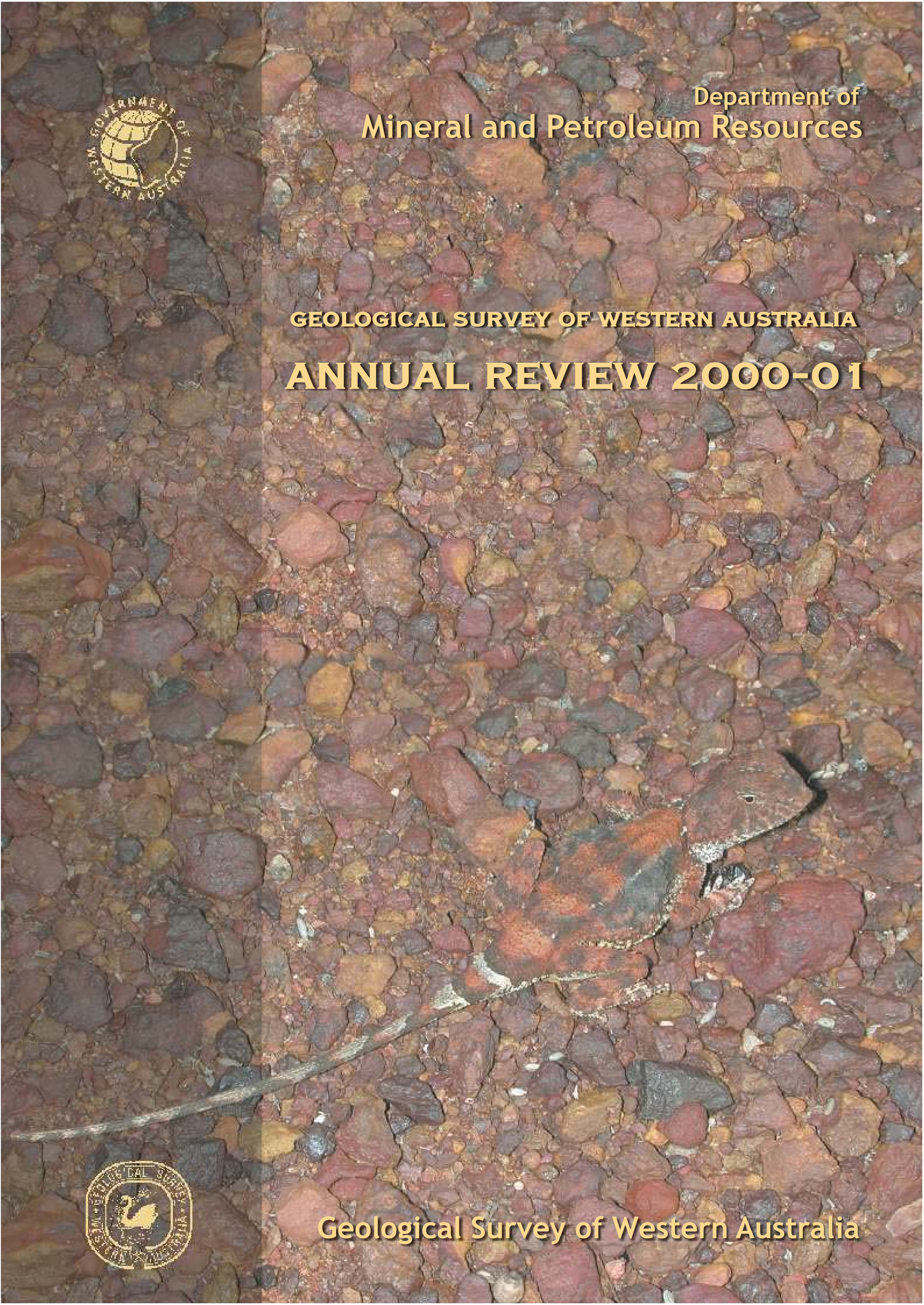

Department of
Mineral and Petroleum Resources

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 2000-01

Geological Survey of Western Australia

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Perth 2002

MINISTER FOR STATE DEVELOPMENT
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Cover:
An Earless Dragon (*Tympanocryptis cephalus*) lizard on the ferruginized rock-covered surface of a ridge south of Kalgoorlie (the lizard is 10 cm long)

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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 minerals exploration industry internationally experienced another flat year. Fortunately, Western Australia has continued to attract about 10% of world exploration expenditure, and is the leading state in Australia in attracting what we trust will be increasing levels of exploration throughout 2001–02. A more buoyant situation has developed in the onshore petroleum exploration sector, which is currently experiencing a boom with a large commitment to exploration drilling. Hot spots include the northern Perth Basin and the Carnarvon Basin.

The resources sector continues as the major contributor to the Western Australian economy. In 2000–01, production value reached $27 600 million and contributed over $1100 million in royalties to the Western Australia Government. The impact of this sector, therefore, is critical to all Western Australians. The immediate impact of exploration is felt in rural areas of the State where most of the exploration is carried out. Perth and regional centres such as Kalgoorlie, where many industry service groups are based, are also noticing the extended downturn in exploration.

It is extremely important that the wider community recognizes and appreciates the benefits that flow from the resources sector across the whole State. We must ensure that all community groups are properly informed about the costs and benefits of new resource projects, and that their input can be considered at an early planning stage. In this way, local communities and Western Australians in general can continue to enjoy the high quality of life the industry has been bringing to our beautiful State over the past decades. The capacity of the Government to provide high standards of health care, law and order, and quality education, and the capacity to ensure our environmental and cultural heritages are preserved and developed, depends on a sustainable resource industry. Although we continue to consume, we have also demonstrated a capacity to develop resources without destroying the environmental and cultural values of a region. In fact, Western Australia has an opportunity to provide an increasingly discerning world with cleaner and more sustainable supplies of minerals and gas. Western Australia must also use all its resources, including highly trained and skilled people, to further value-add to these raw materials.

The February election and the change of Government has resulted in a considerable number of issues that had to be addressed while maintaining our level of production of quality geoscience-information products. The amalgamation of the Department of Minerals and Energy (DME) and the Department of Resources Development (DRD) into the Department of Mineral and Petroleum Resources (MPR), which came into effect at the end of June, offers substantial opportunities for the Geological Survey of Western Australia (GSWA) to work more effectively. In particular, we can better monitor international markets and take advantage of a stronger skills base to promote Western Australia within the international capital-investment community.

Although there has been a change in Government, Western Australia is fortunate that both major parties have a policy of supporting the Geological Survey. This bipartisan support is essential for such a long-term and critical industry to Western Australia's economic well-being. There are many complex issues in relation to the resources sector that must be addressed. The new Government has shown a great capacity to understand the issues and to react positively. In particular, the Minister has honoured a pre-election commitment to provide an additional $20 million over five years, thus allowing us to continue our work with a similar level of funding to that of previous years.

The Fardon Report, and its recommendations for an appropriate level of funding for the Geological Survey, was caught up in the election campaign and has still not been released to the public. In view of the Minister's announcement of the $20 million additional funding for the Geological Survey, it was decided to wait until after the State budget was brought down before giving the Fardon Report full consideration at Cabinet level.

Highlights

The opening of the J. H. (Joe) Lord Core Library in Kalgoorlie–Boulder in July 2000 was a major achievement for the year. This was the culmination of an industry initiative and on-going support that dates back to the early 1980s, and the facility has been attracting considerable industry interest. Some very significant cores have been acquired — including core from the nickel-ore discovery hole at Kambalda. These, and other archived cores, are an extremely valuable resource for study and research, and for the development of today's exploration programs.

The core library was named as a tribute to the late Joe Lord, who was Director of the Geological Survey of Western Australia between 1961 and 1980. A major achievement of the Survey under Joe Lord's directorship was the completion of a State-wide regional geological mapping program that resulted in total coverage of the State at 1:250 000 scale.

Another very significant achievement during 2000–01 was the completion and release of a digital 1:500 000-scale solid geology dataset for Western Australia via the Department's website. This is very much a dynamic dataset and will require regular updates as new geological mapping progresses. It will also form the basis for a State-wide system of rock codes and is to be complemented by a 1:500 000-scale regolith map of the State.

It is well known by geologists working in Western Australia that our landscape is dominated by regolith. It is therefore appropriate for the Geological Survey to release a new classification scheme that can be applied at a range of scales across the whole of the State. The scheme, which was released in March 2001, is largely descriptive — based on landform position and the principal regolith-forming processes, qualified by the composition of the regolith.

During 2000–01, the Geological Survey acquired and released seventy-eight 1:25 000-scale geological map sheets from the Murchison that had been compiled by Dr Jack Hallberg over a five-year period in the early 1990s. This map series will provide the basis for a more systematic mapping project in future years. Accompanying the maps are six reports that include detailed petrographic descriptions and whole-rock chemical analyses. Thin sections and air photographs used in Dr Hallberg's work can be accessed through the Department's library.

The launch in October 2000 of the Cowaramup–Mentelle 1:50 000-scale map and digital dataset in the Margaret River district illustrates the great diversity of uses of outputs from the Urban and development areas geological mapping program. People representing a wide range of interests were at the launch. They included people with interests in building and construction materials, planners for local infrastructure and risk assessment, and the agricultural sector.

RoxMAP.WA is a user-friendly software application developed in-house during the year by staff of the Geological Survey to view and generate maps-on-demand for the seamless 1:100 000 geological data for the Eastern Goldfields. RoxMAP.WA was entered in the Year 2000 Premier's Award and received a High Commendation (second place) in the Innovation category.

A new and important initiative in 2000–01 was the release of GeoVIEW.WA, an interactive geoscience mapping facility on our website. Unique maps combining a wide range of Western Australian geoscience data can be generated using the GeoVIEW.WA browser-based interface. Attribute data are readily available for the various datasets that include: State-wide 1:2 500 000-scale geology, tectonic units, and basin subdivisions; selected 1:100 000- and 1:250 000-scale geology; mineral resource data from MINEDEX; geochronological data; petroleum exploration wells; indexes to aeromagnetic data and petroleum-exploration seismic data; as well as regularly updated mining tenement information.

GSWA was again successful in meeting its production targets for 2000–01, publishing 33 geological maps and geophysical images at a range of scales, 38 reports, and 18 digital datasets. It can be seen from the Program review published in this volume that these products provide a wide range of material in both brownfields and greenfields areas of Western Australia. Of particular interest was the release of the Fortescue Bulletin, six years after the last-published Geological Survey Bulletin on the 'Hydrogeology and groundwater resources of the Perth Region'.

The Petroleum open day, held jointly with the Petroleum Division in October 2000, and the GSWA 2001 open day in March 2001 were again important events in our annual calendar, and attracted a large number of customers from the resources sector. The open day in March was very important as it provided a great opportunity to demonstrate to the new Minister for State Development the extent of the work being carried out by the Geological Survey to encourage exploration.

At the end of 2000–01, I announced a new approach to the way the Geological Survey will carry out its work programs. We have introduced a 'terrane custodian' approach to manage our future work programs. Terrane custodians have been selected to ensure that all data collected and incorporated in the Geological Survey's corporate database (GeoBASE.WA), and geoscience map products produced from that database, reflect a consistent level of information across the terrane. The custodians, for the Archaean, Proterozoic orogenic belts, and sedimentary basins, will work closely with the Chief Geoscientist to develop State-wide standards for data collection and mapping priorities.

Ongoing work program

There are many important projects that will continue with vigour next year. These include the major regional mapping projects in the Pilbara, Earaheedy, and the Southern Cross region; detailed mapping of urban and development areas in the Kalgoorlie–Boulder district; the completion of the third phase of the Eastern Goldfields seamless 1:100 000 geoscience database; further mineral occurrence mapping in the Pilbara and Kimberley; and the regular program of SHRIMP geochronology to support the mapping program.

The Geological Survey will be supporting the 4th International Archaean Symposium in September 2001 by publishing all field guides and being an active contributor to many of the excursions that showcase the results of our mapping program.

Enhanced web access to geoscience data for Western Australia will be achieved in 2001–02. A wide range of information on mineral deposits and resources held in the MINEDEX database will be made available through web-based application with easy-to-use query tools. In addition, an initiative to develop the capacity to view scanned WAMEX reports via the web will be made available. WAPIMS, featuring a new system to display and drill down to a comprehensive array of petroleum exploration data (a cooperative project with the Petroleum Division) will be commissioned. In addition, GeoVIEW.WA, the interactive map-making tool, will be developed to offer more choices of data for inclusion in customized maps and a system to deliver maps by email so that a high-quality map can be plotted in the customer's office.

The second phase of the WA Integrated Core Storage Facility, a core library in Perth to complement the Joe Lord Core Library in Kalgoorlie, will be constructed, with completion programmed for late 2002.

A major program to reprocess 2000 km of existing seismic data from the northwestern part of the Officer Basin will be completed as part of an extensive program to attract petroleum exploration into these underexplored parts of Western Australia.

The Geological Survey will continue its cooperative work with AGSO-Geoscience Australia in setting common standards for geoscience databases across Australia. A major joint program of seismic-refraction data collection will be undertaken in the northern Eastern Goldfields through Leonora, Laverton, and eastwards 100 km beyond the Yeo Nature Reserve. The profile will collect data on the granite–greenstone rocks of the Yilgarn Craton, and the Officer Basin sequences that overlie the eastern margin of the craton.

Involvement in two new Cooperative Research Centres, Predictive Mineral Discoveries, and Landscape Environments and Mineral Exploration, will provide an opportunity for the Geological Survey to benefit from extensive research and development in Western Australia, and elsewhere, in future years.

Dr Mike Donaldson has been recruited to the vacant General Manager Mapping position and will take up the role in June 2001. Mike brings a wealth of industry experience to the Geological Survey, thus enabling us to further develop projects and products with a strong customer focus.

Conclusion

The Geological Survey of Western Australia continues to remain focused on its field-based activities, and the acquisition and interpretation of new geoscience data to build on the geological framework of Western Australia. The increasing pressure on funds to do this creates a major challenge, especially as we strive to encourage exploration investment in greenfield areas of the State in particular.

Our close cooperation with AGSO must be developed in terms of data acquisition, processing, and interpretation, where AGSO has specialized skills, but also in the promotion of the prospectivity of Western Australia as part of a coordinated Australian effort to tap into the major investment institutions, particularly in Europe and North America.

The amalgamation to form the new Department of Mineral and Petroleum Resources has improved the experience and skillbase that is now available in-house, and will help us to be more successful in attracting exploration to Western Australia. The Department now addresses the full spectrum of opportunities for the resources sector in Western Australia, from upstream, grass-roots exploration to downstream processing and value adding of our resource base.

Overview of the mineral sector in Western Australia in 2000–01

by D. J. Flint[1]

Mineral exploration trends

Western Australia's prospectivity is highlighted by the continuing high proportion (61%) of Australian mineral exploration expenditure that the State attracts (Fig. 1). However, in line with worldwide trends and Australia as a whole, Western Australia experienced subdued exploration activity during 2000–01. Mineral exploration expenditure (excluding petroleum) in Western Australia, at $438.9 million*, experienced an increase of $23.9 million or 5.8% on the previous year. Exploration activity is now at levels of around 36% lower than the peak of activity in 1996–97 when $691.7 million was spent. After three years of substantial falls, the turnaround and modest increase are heartening and hopefully will be sustained. Mineral exploration expenditure in Western Australia, on a quarterly basis, is hopefully showing signs of forming a base for a more sustained recovery (Fig. 2).

The current level of mineral exploration activity in Australia is well below the record levels of over $1000 million that were achieved in 1996–97 and 1997–98. Australia-wide expenditure figures for 2000–01 showed a modest increase of $45.1 million (6.7%) to $721.4 million. The percentage increase is similar to that experienced in Western Australia, which still continues to attract the greatest portion of all Australian exploration expenditure (60.8% compared to 61.4% previously). This has remained relatively constant at 60–62% over the last five years throughout the large cutbacks that have occurred in exploration expenditure, especially those in the gold sector (Fig. 1).

Western Australia† still attracts the major part of the Australian exploration dollar for iron ore (99.1%), gold (74.5%), diamond (55.7%), base metals including Ni–Co (44.3%), and heavy mineral sands (22.5%). These statistics are encouraging because they apply at a time when companies are being very selective about where they explore, and the statistics also indicate that the perceived prospectivity for these commodities in Western Australia is very high.

The decline in mineral exploration in Australia since 1996–97 was matched by declines worldwide, but with Australia and Western Australia maintaining their share of global exploration at around 17.5 and 10% respectively (based on worldwide surveys by the Metals Economic Group of Canada). The continued decline is attributed to low metal prices in general in recent years, particularly in the case of the gold price, which reached a 20-year low point in $US terms during 1999–2000. In recent years, companies have focused on increasing their return on capital and on reducing costs. Surveys have shown that, on average, mining is often a low-profit activity, and speculative venture capital continues to be directed away from the resources sector, but not to the same extent as during the 'dot.com' boom of 1999–2000. The perception existed during 1999–2000 that mining was 'old economy' and that exploration,

[1] Principal industry and commodity analyst, Investment Attraction Division

* All amounts in $A unless otherwise specified.

† For locations, see 'Western Australia atlas of mineral deposits and petroleum fields 2001' published by Geological Survey of Western Australia.

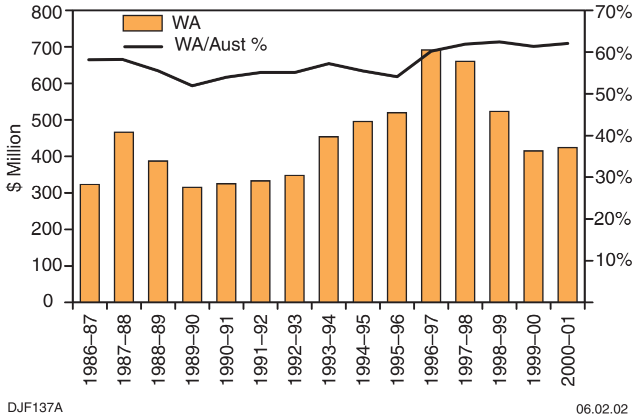


Figure 1. Mineral exploration expenditure in Western Australia, by year (dollars of the day)

particularly greenfields exploration, destroyed shareholder value. This perception continued throughout 2000–01 and resulted in reduced exploration activity, less preparedness to risk funds on greenfields exploration, and a lower percentage of profits directed back as exploration expenditure. In Australia, the effect of Native Title issues on land access continues to compound the problem. These negative factors have presumably, at least to some degree, outweighed the positive impact from a weak Australian dollar.

The pace of consolidation or mergers and acquisitions, at both the international and national level, continued during 2000–01. This trend is regarded as having a negative impact on exploration expenditure in the short term at least. The merged entities often rationalize their exploration portfolio and have an exploration budget that is smaller than the aggregate of the pre-merger entities. Examples of the substantial consolidation within the industry include the takeover by Rio Tinto Ltd of North Limited and Ashton Mining Ltd, BHP merging with Billiton, Barrick Gold Corp merging with Homestake Mining Corporation, Delta Gold Ltd merging with Goldfields Ltd, Sons of Gwalia Ltd purchasing PacMin Mining Corporation Ltd from its Canadian parent Teck Cominco Ltd, Gold Fields Ltd purchasing WMC's St Ives and Agnew gold operations, Croesus Mining NL acquiring Central Norseman Gold Corporation Ltd, and the takeover battle between AngloGold Ltd and Newmont Mining Corp for Normandy Ltd. Harmony Gold Ltd of South Africa took over New Hampton Goldfields Ltd, and also has a takeover of Hill 50 Gold NL in progress.

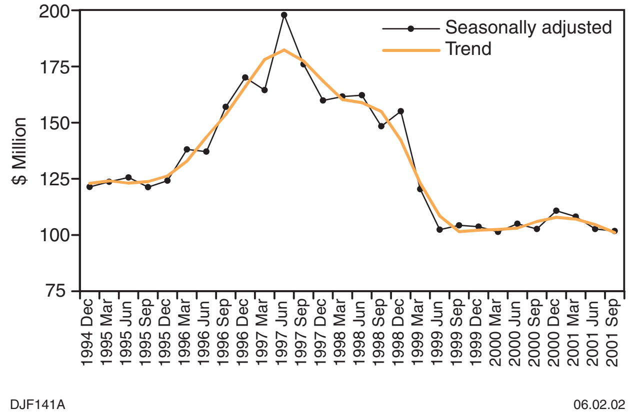


Figure 2. Mineral exploration expenditure in Western Australia, by quarter, on seasonally adjusted and trend terms (dollars of the day)

The trend appears to be for major companies to spend less on early-stage or greenfields exploration, instead relying on junior companies to carry the exploration risk and find the deposits for them. However, research by the Metals Economic Group of Canada indicates that the combined market capitalization of junior mining companies (those with market capitalization of less than $US200 million) throughout the world has dropped by 28% in the three years since mid-1998. The lack of investor sentiment in this sector highlights how difficult it is for junior companies to fund exploration and advance promising projects towards feasibility. It is inevitable that the discovery rate of new deposits will decline and that this will have a negative impact in the longer term on new mine development and production, with the inevitable flow-on effect to exports.

Another trend in recent times is for direct foreign investment to be strategically focused on supporting exploration and development of selected projects. Examples include Kemet Corporation funding exploration and development of the Dalgaranga tantalite project in the Murchison Granite–Greenstone Terrane, Inmet Mining Corporation assisting Pilbara Mines Ltd with exploration of the Teutonic Bore volcanogenic massive-sulfide deposits in the Eastern Goldfields, and Anglo American Australia Pty Ltd supporting Greenstone Resources NL in exploration of the Albany–Fraser Orogen and overlying Mount Barren Beds near Ravensthorpe (i.e. near the polymetallic Trilogy deposit that was discovered in 1997).

Mineral exploration expenditure by commodity and industry highlights

Gold remains the main focus of mineral exploration in Western Australia, accounting for about 66% of all exploration expenditure in Western Australia, followed by base metals and nickel–cobalt (19%), iron ore (5%), diamond (5%), and heavy minerals (1%). All other commodities total only 4% of recorded expenditure, with the main interest during 2000–01 being tantalum and platinum exploration.

Gold

During 2000–01, the gold industry in Western Australia staged a modest comeback after three years of substantial decline (Fig. 3). Gold exploration expenditure in Western Australia rose by 13.3% ($33.7 million) to $286.7 million in 2000–01, but this level is still down 46% ($245 million) from the peak activity of $531.7 million in 1996–97. Gold exploration expenditure is currently at levels last seen during the recession in the early 1990s. The modest recovery in the Western Australian gold sector is ahead of that in other States, reflecting the greater production base and perceived prospectivity of Western Australia. Western Australia now attracts 74.5% (67.5% in 1999–2000) of the Australian expenditure targeting gold, the highest proportion since at least 1984–85.

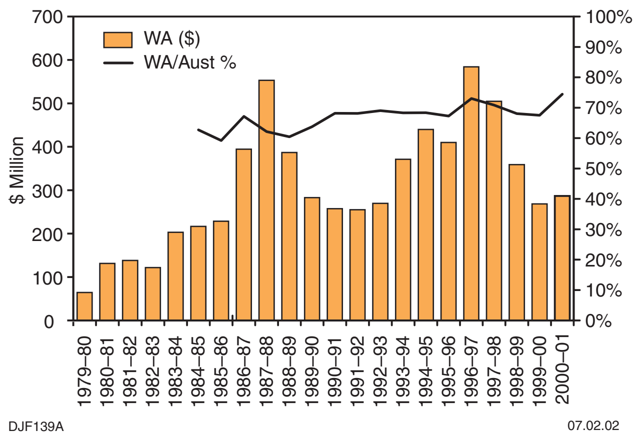


Figure 3. Gold exploration expenditure in Western Australia, by year (2000–01 dollars)

Exploration highlights for the gold sector during 2000–01 include:

- Discovery of high-grade mineralization at the Waugh prospect in the Ashburton Basin near Paraburdoo (Sipa Resources International NL).

- Successful infill drilling by St Barbara Mines Ltd at the nearby Paulsens deposit, hosted by the Hardey Sandstone of the Fortescue Group (Hamersley Basin), has allowed completion of a feasibility study, with mining planned for 2002. The proposed opencut mine, with pre-production capital costs of $43 million, would yield 500 000 tpa of ore over four years, producing gold at the rate of up to 135 000 ounces per year.

- Further high-grade drill intersections obtained from the Raleigh prospect at Kundana near Kalgoorlie (Goldfields Ltd, Tribune Resources NL, and Rand Mining NL), the Temeraire prospect near Kambalda (Western Mining Corporation), and the Frogs Leg deposit near Kalgoorlie (Dioro Exploration NL).

Development highlights for the gold sector during 2000–01 include:

- Commencement of mining by Goldfields Ltd at the spectacularly high-grade Raleigh deposit at Kundana near Kalgoorlie (resource grades of 35–68 g/t).

- AngloGold completed a $110 million upgrade of the Sunrise Dam treatment plant, lifting capacity from 2 Mtpa of ore to 2.5 Mtpa, and annual output to 280 000 – 300 000 ounces of gold.

- Beginning of ore production at the Wallaby mine near Laverton in the Eastern Goldfields (Delta Gold Ltd and Placer Dome Inc).

- Commencement of mining by Croesus Mining NL at the Davyhurst project (Giles opencut mine). The Giles deposit progressed from an exploration prospect to a mine in only nine months. Project resources (all types) total about 6.5 Mt of ore averaging 3.1 g/t Au, for about 650 000 ounces of contained gold. Initial production is at the rate of about 100 000 ounces of gold per annum.

- Commencement of mining by Barra Resources Ltd at the First Hit mine 150 km north-northwest of Kalgoorlie (a bulk sample taken from the first cut through the ore yielded a grade of 27.2 g/t Au).

- Announcement by LionOre Mining International Ltd and Dalrymple Resources NL of the go-ahead for construction of the world-class, low-cost Thunderbox mine near Leinster in the Eastern Goldfields. Openpit reserves are estimated at 10.89 Mt of ore averaging 2.43 g/t Au, with 849 000 ounces of contained gold. Pre-production capital costs are estimated at only $62 million, and production is expected to commence in late 2002, with 220 000 ounces produced in the first year. Average production costs for the initial five-year mine life are forecast at only $304 per ounce, with payback of capital in less than one year after the start of production.

Base metals and nickel–cobalt

Exploration for base metals (including nickel and cobalt) dropped slightly during 2000–01, falling by 6.6% ($5.8 million) to $82.5 million, and this was the third consecutive year of decline. Exploration for base metals (including nickel and cobalt) is now at a level down 29% ($34.1 million) from the peak activity of $117.1 million in 1997–98. Western Australia experienced a substantial growth phase in base metal exploration through the mid- to late 1990s, but this ended with the construction of the major first-phase lateritic nickel operations of Murrin Murrin, Cawse, and Bulong. At the time, Western Australia attracted up to 56.3% of all base-metal exploration expenditure in Australia, but during 2000–01 this declined sharply to only 44.3% of the total. Weak nickel and cobalt prices, ramp-up and commissioning problems at the lateritic nickel-treatment plants, and lack of significant new discoveries have all contributed to the depressed exploration activity for base metals.

Despite the drop in exploration activity, there have still been exploration successes. Highlights include:

- The true greenfields discovery by WMC Ltd in the Musgrave Complex (announced in May 2000) of a large mineralized nickel-sulfide system (with a strike length exceeding 4.5 km).
- Acclaim Exploration NL is drilling at the Wingellina lateritic nickel project in the Musgrave Complex, with the prospect containing inferred resources of 200 Mt at 1.0% Ni and 0.065% Co (based on 1960s data of Inco Ltd).
- Normandy Mining Ltd is continuing with their exploration success at the Golden Grove base metal project in the Murchison Granite–Greenstone Terrane, discovering numerous high-grade Zn–Cu–Pb–Au–Ag lenses, and establishing it as a world-class volcanic-hosted massive sulfide deposit. Development of a decline to the Amity zone commenced in May 2001, and there is consideration of a 5 km-long drive to connect Scuddles with Gossan Hill.
- The brownfields discovery by Jubilee Mines NL at Cosmos Deeps (near Leinster), below the existing Cosmos mine, and the discovery of massive and disseminated nickel sulfides at the nearby Taurus prospect.
- Drilling by Heron Resources Ltd at the Goongarrie lateritic nickel project near Kalgoorlie. Results from the Pamela Jean zone include intersections of 81 m at 1.24% Ni and 0.02% Co, 104 m at 1.33% Ni and 0.09% Co, and 83 m at 1.41% Ni and 0.15% Co.
- Deep drilling by Tectonic Resources NL at the new RAV 8 nickel-sulfide opencut mine near Ravensthorpe has intersected ore-grade zones at depths of 200–250 m below surface that are likely to provide additional ore to the underground mine already under development.
- Infill drilling by Sally Malay Mining Ltd at the Sally Malay deposit, hosted by layered mafic–ultramafic intrusions in the Halls Creek Orogen, has recorded highly encouraging results, including intersections of 9 m at 2.09% Ni and 34 m at 1.87% Ni.

In mine development, highlights for 2000–01 include:

- LionOre Australia (Nickel) Ltd constructed the Emily Ann nickel-sulfide underground mine, west of Norseman, with the first nickel concentrate produced in November 2001. At full production, the mine will have a throughput of 250 000 tpa of ore, producing 6700 t of nickel in concentrates that will be exported to Canada for processing by Inco Ltd.
- Tectonic Resources NL commissioned the RAV 8 nickel-sulfide opencut mine near Ravensthorpe in July 2000, with the ultimate pit depth reached in August 2001. The underground mine is currently under development, and additional deeper ore-grade zones have been recently intersected in exploration drilling. All concentrate is sold under an off-take agreement to WMC Ltd.
- Mincor Resources NL has successfully constructed and brought into production two underground mines near Kambalda. Mincor Resources owns 76% of Miitel (commissioned in March 2001) and Wannaway (commissioned in October 2001). Production from the two mines totals about 13 000 tpa of contained nickel, with cash costs of production less than $US1 per pound. Ore is trucked to WMC's Kambalda nickel operations mill, toll-treated, and sold to WMC Resources Ltd under a long-term off-take agreement.
- WMC is examining the feasibility of a $300 million expansion of its Mount Keith nickel operation, near Leinster, possibly boosting nickel metal output to 70 000 tpa from its current capacity of 45 000 tpa.
- Titan Resources NL continues to enhance the BioHeap process used for the biological recovery of nickel from low-grade base-metal sulfide ores, with a large-scale pilot plant operating adjacent to its Radio Hill underground mine in the Pilbara Craton. This is causing a major reassessment of development options for other low-grade base-metal sulfide ores in Western Australia, with WMC acquiring the large Yakabindie

disseminated nickel-sulfide project north of Leinster from Rio Tinto Ltd during 2001.

Diamond

Diamond exploration in Western Australia fell by about 7% ($1.8 million) to $23.0 million during 2000–01. This is the lowest exploration expenditure for diamond since 1988–89, and continues the steady decline from the peak in recent years of $35.8 million that was spent in 1996–97. The level of diamond exploration is now well below the historical peaks of activity in 1981–82 ($50 million) and 1993–94 ($47 million). The fall is due to the generally difficult conditions in raising equity capital, combined with the paucity of significant discoveries in recent years.

However, the success of Kimberley Diamond Company NL at Ellendale, with mining planned to commence in mid-2002, has renewed interest in diamond exploration in Western Australia.

Iron ore

Iron-ore exploration expenditure in Western Australia has declined sharply during the last two years despite increasing production, with exploration expenditure falling by 41% ($16.4 million) to $23.2 million for 2000–01. This is due to a combination of factors, including uncertainty over the development scenarios of Hope Downs where access to existing railway infrastructure is yet to be obtained, and funding problems being experienced by Kingstream Steel Ltd for the Mid West project.

The iron ore industry followed the pattern of the gold sector, with substantial consolidation during 2000–01. Rio Tinto Ltd acquired North Limited, which owned a majority stake in Robe River, leading to a domination of the Western Australian iron-ore industry by Rio Tinto Ltd and BHP Billiton.

Other highlights include:

- Commencement of construction by the Robe River Iron Associates of the West Angelas project (Marra Mamba ore), with initial production scheduled for mid-2002 and reaching a rate of 15 Mtpa after five years. A mine life of at least twenty years is forecast.
- Portman Ltd, Western Australia's smallest iron ore producer, expanded production from the Koolyanobbing project from 1.7 to 2.3 Mtpa, and has plans to increase annual output to over 8 Mtpa in the next five years.
- Austeel Pty Ltd has signed a memorandum of understanding regarding construction of a steel mill in Newcastle, with ore to be sourced from its Cape Preston project (magnetite ore) southwest of Karratha.
- Launch of a prospectus by Mount Gibson Iron Ltd to progress development of the Mount Gibson deposit, 400 km northeast of Perth. The plan is for early production of direct-shipping grade hematite, with potential increased production through beneficiation of lower grade hematite, and a possible later expansion to produce high-quality magnetite concentrate suitable for the manufacture of iron pellets.

Heavy mineral sands

Exploration expenditure for heavy mineral sands in Western Australia declined by an estimated 17% ($1.2 million) to $5.8 million during 2000–01. The downturn is undoubtedly largely caused by the focus in recent years by explorers on heavy mineral deposits of the Murray Basin in the eastern States of Australia. However, the ongoing success by Magnetic Minerals Ltd in delineating substantial resources at its Dongara project, only 35 km from Eneabba, has rekindled interest in exploring for heavy minerals in Western Australia.

Tantalum

Tantalite was one of the glamour commodities for 2000–01 (along with platinum–palladium), with highlights for the year including:

- Ongoing expansion by Sons of Gwalia Ltd of its existing operations at Greenbushes and Wodgina. Sons of Gwalia currently produces about 25% of the world's tantalite.

- Construction of the Bald Hill tantalite mine by Haddington International Resources Ltd, based on resources of 1.14 Mt of ore averaging 472 ppm Ta_2O_5. Initial production is at the rate of about 145 000 pounds of tantalite in concentrate per annum, but Haddington's output is being lifted to about 300 000 pounds of tantalite in concentrate with the construction (in progress) of the Cattlin Creek mine. The combined output would represent about 5% of world production of tantalite.

- Tantalum Australia Pty Ltd (Australasian Gold Mines NL 50% and Kemet Tantalum Pty Ltd 50%) operated a pilot plant at Dalgaranga and constructed an opencut mine. A total of 19 700 t of old tailings from Dalgaranga and Mount Farmer were treated, yielding 1271.1 kg of contained Ta_2O_5.

- Tantalum Australia Pty Ltd has substantially increased resources at the Mount Deans prospect near Norseman, and a feasibility study is in progress. Resources (of all classifications) within 60 m of the surface total 9.1 Mt averaging 216 g/t Ta_2O_5, with 4.32 million pounds of contained Ta_2O_5.

Platinum–palladium

Western Australia already produces small quantities of platinum and palladium as byproducts from the mining of nickel sulfide deposits. During 2000–01, two platinum–palladium projects advanced closer to development:

- Platinum Australia Ltd advanced the Panton Sill platinum–palladium–gold project in the Halls Creek Orogen, with completion of a prefeasibility study and commencement of a bankable feasibility study. Bulk samples, from both an opencut and from underground exploration development, are being collected for metallurgical testing in South Africa.

- Helix Resources Ltd completed a scoping study of the Munni Munni platinum–palladium–rhodium–gold project in the Pilbara Craton, where inferred resources total 13.5 Mt averaging 3 g/t of Pt + Pa + Rh + Au. Exploration is progressing towards a full feasibility study, which will be funded by Lonmin Pty Ltd Co., the world's third largest producer of platinum.

Mineral tenement activity

In general, the trends in mineral exploration expenditure are also reflected in mineral tenement statistics. Mineral tenements in force and the area held under tenure as at 30 June 2001 show a stabilization at levels comparable to those 12 months ago (Fig. 4). For all tenement types under the Mining Acts of 1904 and 1978, the area under tenure has remained essentially unchanged at 23.8 million hectares. The number of tenements in force as at 30 June 2001 increased by a modest 6% (1046 tenements) to 17 326 after a four-year decline,

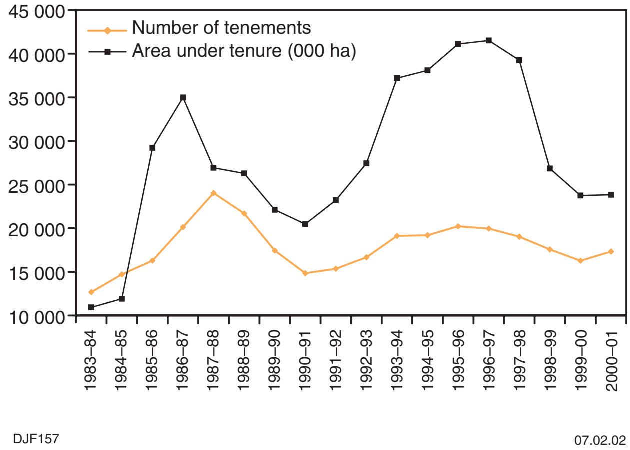


Figure 4. Tenements in force (1904 and 1978 Mining Acts)

but this was greatly bolstered by the grant of numerous miscellaneous purposes licences related to infrastructure. The number of exploration and prospecting licences that were current at mid-2001 were both lower than a year previously.

The data are consistent with the view that large greenfields exploration tenements and related expenditure have declined substantially since the peak of the boom in 1996–97 but are stabilizing, and the number of tenements in force has also reached its low point.

Figure 4 illustrates differences between the 1986–87 and 1996–97 boom periods. The more recent boom was of much longer duration and apparently involved exploration of much new ground, with about 17% (6 million hectares) more ground under tenure by comparison with the 1986–87 boom. However, the response in tenement numbers during the more recent boom is relatively subdued. This latter effect is interpreted to be largely due to the problems of processing tenement applications through the Native Title process, with a total of 10 914 tenement applications (for all tenement types) outstanding and yet to be granted as at 30 June 2001.

The Western Australian Government recognizes that the decline in exploration expenditure is a major issue and that access to land is a key consideration, and has undertaken two initiatives:

- The State Government carried out an expert review (the 'Wand review') of Native Title negotiating principles in a bid to speed up the settlement of the State's 130 Native Title applications, and
- Established a technical taskforce to examine ways to accelerate the processing of mining, exploration, and land-title applications in areas where Native Title might survive. The taskforce is also considering options to reduce the volume of outstanding tenement applications.

In a separate exercise, the State Government is carrying out a review (the 'Keating review') to determine how to improve the system for obtaining approvals for resource projects in Western Australia.

Drilling activity

Drilling activity since the peak of exploration in 1996–97 clearly shows that cutbacks in exploration budgets have had a severe impact on rotary air blast (RAB) and reverse circulation (RC) drilling (Fig. 5). 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 have continued their decline during 2000–01, with the drilling data reported to the Department showing a decline in RAB and RC drilling of an estimated 20% (0.391 million metres) and 25% (0.860 million metres) respectively, whereas diamond drilling has increased by an estimated 10% (0.86 million metres).

Given that there is approximately a one-year delay in companies reporting drilling statistics (via the annual statutory mineral-exploration reports) to the Department, the stabilization of overall exploration expenditure during 2000–01 is likely to lead to a leveling off of drilling activity data during 2001–02.

The falls in RAB and RC drilling statistics from their earlier peak levels are more severe than the general fall in overall exploration expenditure. RAB and RC drilling has borne the brunt of the cutbacks. RAB drilling has now declined by 67% (3.35 million metres) since the peak activity of 4.976 million metres in 1996–97. RC drilling has declined by a substantial 45% (2.2 million metres) since the peak activity of 4.825 million metres in 1997–98. The decline in RAB and RC drilling since the peak of the boom, 67 and 45% respectively, should be compared with the corresponding drop of 'only' 36% in total exploration expenditure. It is evident that exploration and prospect drilling has been severely curtailed in recent years, thus significantly lowering the chances of discovering new mineable deposits. Clearly, this trend must be turned around if the mineral industry is to be sustainable in the longer term.

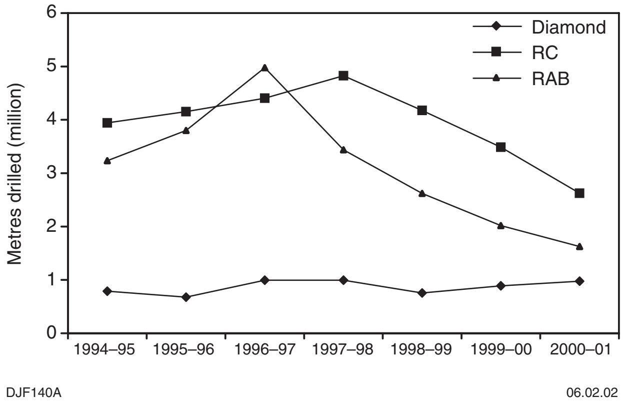


Figure 5. Mineral exploration drilling in Western Australia, by drilling type and year

However, diamond drilling activity has changed relatively little over the last seven years, with recent levels almost unchanged from those at the middle of the 1996–97 boom (Fig. 5). This is apparently a result of ongoing brownfields exploration where there is a need for the drilling of deep targets close to existing mine sites. Such drilling is often successful in the short-to-medium term in finding additional resources and reserves, but does not find the big discoveries in greenfield areas that are required in the longer term.

Mineral resources

The substantial resources of major mineral commodities produced in Western Australia are listed in Table 1.

Despite the gold exploration industry being at recession levels of activity, the State's inventory of measured and indicated gold resources (including any

Table 1. Estimates of mineral resources for major commodities in Western Australia

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

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

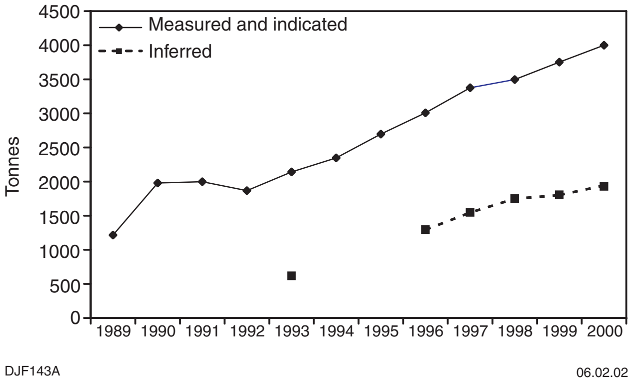


Figure 6. Estimates of gold resources in Western Australia, by year

converted to reserves) increased during 2000–01 (Fig. 6). Gold resources (measured and indicated only) increased by 247 t (6.6%) to 3999 t (Table 1). This increase was slightly less than that recorded in the previous year, but was again achieved with an average discovery cost of around $A20 per ounce (Table 2). If inferred resources are also included, then average discovery costs drop to about $A16 per ounce. The data continue to highlight the gold prospectivity of Western Australia, and are also interpreted to mean that the trend to brownfields exploration since 1996–97 has been successful overall in finding additional resources to keep existing plants operating in the short-to-medium term.

The 1990s has seen an unprecedented boom in nickel exploration that has been extremely successful in converting exploration effort into resources in the ground, but nickel resources (measured and indicated) in Western Australia recorded a drop after almost seven years of increases (Fig. 7). There are two reasons why nickel resources (measured and indicated) decreased by 2.79 Mt (13.8%) to 17.44 Mt of contained metal. Firstly, substantial resources were restated with a higher cut-off grade following a lower nickel price (estimates of lateritic resources are sensitive to the cut-off grade used), and secondly some resources were reclassified to the 'inferred' category. Inferred resources of nickel increased by 4.35 Mt (36%) to 15.94 Mt of contained metal, the increase boosted by a new estimate of 2.0 Mt of contained nickel in the Wingellina lateritic nickel prospect. Resource estimates, by broad mineralization style and by resource category, for nickel projects in Western Australia are shown in Figures 8 and 9.

Mineral production

Western Australia is one of the great mineral provinces of the world. There are more than 300 commercial mining and petroleum projects in operation producing over 50 different mineral and petroleum products for distribution to markets across the globe. The minerals and petroleum sector continues to drive the State's economy, accounting for close to 70% of its export income

Table 2. Gold discovery costs per ounce of measured and indicated resources, Western Australia[(a)]

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

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

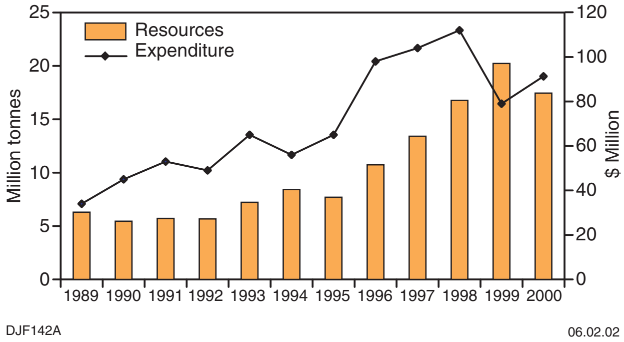


Figure 7. Nickel resources in Western Australia versus base-metal exploration expenditure, by year (dollars of the day)

and around 32% of gross State product. Royalties to the State Government from the resources sector totalled a record $1.2 billion for 2000–01.

In the 2000–01 financial year, the value of mineral and petroleum production rose sharply by $6248 million (29.3%) and totaled $27 593 million, setting a new record for Western Australia. The value of mineral production alone (i.e. excluding petroleum) also rose sharply by $3307 million (24.1%) to a total of $17 037 million, with rises recorded for the value of alumina, base metals, ilmenite, upgraded ilmenite, rutile, leucoxene, zircon, iron ore, manganese, nickel, cobalt, spodumene, tantalite, tin, and vanadium. The rise in production value of the major commodities (alumina, gold, iron ore, and nickel) during the last eight years is illustrated in Figure 10, with the increases greatly assisted by the fall in the value of the Australian dollar. During 2000–01, the value of the alumina industry exceeded the gold industry for the first time. In addition, the value of the nickel industry may exceed that of the gold industry within the next two years. For the first time ever, Western Australia became a producer of staurolite during 2000–01. Falls were recorded for the production value of coal, diamond, and garnet.

In a world-market context, Western Australia continues to be a very significant producer of the following minerals or mineral products (with an estimate of the proportion of world production shown in brackets) —

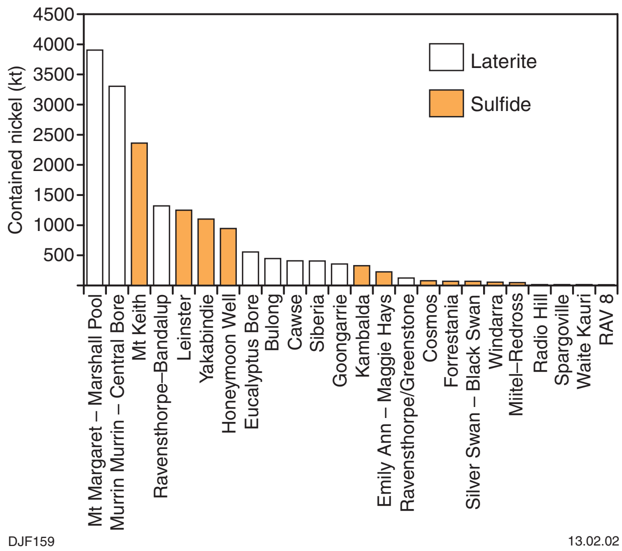


Figure 8. Ranking of nickel projects in Western Australia by contained metal in measured and indicated resources

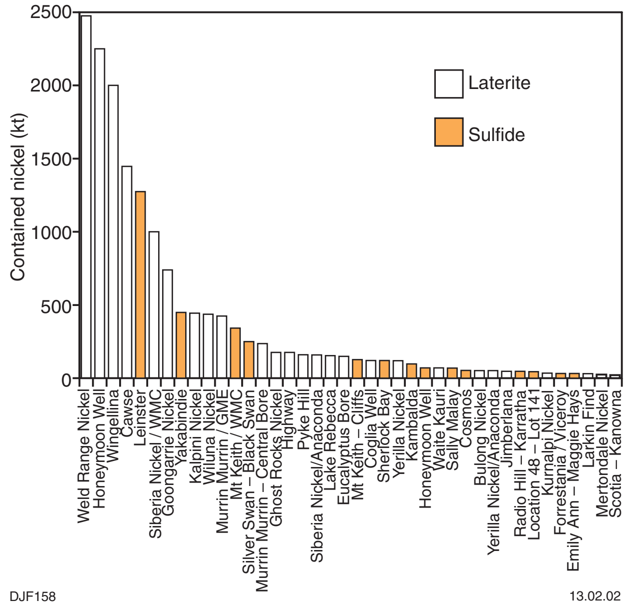


Figure 9. Ranking of nickel projects in Western Australia by contained metal in inferred resources

diamond (38%, includes industrial diamond), zircon (32%), tantalite (25%), rutile (24%), ilmenite (20%), alumina (20%), iron ore (14%, and with 34% of world seaborne trade in iron ore), nickel (14%), gold (8%), and vanadium (7%).

Acknowledgements

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

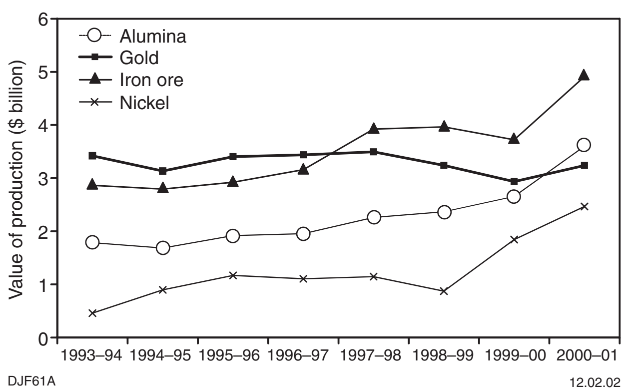


Figure 10. Comparative value of mineral production for major commodities in Western Australia, by year (dollars of the day)

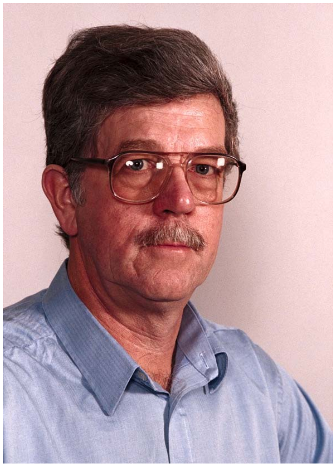
data in them that relate to the previous period). The Royalties Branch of the Department supplied information on the quantity and value of mineral production from Western Australia for 2000–01. Information on mining tenements in Western Australia was supplied by the Mineral Titles Division of the Department.

Inside the GSWA

Staff profiles

Arthur Hickman

Approaching the dawn of a fourth decade with GSWA, Arthur Hickman finds himself the third longest serving geologist in the organization. Over the last 29 years, Arthur has left an indelible mark on our understanding of the geology of Western Australia, and through his long-term love affair with the Pilbara Craton he has also provided internationally recognized foundations for studies of Archaean terrains. Along the way, he has helped guide the professional development of numerous other younger staff members with his steady and measured advice.



Arthur was born in Manchester, United Kingdom, and completed a BSc (Hons) and a PhD degree at the University of Birmingham. His doctoral work involved detailed geological mapping, structural analysis, and sedimentary geochemistry of an area in the Scottish Highlands. There he could combine his passion of geology with a love for the outdoors, and particularly for mountain walking. But it was undoubtedly the Scottish Highlands that swayed Arthur to seek warmer and flatter places to work, and seeking 'geology' and 'outdoors' his attention naturally turned to Western Australia. Joe Lord, the then Director of the Geological Survey, obviously thought that anyone willing to endure a winter field season in the Scottish Highlands was well suited for GSWA.

So Arthur joined GSWA in March 1972 as a geologist with the Mineral Resources Section. Judged to be experienced in like terrains and conditions, he was almost immediately despatched to Marble Bar — where his first tasks were to learn to drive and to obtain a driver's licence (in any order). Over the next four years, Arthur was the major contributor to the regional geological mapping of the east Pilbara. After an additional year mapping in the west Pilbara, he produced GSWA Bulletin 127. This Bulletin detailed a geological synthesis of the granite–greenstone terrains of the Pilbara Craton, and included a major new interpretation on their geological evolution. This represented a 'landmark' in Archaean geological studies.

Skirting his way around younger terrains, Arthur's attention next turned to the Yilgarn Craton, and after a years mapping in the Wheatbelt, in 1979 he was appointed officer-in-charge of the newly opened Kalgoorlie regional office. The opening of this new office saw Arthur, together with other GSWA staff, working closely with mining and exploration companies, prospectors, and various local administrative bodies. With a promotion to Senior Geologist, Arthur returned to Perth in 1981, and between then and 1987 concentrated on regional mapping and metallogenic studies of the Murchison region. These studies formed the basis of GSWA Bulletin 137.

It is unclear whether curiosity finally got the better of him, or if he was simply lured by the opportunity to again get close to *his* Pilbara Craton, but in 1989

Arthur commenced detailed 1:100 000-scale mapping of 'young' rocks — in the Palaeoproterozoic Paterson Orogen. But for Arthur, the 'riddle of the Rudall' was left unsolved, as in the early 1990s he left the project to take on a more supervisory and advisory role in the Mineral Resources Section.

With the major restructuring of the GSWA in 1993–94, mapping assets of the Mineral Resources Section (i.e. Arthur) were amalgamated into the new Regional Geoscience Mapping Section. With this new section came a push for new mapping projects, and one strongly promoted by Arthur was the remapping of the Pilbara Craton. By this stage, the Pilbara maps that Arthur had contributed to were already 20 years old, but represented our most recent studies of the region. With renewed industry interest in the Pilbara, the proposal needed little further justification, and a regional 1:100 000-scale mapping project was commenced under Arthur's supervision.

A major change in Arthur's life took place at Easter 2000, when he married a long-time GSWA colleague and geological map editor, Caroline Strong — finally providing a perfect union between geological fieldwork and geological map production.

Arthur's outside interests are travel, philately (especially Australian State stamps), bushwalking, photography, and fishing, and since meeting Caroline he has learned to appreciate the finer qualities of cats.

Angela Riganti

Angela started work in the Kalgoorlie regional office of GSWA in 1997. She was born and educated in northern Italy, but would like it noted that she differs from most Italians as she hates olives. After finishing her BSc (Hons) at the University of Milan in 1989, she moved to South Africa and completed a MSc in Economic Geology at Rhodes University, with a thesis on the stratigraphy and geochemistry of the Archaean Usushwana mafic layered intrusion. Angela spoke little English upon arrival in South Africa, but quickly became fluent through her studies, largely due to enforced presentations less than a month after her arrival. She did her PhD at the University of Natal where she met her husband Bruce Groenewald, who also works in the GSWA Kalgoorlie office. Angela's PhD thesis looked at the early Archaean Nondweni greenstone belt, focusing on geochemistry and petrography of komatiitic lavas and unusual quartzite units. Angela and Bruce moved to Namibia in 1996, where Angela worked for two years at the Geological Survey of Namibia as Museum Curator. During this time she also organized and took part in several international geological expeditions.

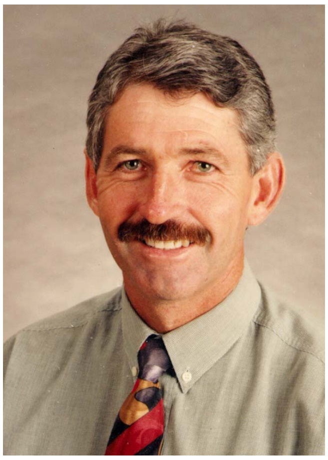
Angela's passion for geology was initiated as a child, with her love for collecting minerals and stamps with minerals. She remembers numerous gold-panning trips in Italy that also inspired her to study geology. Angela is still a serious collector and, when she can, travels to various locations in Western Australia to find more samples to add to her collection. Angela is a founding member of the Mineralogical Society of Western Australia. She also has a general interest in the natural sciences.

Since commencing work in GSWA, Angela has been involved in mapping the Southern Cross Granite–Greenstone Terrane in the Yilgarn Craton. Angela has been an invaluable member of the Southern Cross team, contributing significantly to the understanding of the volcanic and sedimentary evolution of the region. It is well known within the Kalgoorlie office, however, that Angela is a rain goddess, because of the common but uncanny coincidence of bad weather with her fieldwork.

Angela is actively involved with many community projects and charity work in Kalgoorlie, particularly with the Lions Club. She regularly helps raise money through sausage sizzles and doughnut making, and considers herself to be the undisputed doughnut-making champion of Kalgoorlie. Angela's hobbies are numerous and include gardening, stamping, paper making, jigsaw puzzles, and bird watching. She loves to travel and has covered most of Europe and southern Africa, and hopes to visit South America in the next couple of years. Angela and Bruce received their Australian citizenship on the 5th April 2000 and intend, with Smokey their cat, to make Australia their home. She admits, however, to missing her family and good Italian food, especially cheese, and tries to make sure she makes regular visits back to Italy.

Andrew Goss

All those who are familiar with Andrew Goss will be aware of his enthusiasm, energy, and humour. His lively spirit and artful style are most evident. While these traits may have been a handful for his parents and teachers, they have been a real bonus for the Geological Survey, where he has earned a reputation for 'getting things done', often in a beguiling manner. Tags of Sergeant Bilko and Arthur Daly (of the TV show Minder fame) have been well earned!



Andrew is the fifth child of a family of eight children, and after completing his schooling in 1972 he began as a cadet cartographer with the Surveys and Mapping Division of the Department. Through his four-year cadetship he studied cartography at Wembley TAFE and attained a Diploma. This surprised some managers and a few of his colleagues, as the self-confessed, discretional time he spent at the 'annex' (Wembley Hotel) did not go unnoticed. In fact, not a lot about Andrew does go unnoticed!

This learning experience, combined with enjoying a working relationship with a number of like-minded young cadets and being a member of a large family, has helped tune the characteristics for which he is renowned. His leadership in organizing carpark sales, grocery markets, chocolate-wheel raffles, and other 'investment opportunities' are all in the annals of Surveys and Mapping history. Management also recognized his people skills and offered him the opportunity (not obligation!) to manage the Reprographic Section of the Surveys and Mapping Division. This allowed him to enlarge his network of contacts and become more recognized throughout the Department. The marketing possibilities became endless!

After the introduction of Program Management by the Treasury in 1994, the activities of the Surveys and Mapping Division were distributed throughout the Department. The Reprographic Section became centralized under the Corporate Services Branch, and was disbanded within a month of relocating. The reprographic services were then outsourced under the policies of the day. With a reputation of always having 'his glass half full', and never being known to carry any 'baggage', Andrew was not deterred. New trails were there to be blazed. His reputation of 'getting things done' as a manager was much appreciated, and Andrew was appointed to a position of Projects Officer in GSWA.

Andrew wears many hats in his current role, with his most noticeable tasks being:

- Secretary of the core library development project;
- coordinator of preparation for promotional events and open days;
- facilitator and tour leader for visiting delegations;
- organizer of accommodation for the division (the 'signature' office on the 5th floor is a masterpiece); and
- President and chief fundraiser of the GSWA Social Club.

His time is not only spent freely for the benefit of others at work, but also for other community causes. Andrew's thoughtfulness and consideration for others should not be understated and they complement his enthusiasm, energy, and humour in all of his efforts. His ability to squeeze the last dollar from unsuspecting pockets for the greater good is legendary!

Andrew was born and bred in the North Beach locality. This has probably contributed to his love of the coast and commitment to surf lifesaving. He is a past President of the Trigg Island Surf Lifesaving Club and has earned a Life Membership through his considerable contribution. The crowning glory of his efforts was the redevelopment of the site of the clubhouse to include a café/ restaurant that now provides ongoing income to the club. This was an enormous and contentious project with many vested interests. On behalf of the members, over two of years of negotiations were undertaken between the club, the City of Stirling, and the State Government. These were eventually successful from a club perspective, largely due to Andrew's persistence and regard for natural justice. His commitment to surf lifesaving is ongoing, and he is currently the Chairman of the State Surf Boat Rowers Committee and mentor and sweep of the U/19 Trigg crew at the local level.

His sporting interests have also extended to rugby league, where he played and was secretary of the North Beach Rugby League Club for many years. Andrew also served as President of the Rugby League Referees Association for a decade. It seems that wherever he goes his energies are directed into 'making a difference' and developing organizations for the benefit of all.

Andrew is also a dutiful and caring husband of Rhonda, and a very proud and supportive father of Francine.

Staff list
(30 June 2001)

GRIFFIN, Tim (Director)

Regional Geoscience Mapping Branch

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

Bangemall Supergroup/ Southern Gascoyne
MARTIN, David
SHEPPARD, Steve
THORNE, Alan

Earaheedy Basin
HOCKING, Roger
JONES, Amanda
PIRAJNO, Franco

Eastern Goldfields
GROENEWALD, Bruce
PAINTER, Matthew
ROBERTS, Ivor

Southern Cross
CHEN, She Fa
GREENFIELD, John
RIGANTI, Angela
WYCHE, Stephen

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

Geochemical Mapping
MORRIS, Paul
SANDERS, Andrew

Lennard Shelf
PLAYFORD, Phillip

Geochronology
NELSON, David

Geophysics
HOWARD, David[1]
SHEVCHENKO, Sergey
WATT, John

Publications
CARROLL, Peter
COSGROVE, Lisa
DAY, Lyn
DOWSETT, Suzanne
EDDISON, Fiona
EDWARDS, Tara
FERDINANDO, Darren
FORBES, Alex
GOZZARD, Margie
HOFFMAN, Arthur
JOHNSTON, Jean
JONES, Murray
MIKUCKI, Jennifer
NOONAN, Kath
REDDY, Devika
STRONG, Caroline
SUTTON, Dellys
TETLAW, Nathan

Map Production and GIS
BANDY, Stephen
BRIEN, Cameron
BURDEN,Phillip
COLDICUTT, Shaun
COLLOPY, Sean
DAWSON, Brian
FRANCOIS, Annick
GREEN, Ellis

GREENBURG, Kay
HAMILL, Sammy
KIRK, John
KUKULS, Liesma (Les)
LADBROOK, David
LENANE, Tom
LOAN, Geoff
PRAUSE, Michael
McCABE, Marian
TAYLOR, Peter
THEEDOM, Erica
VICENTIC, Milan
WALLACE, Darren
WILLIAMS, Brian

Data Integration
GOZZARD, Bob
DOWNING, John

Mineral and Petroleum Resources Branch

ROGERSON, Rick (General Manager)

Petroleum Initiative Basin Studies
APAK, Sukru (Neil)
BLUNDELL, Kelvin
CARLSEN, Greg
DE LEUW, Lorraine
GHORI, Ameed
IASKY, Robert
IRIMIES, Felicia
MORY, Arthur
STEVENS, Mark

Regional Mineralization Mapping
FERGUSON, Ken
HASSAN, Lee
PEIRIS, Elias
RUDDOCK, Ian

Resource Assessment and Advice
ABEYSINGHE, Pathmasekara (Abey)
FLINT, Don
PAGEL, Jutta
TOWNSEND, David

Inventory of Abandoned Mine Sites
COOPER, Roger

Urban and Development Areas Geology
HALL, Glennis
LANGFORD, Richard
MARNHAM, Jodie

Palaeontology
GREY, Kath

Library
CHEUNG, Eunice
CROSS, Robert
KNYN, Brian

Administration and Executive Support
BRADSHAW, Brian
CRESSWELL,Brian
ELLIOTT, Ian
EVANS, Elaine
SLATER, Elizabeth
STOYANOFF, Nell

Special Projects
GOSS, Andrew

Carlisle Operations
BONER, Peter
BRADLEY, John
BROOKS, Chris
BRZUSEK, Marianna
CAREW, Eugene
CLARK, Dean
HOLMES, Mario
LOCKYER, Stuart
MOORE, Brian
WILLIAMS, Gary
WILLIAMS, John

Statutory Exploration Information Group
ARATHOON, Claudette
BELL, Ann
BOVELL, Lisa
DALY, Matthew
DODD, Fiona
ELLIS, Margaret
EMMS, Rosie
FETHERSTON, Michael
FITTON, Ann
HAWORTH, Jeffrey
HUGHES, Bernard
KARNIEWICZ, George
KEPERT, Stephen[2]
LESIAK, Irena
MARTIN, Anne-Louise
MASON, Jan Sandra
McCORQUODALE, Fiona
NAGY, Pearl
STAPLETON, Gladys[1]
WONG, Henrietta[1]

Kalgoorlie Core Library
HITCHCOCK, Wayne

[1] on secondment to other Divisions
[2] on secondment to GSWA

Staff movements
(1 July 2000 to 30 June 2001)

Internal reclassifications
IASKY, Robert — to Level 7
SANDERS, Andrew — to Level 6
SHEPPARD, Steve — to Level 6

Commencements
DONALDSON, Mike
HITCHCOCK, Wayne

Graduate Geologist work experience program
BOVELL, Lisa
MARTIN, Anne-Louise

Resignations
ADAMIDES, Nicos
FLETCHER, Gregory
FOX, Alistair
JOSE, Geoffrey
McGORRIN, Yvonne
MOORS, Henry
OCCHIPINTI, Sandra
VEALE, Anthony

Secondments
LEWIS, Maureen — to GSWA (7 weeks)
STAPLETON, Gladys — to Mineral Titles Division
WONG, Henrietta — to Petroleum Division

Voluntary severance
SMART, David
URBINI, Simon

Casual and Fee for service
APTHORPE, Majory
ARUNDELL, Elizabeth
BARKLA, Bronwyn
CAMERON, Virginia
COPP, Iain
DAVIS, Angela
D'ERCOLE, Cecilia
DOWLING, Sarah
FERGUSON, Andrew
HOLZSCHULT, Joseph
JABLON, Marianne
MacGILL, Gerard
McKEATING, Joan
MILLER, Scott
NOWAK, Ian
PITCHFORD, Andrew
SEARSTON, Stella
SUCHODOLSKI, Christine
VANDERHOR, Fop
WILLIAMS, Geoffrey
WRIGHT, Gareth
ZENGERER, Matthew
ZIKICH, Mark

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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  - *Geochronology*
    David Nelson: 9222 3613
- ***Geophysics and Remote Sensing***
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- ***Geoscience Information Products***
  Steve Bandy: 9222 3201
  - *Map and Text Editing*
    Jenny Mikucki: 9222 3568
  - *Publication Drafting and Design*
    Michael Prause: 9222 3854
  - *Geographic Information System*
    Phillip Burden: 9222 3175
  - *Computer Assisted Map Production*
    Brian Dawson: 9222 3122
  - *Data Integration*
    Bob Gozzard: 9222 3594
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  Franco Pirajno: 9222 3155
- ***Pilbara Craton***
  Arthur Hickman: 9222 3220
- ***Bangemall Supergroup/Southern Gascoyne Complex***
  Alan Thorne: 9222 3335
- ***Lennard Shelf***
  Phillip Playford: 9222 3157

Reporting directly to the Director

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  - *Archaean and Regolith*
    Paul Morris: 9222 3345
  - *Basins*
    Roger Hocking: 9222 3590
  - *Proterozoic Orogens*
    Steve Sheppard: 9222 3566
- ***Promotions***
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    Jeff Haworth: 9222 3214
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    Brian Knyn: 9222 3165
  - *Carlisle Operations*
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  Greg Carlsen: 9222 3760
- ***Western Margin Petroleum Initiative***
  Arthur Mory: 9222 3327
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  Richard Langford: 9222 3632
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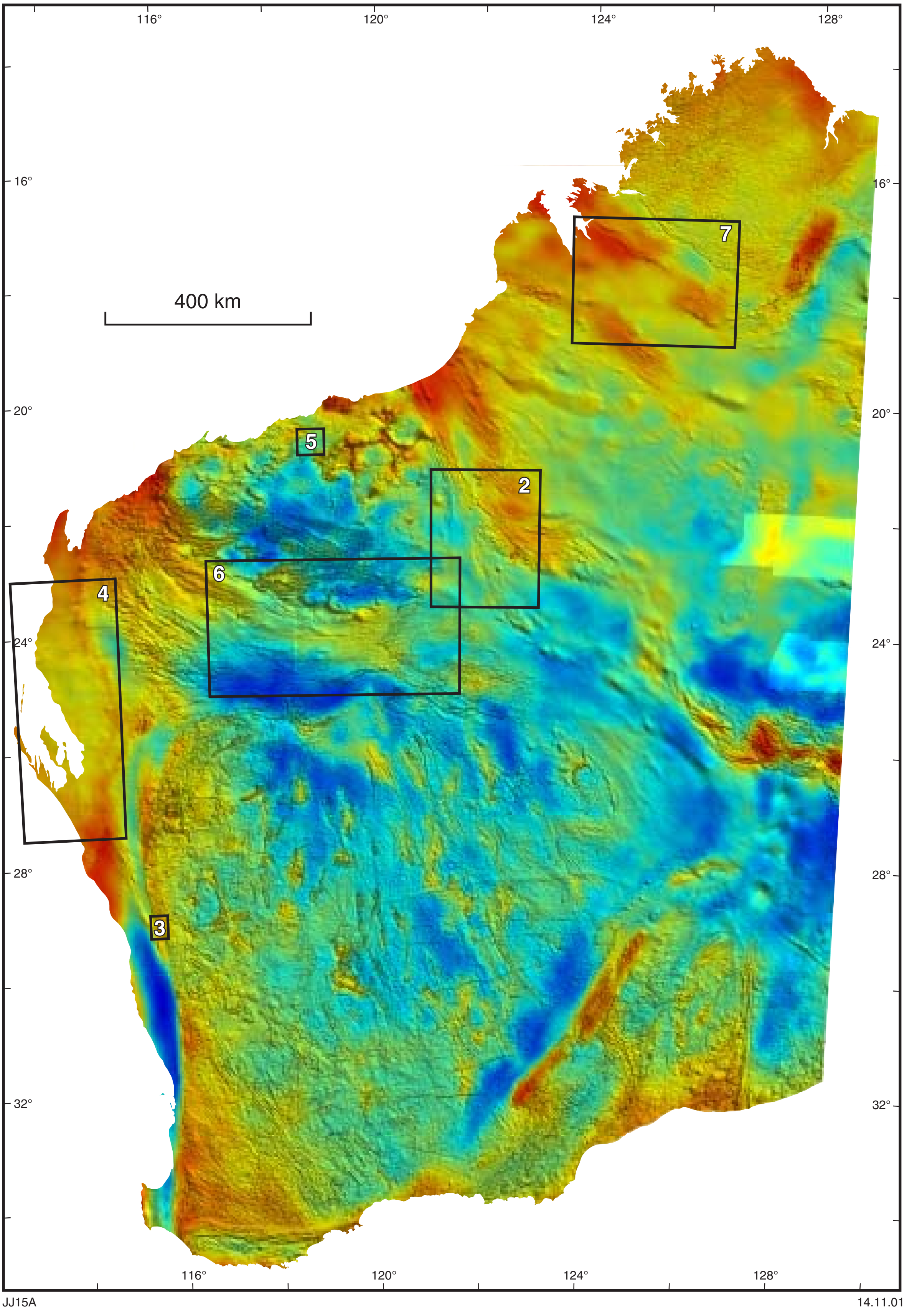
  Ian Ruddock: 9222 3334
- ***Palaeontology***
  Kath Grey: 9222 3508

Revised structure effective 01/07/01

TJG74 22.01.02



Map of Western Australia showing the locations discussed in the seven 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

A revision of the tectonic units of Western Australia

by I. M. Tyler[1] and R. M. Hocking[2]

Abstract

A digital 1:2 500 000-scale tectonic units map of Western Australia has been compiled using boundaries modified from the 1:2 500 000 Geological map of Western Australia (13th edition) and the Basin Subdivisions of Western Australia map. Tectonic units are grouped into basins, cratons or orogens. Most Archaean and Proterozoic basins are parts of cratons or orogens, and have been defined according to tectonic style, age, and type of basin fill. Phanerozoic basins are defined largely on their presently expressed structural elements and boundaries. The cratons are Archaean to earliest Palaeoproterozoic in age, and the orogens range from Proterozoic to early Phanerozoic. The cratons are subdivided into terranes and basins, which can be deformed and metamorphosed within tectonic zones. Orogens are divided into igneous and metamorphic complexes and related basins. Complexes may be subdivided into terranes or zones. Orogenic forelands are reworked areas of adjacent craton and basin margins.

KEYWORDS: Tectonic units, Western Australia, basins, cratons, orogens.

Introduction

Part of the role of the Geological Survey of Western Australia (GSWA) is to reveal the potential for mineral and petroleum resources by providing spatially related geoscientific information, and regional geological, geophysical, and geochemical map products and reports. The basis for the presentation of these data is an up-to-date geological framework for Western Australia that uses consistent geological and tectonic unit hierarchies, nomenclature, and boundaries.

The nomenclature and boundaries of, and the conceptual framework behind, the tectonic units of Western Australia have evolved considerably since the publication of GSWA Memoir 3 (Geological Survey of Western Australia, 1990) because of new geological mapping, combined with more detailed and more comprehensive geophysical, geochemical, isotopic, and geochronological datasets. In particular, the widespread application of SHRIMP (sensitive high-resolution ion microprobe) U–Pb zircon dating has revolutionized our understanding of the tectonic history of the Precambrian rocks in Western Australia. In addition, it is desirable to standardize the boundaries of the tectonic units with the geological unit boundaries shown on the latest regional map of Western Australian geology, the 1:2 500 000 Geological map of Western Australia (13th edition; Myers and Hocking, 1998), and with the basin subdivisions defined by Hocking (1994). The new map (Figs 1 and 2; Tyler and Hocking, 2001) retains the basic grouping of tectonic units into basins, cratons, and orogens adopted in GSWA Memoir 3, although modifications to their definitions have been necessary to accommodate our better understanding of their tectonic evolution.

The map is available as a plotted hard copy product or can be viewed as a searchable GIS dataset on the Western Australian Department of Mineral and Petroleum Resources website (www.mpr.wa.gov.au). Basic information is provided on the age (Archaean, Palaeoproterozoic, Mesoproterozoic, Neoproterozoic, Phanerozoic) and dominant lithological associations (granite–greenstone, igneous and metamorphic, sedimentary and volcanic) of each tectonic unit. This paper describes the most significant revisions, and identifies areas where further revision may be required.

Basins

Basins were defined in GSWA Memoir 3 as areas 'underlain by a substantial thickness of sedimentary rocks which possess unifying characteristics of stratigraphy and structure, due to their deposition during a regionally restricted episode of crustal depression or a related sequence of such episodes' (Trendall, 1990a, p. 4). The term

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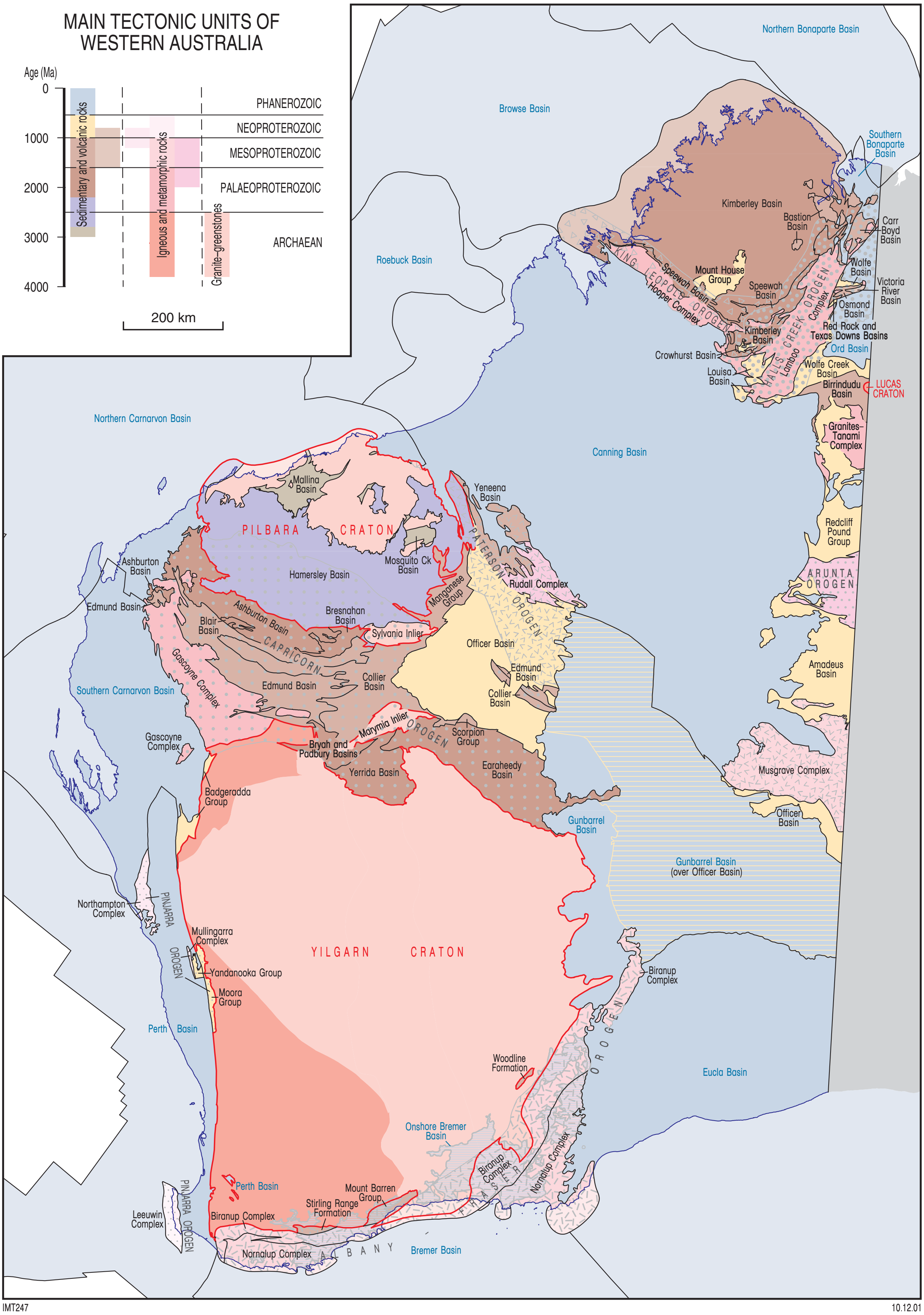

Figure 1. Main tectonic units of Western Australia

basin can be applied to the deposited rocks, their areal extent after erosion, and the crustal depression in which they accumulated.

Within GSWA, usage has differed between groups working in Precambrian and Phanerozoic basins. Most Precambrian basins are considered to be parts of Archaean to earliest Palaeoproterozoic cratons or Proterozoic orogens, and have been defined according to tectonic style, and the age and type of basin fill. These basins equate to discrete major depositional episodes, are tectono-stratigraphic, and commonly not polycyclic. They are discussed under **Cratons** and **Orogens** below. The Phanerozoic basins have been defined largely on their presently expressed structural elements and boundaries, rather than the nature and age of the contained succession, so that the basin is the container in which all of the succession sits. The contained succession may be a single depositional phase or several variably related phases (polycyclic). This usage has largely continued up today (as in, for example, the onshore Canning Basin), although two stacked basins were recognized by Hocking (1994): the Phanerozoic Gunbarrel Basin, which rests on the Neoproterozoic to earliest Phanerozoic Officer Basin, and the Westralian Superbasin, which onlaps and overlies (at depth) older Phanerozoic basins.

A comprehensive, consistent, structurally based set of subdivisions of the Neoproterozoic and Phanerozoic basins within Western Australia was proposed by Hocking (1994; see also Hocking et al., 1994, and Hocking and Preston, 1998) and is largely followed here. Two superbasins are recognized: the Neoproterozoic Centralian Superbasin and the Phanerozoic Westralian Superbasin, which are discussed below. Each superbasin groups a set of basins showing common age, tectonic style, and fill. Several Proterozoic sedimentary units have been identified as equivalent to basins or sub-basins, but have not yet been formally described as such because of uncertainty about their stratigraphic affinities. They are referred to here and on the map by their formal stratigraphic names.

Proterozoic basins not within orogens

A few Proterozoic basins cannot be related to the development of orogens. The Palaeoproterozoic Kimberley Basin (Fig. 2b) extended across the earlier Palaeoproterozoic Hooper Complex (Griffin and Tyler, 1995). The Palaeoproterozoic Texas Downs and Revolver Creek Basins, although contained and deformed entirely within the Halls Creek Orogen, may be equivalent to the Kimberley Basin (Tyler, 2000). Similarly, the Mesoproterozoic Bastion and Birrindudu Basins may be equivalent to the Crowhurst Basin within the Halls Creek Orogen (Tyler, 2000), and may originally have extended across the Palaeoproterozoic Lamboo and Granites–Tanami Complexes (Fig. 2b).

The tectonic settings of the Mesoproterozoic Woodline Formation (Fig. 2d) and the Neoproterozoic Badgeradda Group (Fig. 2c) , both of which overlie the Yilgarn Craton, are not known.

Centralian Superbasin

The Centralian Superbasin consists of Neoproterozoic to earliest Phanerozoic basins within central and northern Australia (Walter et al., 1995; Tyler, 2000) that are related by age, common tectonic styles, and closely comparable sedimentary successions. The basins included are the Officer, Wolfe Creek, Louisa, and Amadeus Basins, the Redcliffe Pound Group (previously included with the Mesoproterozoic Birrindudu Group in the Birrindudu Basin), the upper part of the Victoria River Basin, the Mount House Group, and the Oscar Range Group exposed within the Oscar Range Inlier (Fig. 2b,d).

The ‘Savory Basin’ of Williams (1992) is now considered to be a northwestern extension of the Officer Basin, as is the former ‘Karara Basin’, and what was the southwestern part of the Yeneena Basin (Bagas et al., 1999). Hocking (1994) divided the Neoproterozoic and Phanerozoic sedimentary rocks that were previously all included within the Officer Basin into an underlying Officer Basin and an overlying Gunbarrel Basin (Fig. 2d), with the boundary taken as the base of widespread early Palaeozoic flood basalts. This is consistent with the relationship between other Neoproterozoic basins and overlying Phanerozoic basins in Western Australia, where a widespread unconformity reflects major orogenic events during the latest Neoproterozoic to earliest Phanerozoic (Myers et al., 1996; Tyler et al., 1998). Apak and Moors (2000, 2001) suggested that the subdivisions within the Officer Basin shown by Hocking (1994), who followed Iasky (1990), cannot be recognized in seismic and well data. However, they were considering subdivisions in terms of depocentres rather than presently expressed structural elements. The subdivisions of Hocking (1994) are on the latter basis, so they are retained here and linked to the exposed northwest Officer Basin. Some subdivisions will alter as the status of a possibly underlying basin or basins is resolved.

Phanerozoic basins

The nomenclature and boundaries for Phanerozoic basins and sub-basins largely follows that of Hocking (1994), although changes have been made to the units recognized and to the boundaries between and within the Canning, Northern Carnarvon, Southern Carnarvon, and Perth Basins.

In the Canning Basin, the Tabletop Shelf is underlain by the Paterson Orogen (Fig. 2b,d), and is differentiated from the southern part of the Anketell Shelf. The boundary between the Canning and Gunbarrel Basins is arbitrary, and reflects the underlying front of the Paterson Orogen, linking the Rudall Complex and the Musgrave Complex. It is not marked by a surface structure or change in sedimentary succession, although earlier Palaeozoic sedimentary rocks may be absent along this zone, and may differ in character in the Canning and Gunbarrel Basins on either side. The late Palaeozoic and Mesozoic succession of the Gunbarrel Basin could be considered a southward extension of the Canning Basin.

In the Southern Carnarvon Basin (Fig. 2c), Iasky and Mory (1999) changed the boundaries between the Merlinleigh Sub-basin, Gascoyne Platform, and Byro Sub-basin, after recognizing that the Wandagee

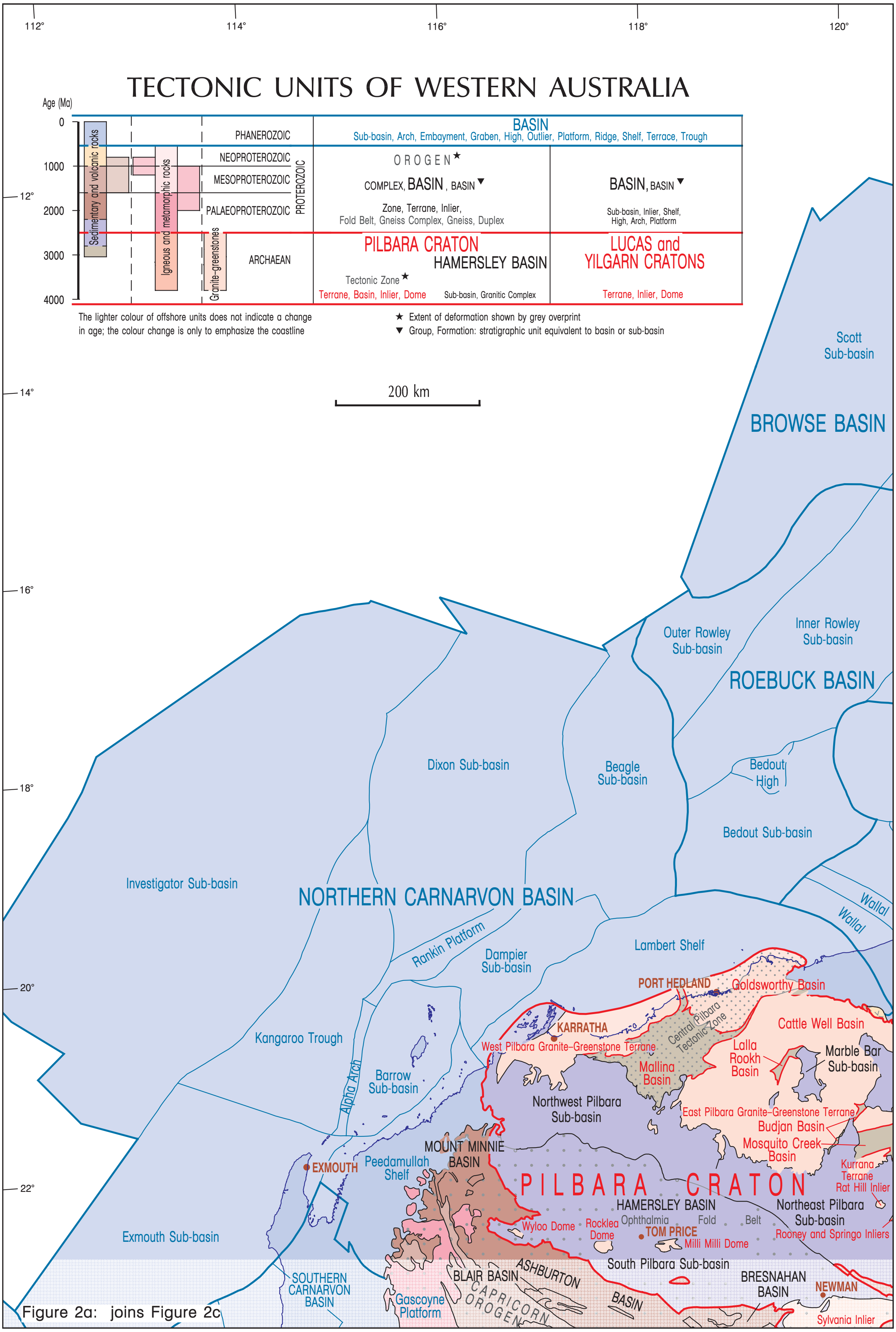

Figure 2a: joins Figure 2c

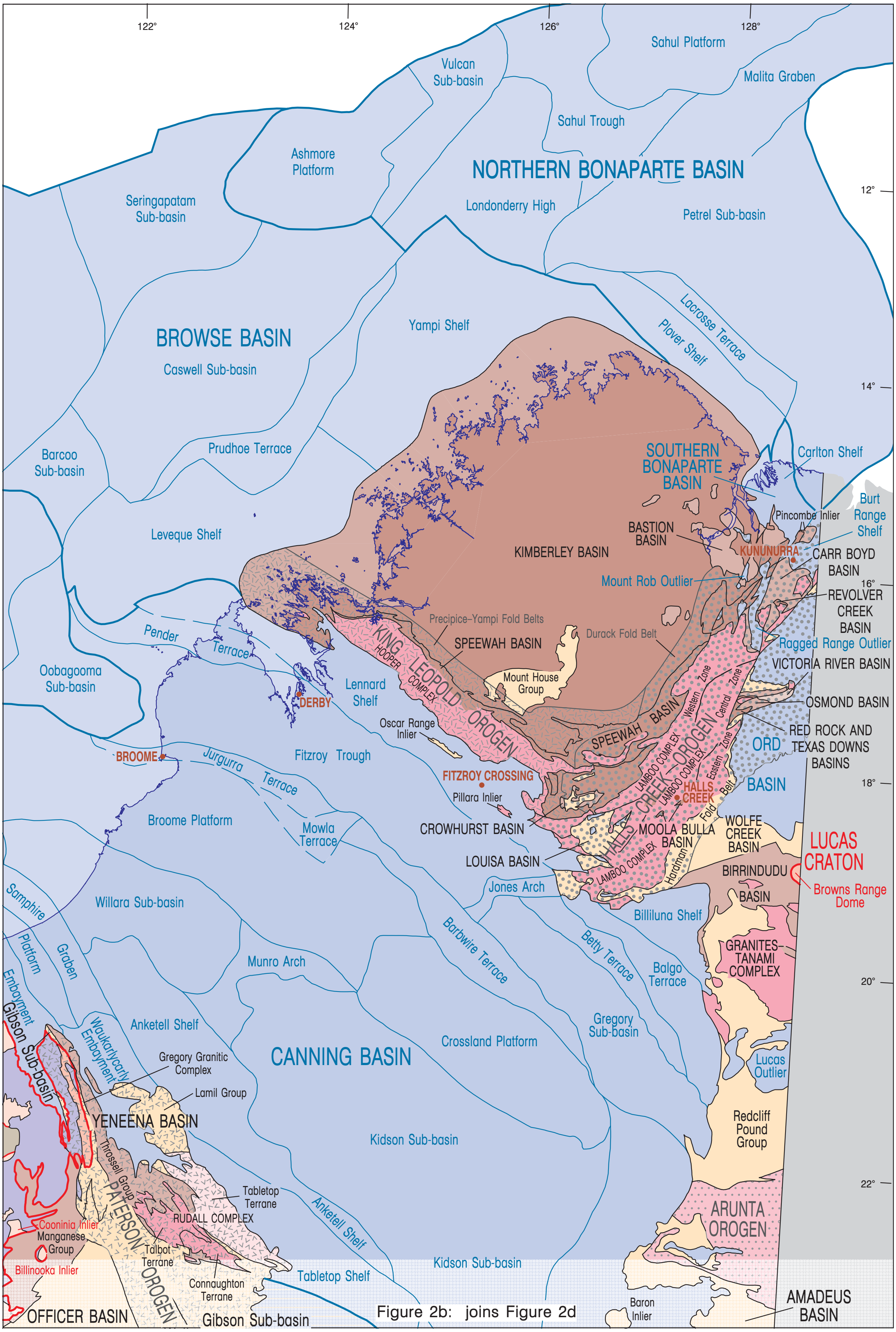

Figure 2b: joins Figure 2d

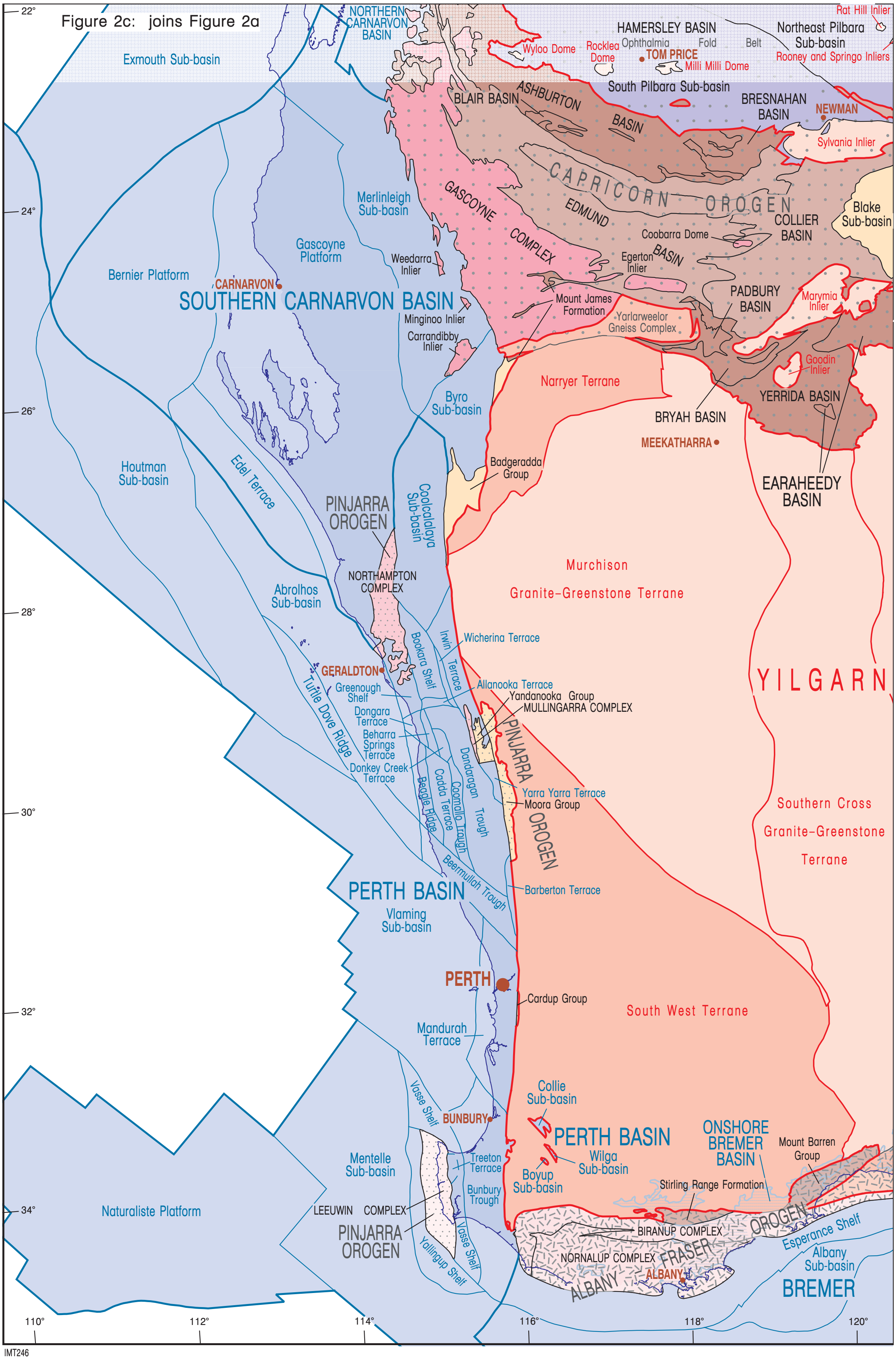
Figure 2c: joins Figure 2a
Exmouth Sub-basin
NORTHERN CARNARVON BASIN
HAMERSLEY BASIN
Northeast Pilbara Sub-basin
Rat Hill Inlier
Wyloo Dome
Rocklea Dome
Ophthalmia Fold Belt
TOM PRICE
Milli Milli Dome
Rooney and Springo Inliers
South Pilbara Sub-basin
BLAIR BASIN
ASHBURTON BASIN
BRESNAHAN BASIN
NEWMAN
Sylvania Inlier
Merlinleigh Sub-basin
CAPRICORN OROGEN
GASCOYNE COMPLEX
EDMUND BASIN
COLLIER BASIN
Blake Sub-basin
Coobarra Dome
Gascoyne Platform
Weedarra Inlier
Egerton Inlier
Bernier Platform
CARNARVON
SOUTHERN CARNARVON BASIN
Mount James Formation
PADBURY BASIN
Marymia Inlier
Minginoo Inlier
Yarlarweelor Gneiss Complex
Carrandibby Inlier
Goodin Inlier
Narryer Terrane
Byro Sub-basin
BRYAH BASIN
YERRIDA BASIN
MEEKATHARRA
Houtman Sub-basin
Edel Terrace
Badgeradda Group
EARAHEEDY BASIN
PINJARRA OROGEN
Coolcalalaya Sub-basin
Murchison Granite–Greenstone Terrane
NORTHAMPTON COMPLEX
Abrolhos Sub-basin
Wicherina Terrace
Irwin Terrace
Bookara Shelf
GERALDTON
Turtle Dove Ridge
Greenough Shelf
Allanooka Terrace
Yandanooka Group
MULLINGARRA COMPLEX
YILGARN
Dongara Terrace
Beharra Springs Terrace
Donkey Creek Terrace
Dandaragan Trough
PINJARRA OROGEN
Beagle Ridge
Cadda Terrace
Coomallo Trough
Yarra Yarra Terrace
Moora Group
Southern Cross Granite–Greenstone Terrane
Beermullah Trough
PERTH BASIN
Barberton Terrace
Vlaming Sub-basin
PERTH
Cardup Group
South West Terrane
Mandurah Terrace
Collie Sub-basin
Vasse Shelf
BUNBURY
PERTH BASIN
ONSHORE BREMER BASIN
Mount Barren Group
Mentelle Sub-basin
Treeton Terrace
Wilga Sub-basin
Boyup Sub-basin
Stirling Range Formation
Bunbury Trough
LEEUWIN COMPLEX
Naturaliste Platform
PINJARRA OROGEN
Yallingup Shelf
BIRANUP COMPLEX
NORNALUP COMPLEX
ALBANY FRASER OROGEN
ALBANY
Esperance Shelf
Albany Sub-basin
BREMER
22°
24°
26°
28°
30°
32°
34°
110°
112°
114°
116°
118°
120°
IMT246

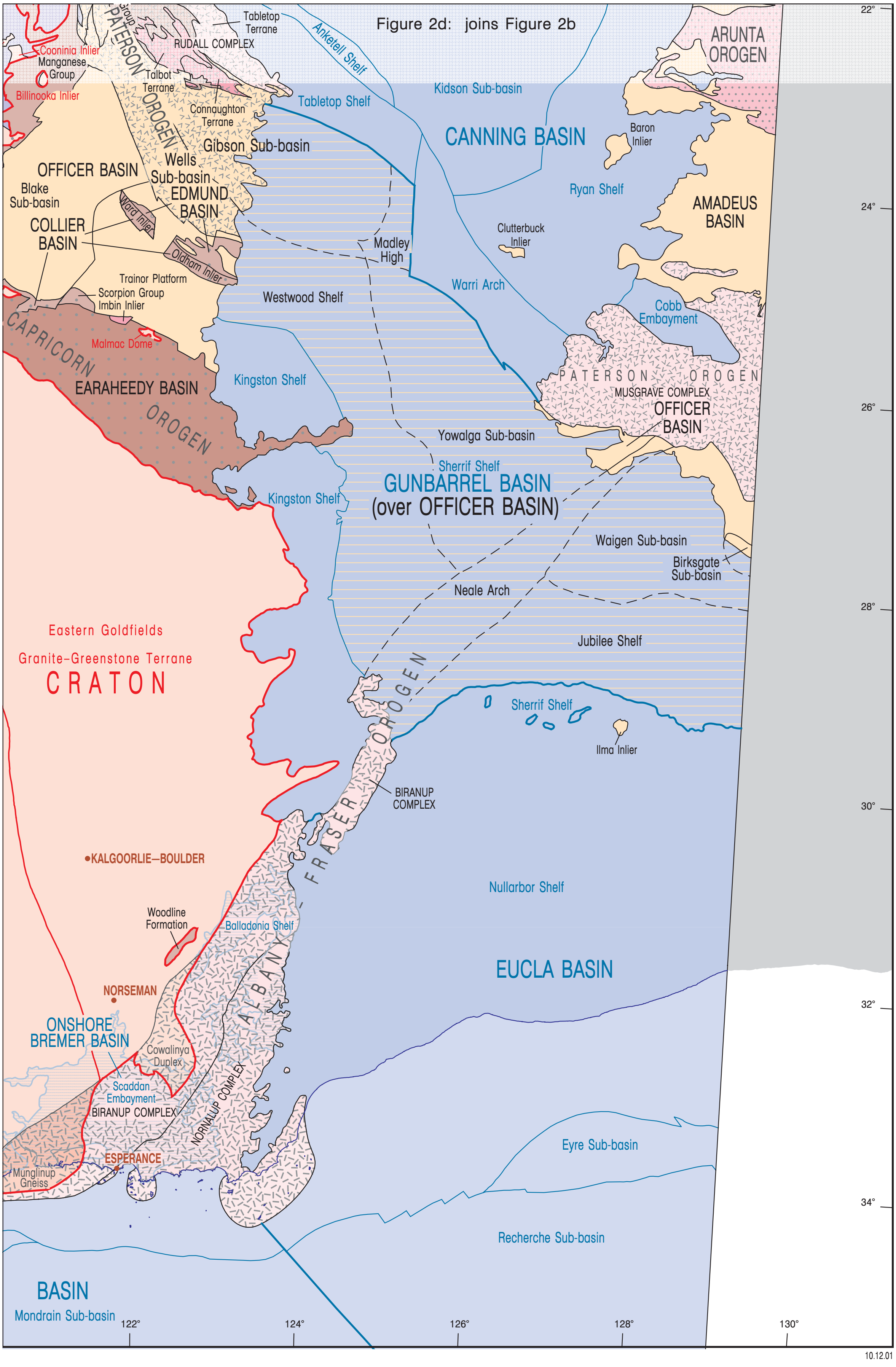
Figure 2d: joins Figure 2b
Tabletop Terrane
RUDALL COMPLEX
Anketell Shelf
ARUNTA OROGEN
Coonina Inlier
Manganese Group
Talbot Terrane
Billinooka Inlier
PATERSON OROGEN
Connaughton Terrane
Tabletop Shelf
Kidson Sub-basin
CANNING BASIN
Baron Inlier
Gibson Sub-basin
Wells Sub-basin
OFFICER BASIN
Blake Sub-basin
EDMUND BASIN
Ryan Shelf
AMADEUS BASIN
COLLIER BASIN
Ward Inlier
Clutterbuck Inlier
Madley High
Oldham Inlier
Trainor Platform
Scorpion Group
Imbin Inlier
Westwood Shelf
Warri Arch
Cobb Embayment
CAPRICORN OROGEN
Malmac Dome
EARAHEEDY BASIN
Kingston Shelf
PATERSON OROGEN
MUSGRAVE COMPLEX
OFFICER BASIN
Yowalga Sub-basin
Sherrif Shelf
GUNBARREL BASIN
(over OFFICER BASIN)
Kingston Shelf
Waigen Sub-basin
Birksgate Sub-basin
Neale Arch
Jubilee Shelf
Eastern Goldfields
Granite–Greenstone Terrane
CRATON
Sherrif Shelf
Ilma Inlier
BIRANUP COMPLEX
FRASER OROGEN
KALGOORLIE–BOULDER
Nullarbor Shelf
Woodline Formation
Balladonia Shelf
ALBANY
EUCLA BASIN
NORSEMAN
ONSHORE BREMER BASIN
Cowalinya Duplex
Scaddan Embayment
BIRANUP COMPLEX
NORNALUP COMPLEX
Eyre Sub-basin
ESPERANCE
Munglinup Gneiss
Recherche Sub-basin
BASIN
Mondrain Sub-basin
22°
24°
26°
28°
30°
32°
34°
122°
124°
126°
128°
130°
10.12.01

Ridge (along the eastern edge of the Gascoyne Platform) did not extend north to the Peedamullah Shelf (Fig. 2a). The former 'Bidgemia Sub-basin' is now assigned to the Merlinleigh Sub-basin. The boundaries of the Edel Terrace and Gascoyne Platform with the Abrolhos Sub-basin in the Perth Basin were modified by Crostella (2001; Fig. 2a,c). In the Northern Carnarvon Basin (Fig. 2a), Crostella et al. (2000) amended the boundaries between the Peedamullah Shelf and the Barrow Sub-basin.

Extensive changes have been made within the subdivisions of the Perth Basin (Mory and Iasky, 1996; Crostella and Backhouse, 2000; Fig. 2c). The Dandaragan Trough and the former 'Dongara Saddle' have been subdivided into the Bookara Shelf and Greenough Shelf, the Allanooka, Wicherina, Dongara, Beharra Springs, Donkey Creek, Yarra Yarra, Barberton, and Mandurah Terraces, and the Coomallo and Beermullah Troughs. The former 'Collie Basin', together with what were the 'Wilga and Boyup Outliers', are now regarded as sub-basins of the Perth Basin.

The Balladonia Shelf is at the western edge of the Nullabor Shelf of the Eucla Basin (Fig. 2d). This contains clastic material marginal to the Eucla Basin, similar in nature to the deposits of the Bremer Basin farther southwest. The onshore Bremer Basin is shown as an overprint (Fig. 2c,d) because it is at best a discontinuous veneer, and the boundaries are amended where drilling has provided better delineation of the extent of the sedimentary rocks.

Westralian Superbasin

The Westralian Superbasin is a grouping of related basins along the North West Shelf (Fig. 2a,b). The basins included are the Northern Bonaparte, Browse, Roebuck, and Northern Carnarvon Basins, all of which are mostly offshore and dominated by Mesozoic and lesser amounts of Cainozoic fill. The superbasin reflects the breakup and subsequent drift apart of Gondwana. The boundary between the Northern Carnarvon and the Roebuck and Canning Basins has been revised. The Lambert Shelf (Northern Carnarvon Basin) has been extended eastwards to a logical boundary against the Wallal Embayment (Canning Basin), rather than arbitrarily breaking the Lambert Shelf where no change is apparent.

Cratons

Cratons were defined in the Western Australian context in GSWA Memoir 3 as a part of the Earth's crust that attained stability by about 2.4 Ga, since which time they were regarded as being little-deformed in comparison with adjacent parts of the crust (Trendall, 1990a, p. 4). The essence of this definition is retained here, but may be reconsidered in a later revision in light of the recognition of the formation of younger, separate, North, West, and South Australian 'cratons' by Palaeoproterozoic orogenic processes at c. 1.8 Ga, and their amalgamation as a single 'Proterozoic Australian craton' by Mesoproterozoic orogenic processes at c. 1.3 Ga (Myers et al., 1996). The effects of these later orogenic events within the margins of the pre-2.4 Ga cratons were discussed in GSWA Memoir 3 (Trendall, 1990a, p. 5). However, in contrast to GSWA Memoir 3, the extent of overlap of orogenic deformation, meta-morphism, and igneous intrusion into the pre-2.4 Ga cratons is shown on the new map (Figs 1 and 2). The rocks within these orogenic forelands can be regarded, in terms of their tectonic evolution, as part of both the earlier craton and the later orogen.

There are three areas of crust in Western Australia that stabilized prior to 2.4 Ga: the Pilbara and Yilgarn Cratons, which were defined in GSWA Memoir 3, and the Lucas Craton, which was recognized by Myers et al. (1996). The cratons have been divided into basins and terranes, which are defined here as fault-bounded bodies of rock of regional extent, characterized by a geological history different from those adjacent to them (Jackson, 1997).

Pilbara Craton

The Pilbara Craton is made up of Archaean granite–greenstones and basins that stabilized prior to 2.8 Ga and, given that a craton is defined here as stabilizing prior to 2.4 Ga, also includes the unconformably overlying latest Archaean to earliest Palaeoproterozoic Hamersley Basin (Fig. 2a,b). The northern part of the Pilbara Craton has been divided into the West Pilbara Granite–Greenstone Terrane, East Pilbara Granite–Greenstone Terrane, and the Kurrana Terrane, together with the Mallina, Lalla Rookh, Cattle Well, Goldsworthy, Budjan, and Mosquito Creek Basins (Hickman et al., 2000; Hickman, 2001). The Mallina Basin, together with part of the East Pilbara Granite–Greenstone Terrane, has been deformed, metamorphosed, and intruded by granite plutons within the Central Pilbara Tectonic Zone (Fig. 2a). The granite–greenstones extend to the south and southeast beneath the Hamersley Basin, and outcrop as a series of inliers and domes in both the Hamersley Basin and the overlying Mesoproterozoic Collier Basin (Fig. 2c). The Hamersley Basin has been subdivided into the Marble Bar, Northwest Pilbara, Northeast Pilbara, and South Pilbara Sub-basins (Thorne and Trendall, 2001). The Gregory Granitic Complex (Fig. 2b) is the intrusive equivalent of felsic volcanic rocks in the lower part of the Northeast Pilbara Sub-basin succession.

Yilgarn Craton

The Yilgarn Craton consists of extensive Archaean granite–greenstones, as well as areas of Archaean medium- to high-grade metamorphic rocks and intrusive igneous rocks. The subdivision of the Yilgarn Craton largely follows that of Myers (1997) and Witt et al. (1998). To be consistent with the nomenclature of the Pilbara Craton, the Eastern Goldfields, Southern Cross, and Murchison Granite–Greenstone Terranes are recognized, together with the igneous and higher grade metamorphic rocks of the Narryer and South West Terranes (Fig. 2c,d). Further subdivision into smaller terranes was suggested for the Southern Cross and Eastern Goldfields Granite–Greenstone Terranes by Myers (1997) and Witt et al. (1998), and for the South West Terrane by Wilde et al. (1996). This has not been attempted here as the boundaries are difficult to establish on the 1:2 500 000 Geological map of Western Australia, and the status of some of the 'terranes' is controversial (e.g. Groenewald et al., 2000). Along the northern margin of the Yilgarn Craton, granite–greenstones outcrop in a series of inliers within Proterozoic basins.

Lucas Craton

In the northeast of Western Australia, latest Archaean (c. 2.5 Ga) igneous and metamorphic rocks are exposed in the Browns Range Dome (Page et al., 1995), which is an inlier within the Mesoproterozoic Birrindudu Basin (Fig. 2b). Myers et al. (1996, fig. 4) suggested that this formed part of the Lucas Craton which, to the east in the Northern Territory, also outcrops as the Billabong complex. The craton formed a basement to the Palaeoproterozoic rocks now exposed within the Granites–Tanami Complex.

Orogens

Orogens were defined in GSWA Memoir 3 as tectonic belts characterized by regional metamorphism and abundant plutonic intrusion, which were established by a distinct tectonic pulse, but could be reactivated by later tectonic episodes, and remained permanent zones of weakness in the Earth's crust (Trendall, 1990a, p. 4). There are seven orogens within Western Australia (shown as a grey overprint on Figs 1 and 2), all of which are long-lived features that may have been reactivated a number of times by different orogenies (Myers et al., 1996; Tyler et al., 1998). They are predominantly Proterozoic in age, although there was significant reactivation of the Halls Creek Orogen (Fig. 2b) during the Palaeozoic Alice Springs Orogeny (Tyler, 2000). The boundaries of the orogens are defined here by the limits of orogenic deformation, metamorphism, and igneous activity that overlap as orogenic forelands, reworking adjacent craton and basin margins.

The orogens are divided into igneous and metamorphic complexes (as defined by Trendall, 1990b, p. 197), and related basins. The igneous and metamorphic complexes may be subdivided into terranes, as defined under **Cratons** above, or zones. The nature of the reworking in the orogenic forelands varies, forming fold belts or duplexes, gneisses, and gneiss complexes. In future revisions the areas within orogens that are affected by individual orogenies will be defined.

King Leopold and Halls Creek Orogens

The King Leopold Orogen (Fig. 2b) includes Palaeoproterozoic igneous and metamorphic rocks of the Hooper Complex along with the Precipice and Yampi Fold Belts, which form an orogenic foreland. This foreland consists of deformed rocks of the Palaeoproterozoic Speewah and Kimberley Basins and the Neoproterozoic Mount House and Oscar Range Groups (Tyler and Griffin, 1990; Griffin et al., 1993).

In the Halls Creek Orogen (Fig. 2b), Palaeoproterozoic igneous and metamorphic rocks of the Lamboo Complex have been divided into Western, Central, and Eastern Zones, each showing different geological histories prior to c. 1820 Ma (Tyler, 2000). The Western Zone is equivalent to the Hooper Complex (Tyler, 2000). A number of Proterozoic basins are present within the orogen, including the Palaeoproterozoic Moola Bulla, Red Rock, Texas Downs and Revolver Creek Basins, the Mesoproterozoic Osmond, Crowhurst, and Carr Boyd Basins, and the Neoproterozoic Louisa Basin (Tyler, 2000). Orogenic forelands are recognized on either side of the orogen: to the west the Durack Fold Belt affects the southeastern edge of the Speewah and Kimberley Basins, and the Phanerozoic Southern Bonaparte Basin; to the east the Hardman Fold Belt affects rocks of the Osmond Basin, the Mesoproterozoic to Neoproterozoic Victoria River Basin, Neoproterozoic Wolfe Creek Basin, and Phanerozoic Ord Basin. The extension of the Precipice Fold Belt affects the Louisa Basin in the southern part of the orogen.

Granites–Tanami Complex and Arunta Orogen

There has been no re-evaluation of the igneous and metamorphic rocks of the Palaeoproterozoic Granites–Tanami Complex and the Palaeoproterozoic to Mesoproterozoic Arunta Orogen (Fig. 2b) in Western Australia since the publication of GSWA Memoir 3. Extrapolation from the Northern Territory suggests that subdivision into terranes or zones is possible, at least in the Arunta Orogen (Tyler et al., 1998)

Paterson Orogen

Igneous and metamorphic complexes within the Paterson Orogen (Fig. 2b,d) include the Mesoproterozoic Musgrave Complex and the Rudall Complex, which is divided into the Palaeoproterozoic Talbot and Connaughton Terranes and the Mesoproterozoic Tabletop Terrane (Bagas and Smithies, 1998). Subdivision of the Musgrave Complex into terranes may also be possible (Tyler et al., 1998). The Yeneena Basin overlies the Rudall Complex and contains rocks of the possibly Mesoproterozoic Throssell Group and the Neoproterozoic Lamil Group (Bagas et al., 2000). The deformed northeastern margin of the Officer Basin, including the Gibson and Wells Sub-basins (Fig. 2d), and the underlying Gregory Granitic Complex and eastern margin of the Hamersley Basin (Fig. 2b) at the edge of the Pilbara Craton, are also included within the Paterson Orogen.

Capricorn Orogen

The Capricorn Orogen (Fig. 2c) consists of the Palaeoproterozoic igneous and metamorphic rocks of the Gascoyne Complex, together with a number of Palaeoproterozoic and Mesoproterozoic basins. To the west, the Gascoyne Complex forms inliers within the Phanerozoic Southern Carnarvon Basin. To the east the complex underlies much of the Mesoproterozoic Edmund and Collier Basins, and outcrops in the Egerton Inlier and the Coobarra Dome (Fig. 2c). It also underlies the northern part of the Palaeoproterozoic Earaheedy Basin, outcropping in the Imbin Inlier (Fig. 2d). Recent remapping suggests that the Gascoyne Complex probably consists of a number of terranes (Occhipinti et al., 1999).

Along the northern margin of the Yilgarn Craton, the Palaeoproterozoic Yerrida, Bryah, Padbury, and Earaheedy Basins (Fig. 2c,d; Pirajno and Occhipinti, 2000;

Hocking et al., 2000) were previously all included in the 'Nabberu Basin'. Along the southern margin of the Pilbara Craton are the Palaeoproterozoic Ashburton, Blair, Mount Minnie, and Bresnahan Basins. The Palaeoproterozoic Mount James Formation overlies the Gascoyne Complex (Fig. 2c).

The Yarlarweelor Gneiss Complex (Fig. 2c), at the southern margin of the Capricorn Orogen, represents reworking of the northwestern margin of the Yilgarn Craton (Occhipinti et al., 1999). Yilgarn Craton granite–greenstones outcrop within the orogen in the Marymia and Goodin Inliers (Fig. 2c), and the Malmac Dome (Fig. 2d).

At the northern edge of the Capricorn Orogen, the South Pilbara Sub-basin of the Hamersley Basin and the underlying granite–greenstones of the southern Pilbara Craton are deformed by the Ophthalmia Fold Belt (Tyler and Thorne, 1990; Fig. 2a).

The overlying Mesoproterozoic rocks, previously placed within the 'Bangemall Basin', have been separated into the older Edmund Basin and the younger Collier Basin (Martin and Thorne, 2001; Fig. 2c,d). These rocks were not previously included within the Capricorn Orogen, but the Edmund Basin, the ?equivalent Scorpion Group, and much of the Collier Basin were deformed above reactivated structures in the underlying units during the late Mesoproterozoic to early Neoproterozoic Edmundian Orogeny (Martin and Thorne, 2001). Therefore, the deformed Edmund and Collier Basins are here included within the Capricorn Orogen. The Manganese Group (Fig. 2b,d) was deposited in a sub-basin of the Collier Basin over the southeast Pilbara Craton, but was little-deformed by the Edmundian Orogeny, and is not included in the Capricorn Orogen. Deformed sedimentary rocks outcropping in the Ward and Oldham Inliers within the Officer Basin (Fig. 2d) form part of the Capricorn Orogen, and may correlate with the Edmund and Collier Groups (Hocking et al., 2000).

Pinjarra Orogen

The Pinjarra Orogen (Fig. 2c) formed along the western margin of the Yilgarn Craton and is largely buried beneath the Phanerozoic Perth Basin. It outcrops as Mesoproterozoic igneous and metamorphic rocks of the Northampton and Mullingarra Complexes, and Mesoproterozoic to Neoproterozoic igneous and metamorphic rocks of the Leeuwin Complex (Fitzsimons, 2001; Wilde and Nelson, 2001). The Neoproterozoic sedimentary and volcanic rocks of the Moora and Cardup Groups overlie the Yilgarn Craton, and the Neoproterozoic Yandanooka Group overlies the Mullingarra Complex (Tyler et al., 1998; Fig. 2c). The Badgeradda Group may be part of this orogen.

Albany–Fraser Orogen

The Albany–Fraser Orogen (Fig. 2c,d) consists of the Mesoproterozoic igneous and metamorphic rocks of the Biranup and Nornalup Complexes, and Mesoproterozoic metasedimentary rocks of the Stirling Range Formation and Mount Barren Group (Myers et al., 1995a,b). Archaean rocks are reworked within the orogen, with the Munglinup Gneiss representing Archaean igneous and metamorphic rocks reworked within the Biranup Complex (Nelson et al., 1995). The Cowalinya Duplex (Fig. 2d) consists of reworked rocks of the Eastern Goldfields Granite–Greenstone Terrane of the Yilgarn Craton (Myers, 1995b).

Future revisions

Continuing remapping and re-evaluation at various scales, combined with new geophysical, geochemical, isotopic, and geochronological data, will continue to highlight geological complexity and inconsistency, with the need for further changes to nomenclature, modification to boundaries of tectonic units, and subdivision of these units. Revision of the map and database will be ongoing as new results and reinterpretations covering major tectonic units become accepted, with periodic releases incorporating major revisions.

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Are the Neoproterozoic Lamil and Throssell Groups of the Paterson Orogen allochthonous?

by L. Bagas[1], A. Camacho[2], and D. R. Nelson[3]

Abstract

Neoproterozoic (c. 1070–680 Ma) metasedimentary formations of the Lamil and Throssell Groups of the Paterson Orogen have detrital zircon age populations that are compatible with a principal source from the Mesoproterozoic Musgrave Complex, 400 km to the southeast. A subordinate source is Palaeoproterozoic rocks of the underlying Rudall Complex or the Arunta Orogen 400 km to the east. However, predominantly northeastward trending palaeocurrents in the Lamil and Throssell Groups suggest that their source was from the southwest, a region now occupied by the Archaean Pilbara Craton. This apparent contradiction may be explained if these groups and the underlying crystalline Rudall Complex have an allochthonous relationship to the Pilbara Craton. The Rudall Complex may be a western extension of the Arunta Orogen that has been displaced by at least 400 km, from central Australia to its present position, along a series of faults that extend from the Vines–Southwest–McKay Faults to the northern margin of the Amadeus Basin. This displacement followed deposition of the Lamil and Throssell Groups, probably during the c. 550 Ma Paterson Orogeny. These groups may be part of the Neoproterozoic Amadeus Basin, thus enhancing its prospectivity for Telfer-style gold and base metal mineralization.

KEYWORDS: Neoproterozoic, Officer Basin, Amadeus Basin, Lamil Group, Throssell Group, Inindia beds, tectonics, zircon dating.

Regional setting

The Palaeoproterozoic to Neoproterozoic Paterson Orogen is delineated by an arcuate series of gravity highs traditionally known as the Warri Gravity Ridge (Iasky, 1990), which, although less than 100 km wide, extends about 2000 km from the east Pilbara region to central Australia (Fig. 1). Rocks of the orogen are exposed in the northwest along the eastern margin of the Archaean Pilbara Craton, and about 400 km to the southeast within the Musgrave Complex and along the northern margin of the Gawler Craton (Fig. 2). The late Neoproterozoic Paterson Orogeny (probably equivalent to the c. 550 Ma Petermann Orogeny in the Musgrave Complex) deformed the orogen into its present ‘z’-shaped configuration by displacement along a major fault zone that extends eastwards towards the northern margin of the Amadeus Basin (Fig. 1).

During the intracratonic Petermann Orogeny in central Australia, Mesoproterozoic (c. 1180 Ma) granulite- and amphibolite-facies gneisses in the Musgrave Complex were heterogeneously overprinted by easterly trending shear zones that formed under eclogite- to greenschist-facies conditions (Camacho et al., 1997). These high-strain shear zones have both strike-slip and reverse movements and may have formed part of a strike-slip-related, crustal-scale, flower-type structure (Camacho and McDougall, 2000). Such structures can account for the burial and subsequent exhumation of approximately 23 km of the granulite-facies gneisses during the Petermann Orogeny within an interval of about 15 m.y. (Camacho and McDougall, 2000).

The Paterson and Petermann Orogenies were active during a period of global plate reorganization, commonly known as the Panafrican event, involving the initiation of subduction and convergent plate-margin activity during a late phase in the breakup of Rodinia (Cawood and Leitch, 2001). This locally involved transpressional, tensional or transtensional and major strike-slip deformation. During this phase of the breakup, the extension direction was orientated northeast–southwest along the Tasman line, which is the boundary between the Precambrian Mount Isa and Broken Hill Orogens to the west and the Phanerozoic Lachlan and Thomson Fold Belts to the east.

The northwesternmost part of the Paterson Orogen has been subdivided into the Palaeo-proterozoic to Mesoproterozoic Rudall Complex basement and Neoproterozoic sedimentary cover rocks. The latter succession has been

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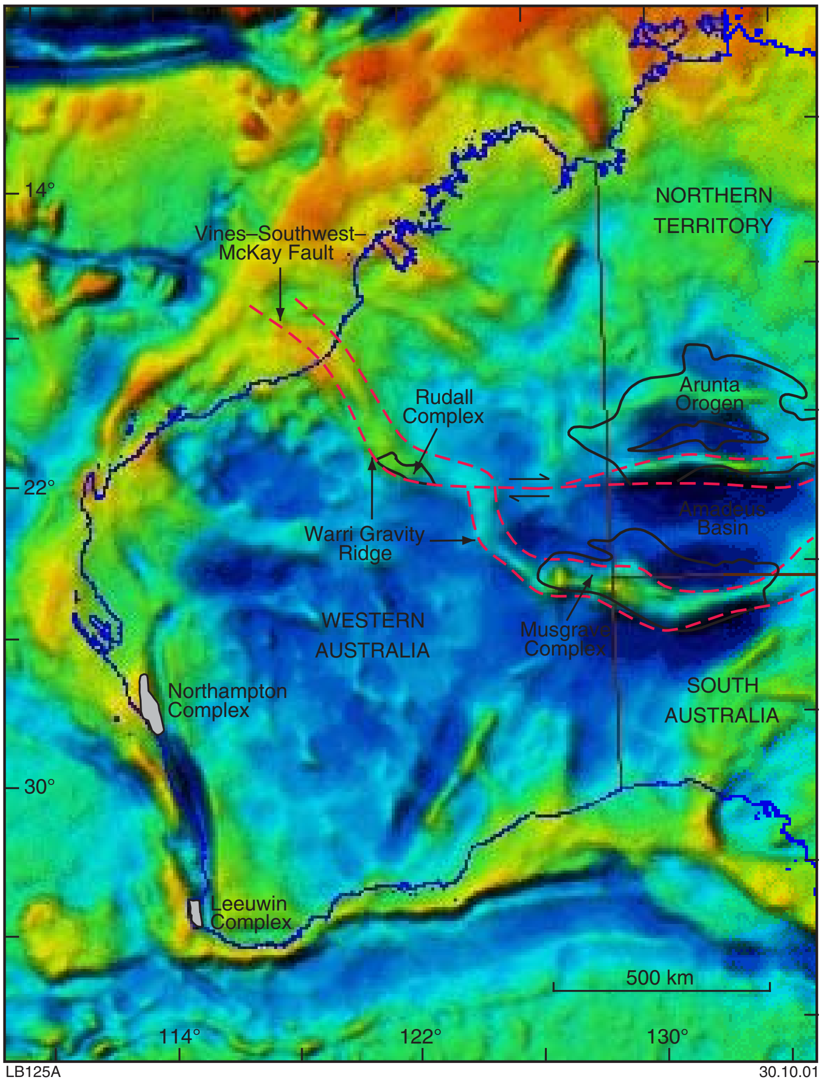

Figure 1. Gravity anomaly map of central and Western Australia (Murray et al., 1997) showing the location of the Warri Gravity Ridge, which approximately outlines the Paterson Orogen

further divided into the Tarcunyah, Throssell, and Lamil Groups (Bagas et al., 1995).

The exposed contact between the Tarcunyah and Throssell Groups is marked by the Vines, Southwest, and McKay Faults, which extend over a distance of 400 km (Fig. 2). These faults are long-lived structures that were last reactivated during the Paterson Orogeny (Williams and Bagas, 1999), and coincide with the southwestern margin of the northern part of the Warri Gravity Ridge (Fig. 1). The faults have both strike-slip and reverse components of movement (Bagas and Smithies, 1998; Hickman and Bagas, 1998; Williams and Bagas, 1999).

On the basis of gravity data, the Throssell and Lamil Groups were juxtaposed along a major concealed northwest-trending fault, which is probably an extension of the long-lived Camel–Tabletop Fault Zone that was also active during the c. 550 Ma Paterson Orogeny (Bagas and Smithies, 1998).

In this paper we constrain the age and provenance of the cover sequences in the northwestern Paterson Orogen to the Neoproterozoic, using sensitive high-resolution ion microprobe (SHRIMP) U–Pb detrital-zircon age distributions, and show that they were not sourced from the neighbouring Archaean terranes.

Cover sequences in the Paterson Orogen

Williams (1990) defined the 'Yeneena Group' as including three geographically separated packages of fluvial–marine sedimentary rocks. These packages have been given 'group' status and, from east to west, are named the Tarcunyah, Throssell, and Lamil Groups (Williams and Bagas, 1999). The 'Yeneena Group' was accordingly redefined as the Yeneena Supergroup to include the Throssell and Lamil Groups, and the Tarcunyah Group was included in the northwestern Officer Basin (Bagas et al., 1995).

Conglomerate, sandstone, siltstone, carbonate, and evaporites of the Tarcunyah Group unconformably overlie the Archaean Pilbara Craton and Mesoproterozoic Bangemall Supergroup (Williams and Trendall, 1998; Fig. 3). Grey and Stevens (1997) and Stevens and Grey (1997) correlated stromatolite and acritarch fossils in the Tarcunyah Group at the base of the northwestern Officer Basin (Bagas et al., 1995) with fossils from Supersequence 1 of the Centralian Superbasin (Walter et al., 1995). Grey and Stevens (1997) identified palynomorph taxa in the Tarcunyah Group, including *Leiosphaeridia* sp., *Synsphaeridium* sp., *Arctucellularia ellipsoidea*, and *Satka* sp. The stromatolites belong to the *Acaciella australica* Stromatolite Assemblage of Grey and Stevens (1997).

The Throssell Group is a sandstone–shale–carbonate succession that unconformably overlies and is locally faulted against the Rudall Complex (Fig. 2). The group is interpreted, on sedimentological grounds, to have been deposited in a shallow-water fluviatile to marine-shelf environment (Bagas and Smithies, 1998; Hickman and Bagas, 1999), probably within a strike-slip basin during the onset of northeast–southwest convergence during the Miles Orogeny (Hickman and Bagas, 1998). No diagnostic stromatolite or acritarch fossils have been identified in the group.

The Lamil Group consists of sandstone, siltstone, and carbonate of the Malu, Puntapunta, and Wilki Formations (Fig. 3; Bagas, 2000). No stromatolite or acritarch fossils have been found in the Lamil Group.

Turner (1982) proposed an intracratonic basin setting for the deposition of the Lamil Group and suggested that deposition occurred at a continental margin or within a failed rift. On the basis of a structural study around the Telfer gold mine (Fig. 2), Harris (1985) suggested that the Lamil Group was deposited in a pull-apart basin developed in an extensional strike-slip system.

Conglomerate, sandstone, shale, and carbonate units exposed just north of the McKay Fault (Fig. 2) were tentatively included in the Throssell Group on the basis of similarities in rock type, structural style, and metamorphic grade (Bagas and Smithies, 1998). However, the stratigraphic position of these units is not clear. Comparisons of detrital zircon age distributions from these units with those of the Coolbro Sandstone (Williams et al., 1976) in the Throssell Group and Malu Formation (Bagas, 2000) in the Lamil Group (Fig. 3) are being undertaken to test these correlations.

Source regions

The precise ages of the Lamil and Throssell Groups are uncertain. Chin and de Laeter (1981) suggested that the former Yeneena Group was deformed at about 1132 ± 21 Ma, which is the Rb–Sr isochron age for pegmatite veining cutting Palaeoproterozoic deformation fabrics in the Rudall Complex. This deformation event has since been referred to as the Miles Orogeny (Bagas and Smithies, 1998).

Exploration programs have since been based on the premise that these rocks are correlatives of the Mesoproterozoic McArthur River Group of northern Australia. Lead-isotope analyses of galena from the Broadhurst Formation of the Throssell Group yielded model-lead ages ranging from c. 940 to 550 Ma (Hickman and Clarke, 1994; Hickman and Bagas, 1998). It was therefore assumed that the Broadhurst Formation must be at least 940 million years old. However, galena lead-model ages are based on the assumption that the isotopic composition of the lead in the galena has evolved along a model ore-growth curve. For ancient rocks (≥3 Ga), deviation

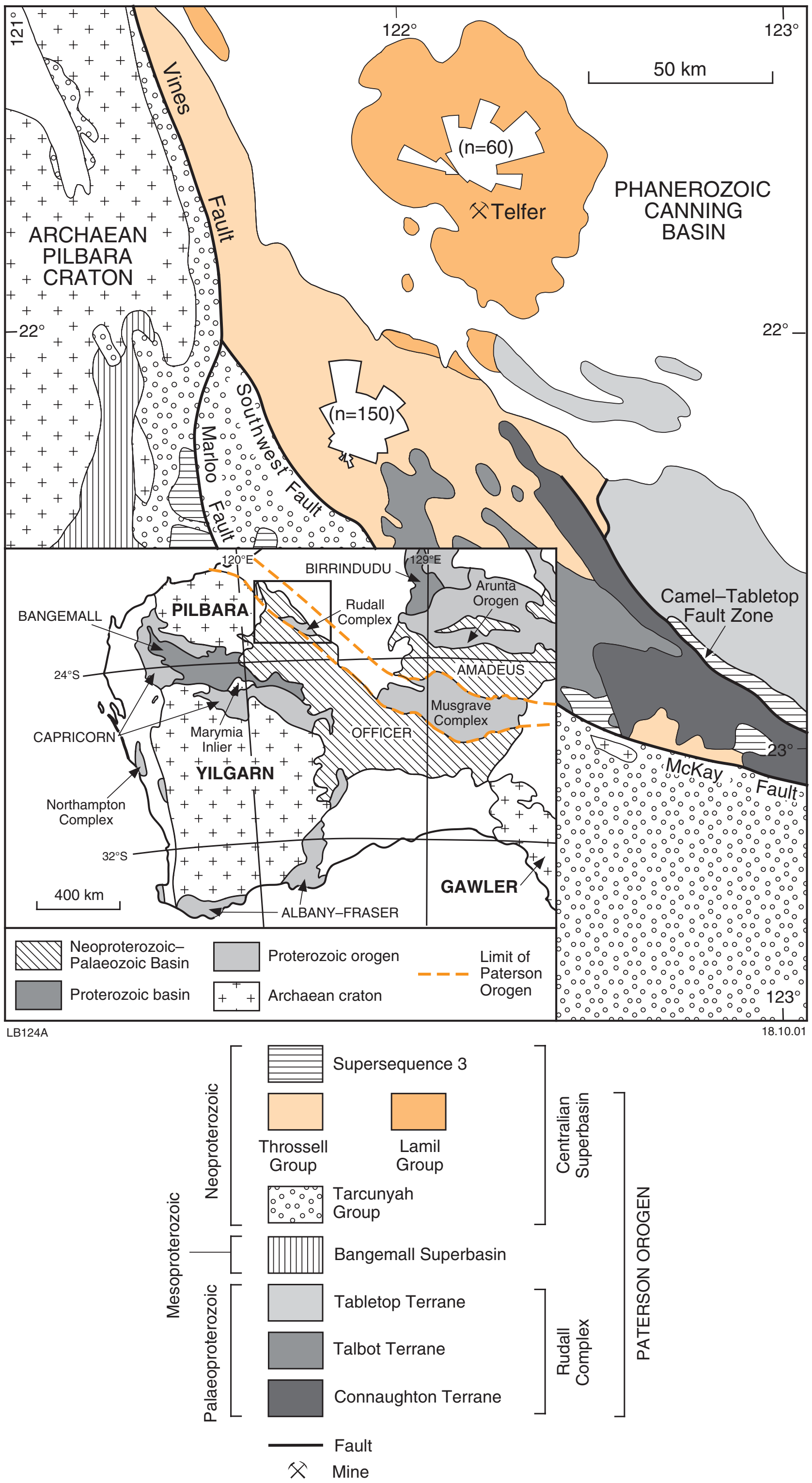

Figure 2. Regional geological setting of the northwestern Paterson Orogen and main tectonic units of central and western Australia. Rose diagrams show palaeocurrent directions for the Lamil and Throssell Groups

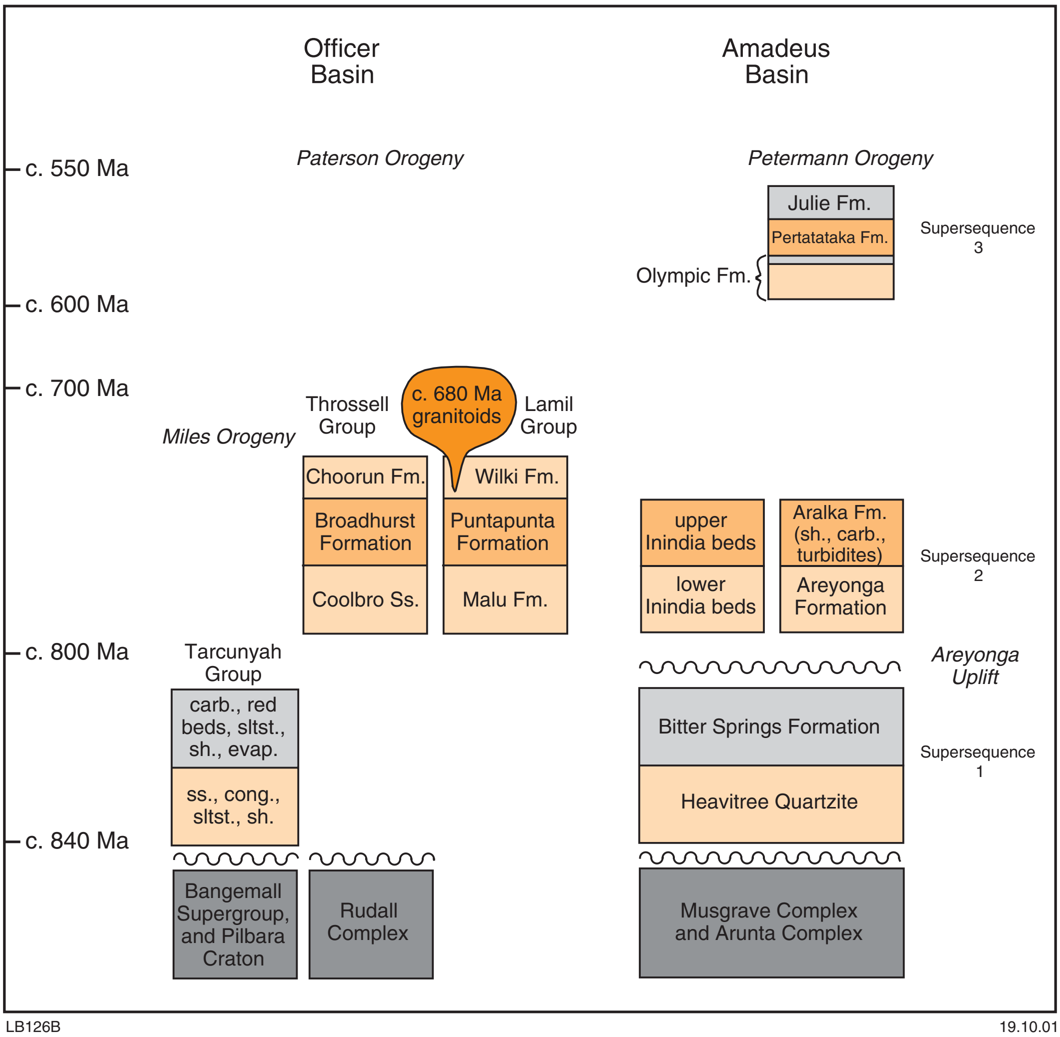

Figure 3. Simplified stratigraphy for the Neoproterozoic sequences of the northwestern Officer Basin, the Throssell and Lamil Groups and the Amadeus Basin (modified after Walter et al., 2000). Abbreviations: carb. = carbonate; cong. = conglomerate; evap. = evaporites; Fm. = Formation; sh. = shale; sltst. = siltstone; ss. = sandstone

from the model ore-growth curve is generally small, but for younger rocks, galena model ages become increasingly unreliable and imprecise. Studies by Anderson (1999) suggested that the lead in the galena from the Broadhurst Formation may have been derived by mixing of primitive and evolved crustal sources. This indicates that model-lead ages determined from the Broadhurst Formation must be regarded as inconclusive.

In an attempt to more accurately determine the depositional age and provenance of the Lamil and Throssell Groups, detrital zircons were analysed from sandstone in the Coolbro Sandstone (GSWA sample 169118) of the Throssell Group, and the Malu Formation of the Lamil Group (GSWA samples 137655 and 137657; Figs 3 and 4).

SHRIMP U–Pb detrital-zircon dates place a maximum depositional age for the Throssell and Lamil Groups at c. 1070 Ma (Fig. 4; Nelson, 2000). Monzogranite and syeno-granite intrusions place a minimum depositional age of c. 678 Ma on the Lamil Group (Dunphy, J., 1999, pers. comm.). Lamil and Throssell Group strata have very similar zircon age distributions (Fig. 4), which suggests the same provenance and possible stratigraphic correlation. Consequently, zircon age distributions collected from these formations have been pooled and compared with those from the Musgrave Complex, the north-western part of the Paterson Orogen, and the Arunta Orogen (Fig. 5).

The zircon ages from the Lamil and Throssell Groups in Figure 5 are most similar to the Musgrave Complex ages. A small number of these zircons have ages that are compatible with derivation from the older Rudall Complex component of the Paterson Orogen and Arunta Orogen. Zircon-bearing rocks of c. 1070 Ma age are known only from the Musgrave Complex (Sun et al., 1996; Camacho et al.,

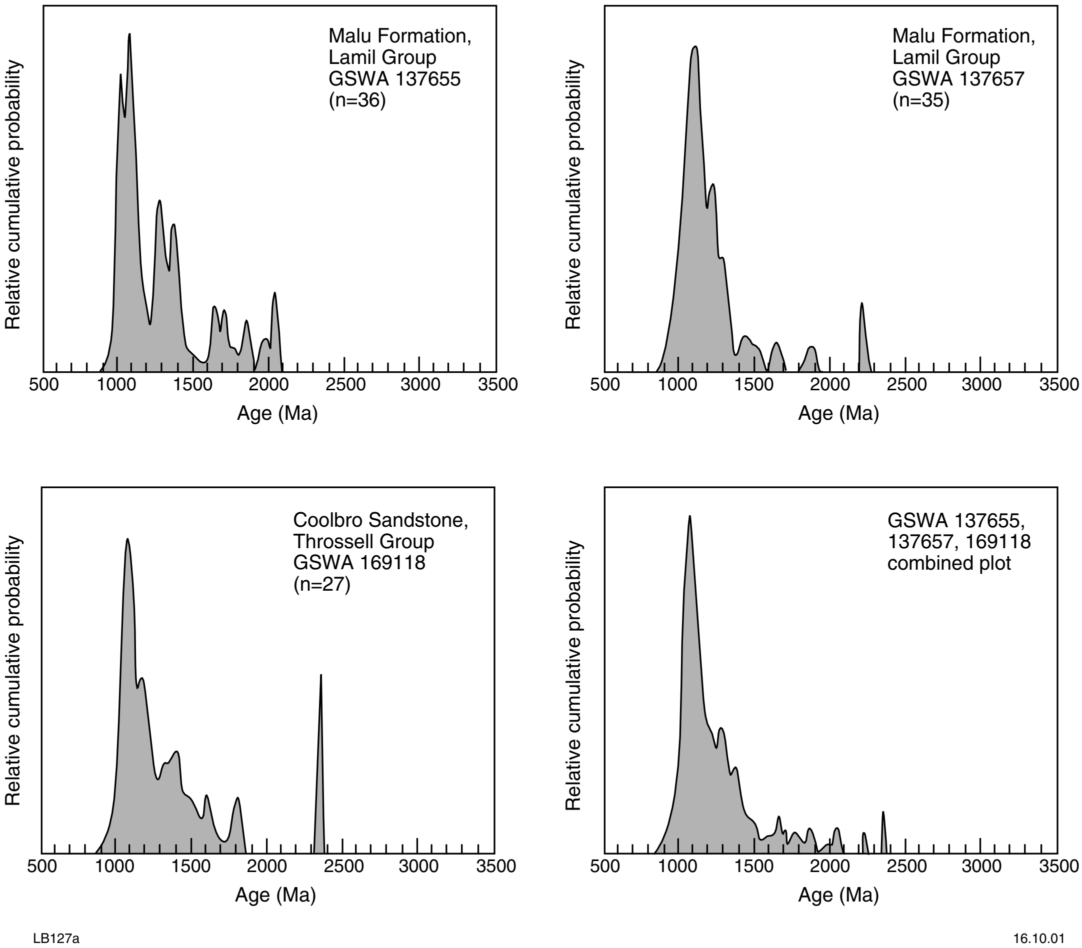

Figure 4. Cumulative probability diagrams of U–Pb SHRIMP ages of detrital zircons in samples GSWA 137655 (n = 36) and 137657 (n = 35) from the Malu Formation (both from MGA Zone 51, 415075E 7597376N) and sample GSWA 169118 (n = 27) from the Coolbro Sandstone (from MGA Zone 51, 414920E 7495289N). Also shown are the pooled detrital zircon components from the Malu Formation and the Coolbro Sandstone

1997; Scrimgeour et al., 1999), the Northampton Complex to the west of the Yilgarn Craton (Bruguier et al., 1999), and the Leeuwin Complex in southwestern Western Australia (Nelson, 1999; Fig. 2).

The Northampton and Leeuwin Complexes are unlikely sources for the Lamil and Throssell Groups, in part because no detrital zircons with ages characteristic of the intervening Yilgarn Craton have been found. In addition, the detrital zircon distribution from the Lamil and Throssell Groups closely resembles that of the lower Inindia beds of the Amadeus Basin (Camacho et al., in prep.; Fig. 6), suggesting a very similar provenance. Walter et al. (2000) included the lower Inindia beds and the Areyonga and Aralka Formations in Supersequence 2 of the Amadeus Basin (Fig. 3).

The lower Inindia beds consist of quartz sandstone, siltstone, and rare dolomite, and overlie a regionally widespread erosional surface on the Bitter Springs Formation. This surface probably represents a depositional hiatus rather than a major deformation event (Lindsay and Korsch, 1991). The lower Inindia beds have been correlated with the tillitic Areyonga Formation in the northern part of the Amadeus Basin (Edgoose et al., 1993). The detrital zircon distributions from the Lamil and Throssell Groups are significantly different to those from units above and below the lower Inindia beds in the Amadeus Basin (Camacho et al., in prep.).

Discussion

The absence of detrital zircons with Archaean ages suggests that the Throssell and Lamil Groups were not derived from the Pilbara and Yilgarn Cratons. In contrast, palaeocurrent data from the Throssell and Lamil Groups (Hickman and Clarke, 1994; Bagas and Nelson, 2001) indicate a source to the southwest, in a region now occupied by the Pilbara Craton (Fig. 2).

There is no evidence that the Pilbara Craton (3600–2400 Ma) was covered by significant thicknesses of Palaeoproterozoic or Mesoproterozoic rocks during the deposition of the Lamil and Throssell Groups, as the sedimentary rocks of the overlying Hamersley Basin are of

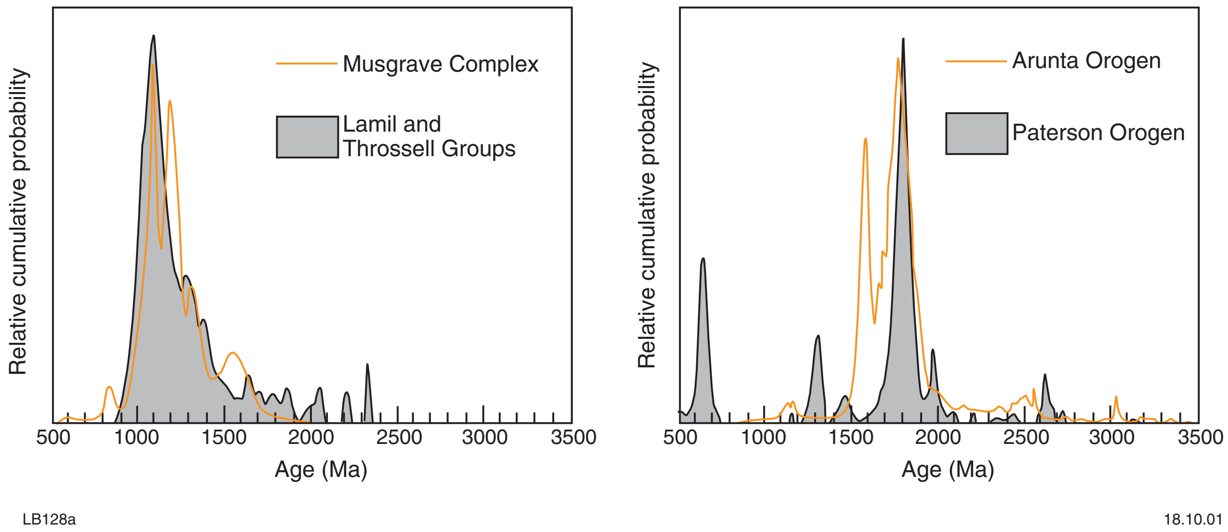

Figure 5. Comparison between relative cumulative probability distributions of pooled detrital zircon components in the Lamil and Throssell Groups and inherited–detrital zircon components of the undifferentiated Paterson Orogen (n = 437; Bagas and Nelson, 2001), Musgrave Complex (n = 1405; Camacho et al., in prep.), and Arunta Orogen (n = 1576; Camacho et al., in prep.)

low metamorphic grade. Furthermore, no felsic, zircon-bearing rocks of c. 1070 Ma age (which is the main zircon population age in the Lamil and Throssell Groups) are known from the Pilbara Craton, Capricorn Orogen, Bangemall Superbasin, or Yilgarn Craton.

The apparent discrepancy between detrital-zircon age populations and palaeocurrent directions can be explained if the Rudall Complex and the younger Throssell and Lamil Groups are considered as a single allochthonous block relative to the Pilbara Craton. The Rudall Complex is interpreted here to represent the western extension of the Arunta Orogen (Fig. 2). The complex was placed into its present relative position by movement of at least 400 km along the Vines–Southwest–McKay fault system in the west and faults along the northern margin of the Amadeus Basin in the east (Fig. 1). Such a large displacement following the deposition of the Lamil and Throssell Groups would have occurred during the c. 550 Ma Paterson Orogeny, which is the youngest recognized orogenic event in the northwestern Paterson Orogen (Hickman and Bagas, 1998). Alternatively, the provenance for both groups could be an unknown area of Mesoproterozoic basement beneath the Officer Basin to the southwest of the Paterson Orogen. Such a provenance, however, would have had to source the same detrital zircon distributions in the lower sandstone units in the Lamil Group, Throssell Group, and the lower Inindia beds.

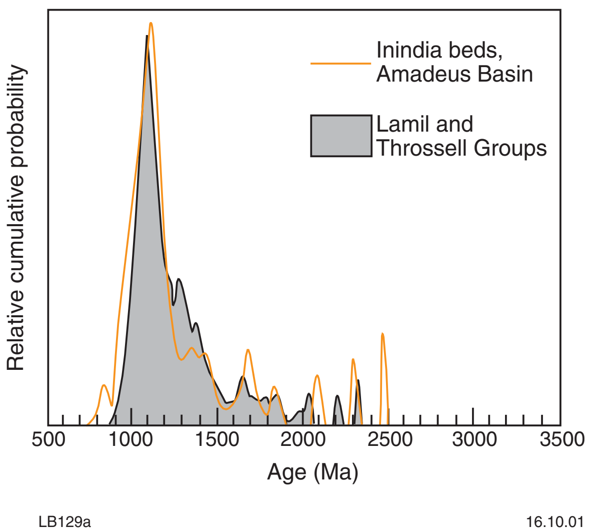

Figure 6. Comparison between relative cumulative probability distributions of pooled detrital-zircon components in the Lamil and Throssell Groups and the lower Inindia beds (n = 50) of the Amadeus Basin (Camacho et al., in prep.)

Further implications of an approximately 400 km displacement of the Rudall Complex and the Lamil and Throssell Groups from central Australia, and the provenance studies using ages for detrital zircons are:

- The Musgrave Complex, Arunta Orogen, and Rudall Complex would have been exposed during the deposition of these groups (and during the deposition of the lower Inindia beds in the Amadeus Basin).
- The Malu Formation of the Lamil Group and the Coolbro Sandstone of the Throssell Group have very similar zircon age populations and may be correlatives.

- The Lamil and Throssell Groups probably correlate with part of Supersequence 2 in the Neoproterozoic Amadeus Basin. This contention is strongly supported by the zircon distributions shown in Figure 6. This has major implications because no Supersequence 2 rocks have been identified in Western Australia until now.
- The term 'Yeneena Supergroup' may no longer be valid.
- The poorly exposed and poorly studied Amadeus Basin in eastern Western Australia, between the Musgrave Complex and Arunta Orogen, could be prospective for Telfer-style gold and copper mineralization, particularly if the Amadeus Basin is intruded by c. 680 Ma granitoids. This assumes that the mineralization at Telfer is at least indirectly related to the granitoids intruding the Lamil Group, as suggested by Rowins et al. (1997).

The hypotheses presented above have major implications for the understanding of the Neoproterozoic geology of central and Western Australia and need to be tested by:

- establishing the stratigraphic relationship between the Neoproterozoic Lamil, Throssell, and Tarcunyah Groups, and the lower and upper Inindia beds;
- establishing $\delta^{13}C$ values for carbonates from the Broadhurst and Puntapunta Formations, which could be tested against curves already published;
- testing for anomalously high $\delta^{34}S$ values in shale of the Broadhurst and Puntapunta Formations, because Supersequence 2 is characterized by anomalous high $\delta^{34}S$ values in shale from the Aralka Formation in the Amadeus Basin (Gorjan et al., 2000). This would also provide support for the Supersequence 2 age if the values were similar;
- comparing the detrital-zircon distributions in the lower sandstone units of the Tarcunyah Group with those in the Lamil and Throssell Groups. If they are similar, it may be inferred that sandstone beds of various ages were derived from the same source regions. However, the lack of significant c. 1070 Ma detrital-zircon populations in the Tarcunyah Group would support the suggestion that the Throssell and Lamil Groups are allochthonous relative to the Pilbara Craton. It is anticipated that at least the lower sandstone units in the Tarcunyah Group have an Archaean detrital-zircon population because they unconformably overlie the Pilbara Craton (Williams and Trendall, 1998).

This preliminary work on the Lamil and Throssell Groups shows that a provenance study combining palaeocurrent and detrital-zircon analyses can be a powerful tool in unravelling the geological history of complex structural terranes such as the Paterson Orogen. This signals the possibility of being able to use the age-distribution plots to fingerprint units in structurally complex regions.

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Foraminiferal assemblages in the Fossil Cliff Member of the Holmwood Shale, northern Perth Basin

by D. D. Ferdinando[1]

Abstract

Three parasequences are present within the type section of the Sakmarian (Early Permian) Fossil Cliff Member of the Holmwood Shale, with each parasequence consisting of a basal shale overlain by calcareous beds. Three distinct foraminiferal assemblages have been recorded from the member. The first is dominated by agglutinated foraminifera mainly from the genera *Hyperammina* and *Ammodiscus*. This assemblage remains consistent throughout each of the three parasequences. The second and third foraminiferal assemblages are characterized by calcareous hyaline and calcareous porcellaneous species respectively, with *Howchinella woodwardi*, *Lunucammina triangularis*, and *Protonodosaria irwinensis* dominating the calcareous hyaline assemblage, and *Hemigordius schlumbergeri*, *H. voltus*, *Calcitornella stephensi*, and *Trepeilopsis australiensis* characteristic of the calcareous porcellaneous assemblage. These calcareous foraminiferal assemblages are found in association with each other. The lowest parasequence is dominated by the calcareous hyaline assemblage, the middle parasequence is a mixture of the two assemblages, and the top parasequence is dominated by the calcareous porcellaneous assemblage. This variation is interpreted as an overall marine regression within the Fossil Cliff Member, in addition to minor eustatic sea-level variations and a change from a high terrigenous input to impoverished terrigenous input.

KEYWORDS: Permian, foraminifera, Fossil Cliff Member, eustacy, biostratigraphy.

Introduction

The type section of the Fossil Cliff Member of the Holmwood Shale lies on the northern branch of the Irwin River at latitude 28°55'S and longitude 115°33'E, 450 km north of Perth and 32 km northeast of Mingenew (Fig. 1). Exposed as a cliff face in the Irwin River valley, this section is approximately 17 m thick and comprises three parasequences, consisting of alternating beds of fossiliferous limestone, sandy siltstone, and shale, forming a progradational parasequence set. The maximum exposed thickness of the Fossil Cliff Member is at Beckett's Gully, 5 km to the southwest, where Playford et al. (1976) measured a 45 m-thick section. The Fossil Cliff Member lies at the top of the Holmwood Shale, and is conformably overlain by the High Cliff Sandstone (Playford et al., 1976), although at the type section the contact between the High Cliff Sandstone and the Fossil Cliff Member is not exposed.

The upper part of the Holmwood Shale lies within the *P. confluens* palynomorph biozone (Backhouse 1998), and the Fossil Cliff Member falls within the *P. pseudoreticulata* palynomorph biozone (Foster et al., 1985), indicating a Sakmarian (Early Permian) age for the member. The presence of the goniatites *Juresanites jacksoni*, *Uraloceras irwinensis*, and *Metalegoceras kayi* lower in the formation provides further support for this age (Glenister and Furnish, 1961).

Stratigraphy of the Fossil Cliff Member

The Fossil Cliff Member consists of three parasequences forming a progradational parasequence set. Each parasequence consists of basal, black, finely laminated shale overlain by muddy calcarenite beds, the uppermost bedding surface of which marks the parasequence boundary (Fig. 2). Above the third parasequence is a bed of sandy siltstone to siltstone. The Fossil Cliff Member contains a diverse fossil assemblage, dominated by bryozoa and productid and spiriferid brachiopods, particularly in the second and third parasequences. The thickness of the shale beds at the base of each parasequence decreases up the parasequence set, and the exposed top-section of the third parasequence grades into a coarsening-upward sandstone bed. The coding scheme used for the facies outlined below follows that used by Le Blanc Smith and Mory (1995) and is summarized in Table 1.

Terrigenous facies

The shale lithofacies (*Al*) at the base of each parasequence consists of a

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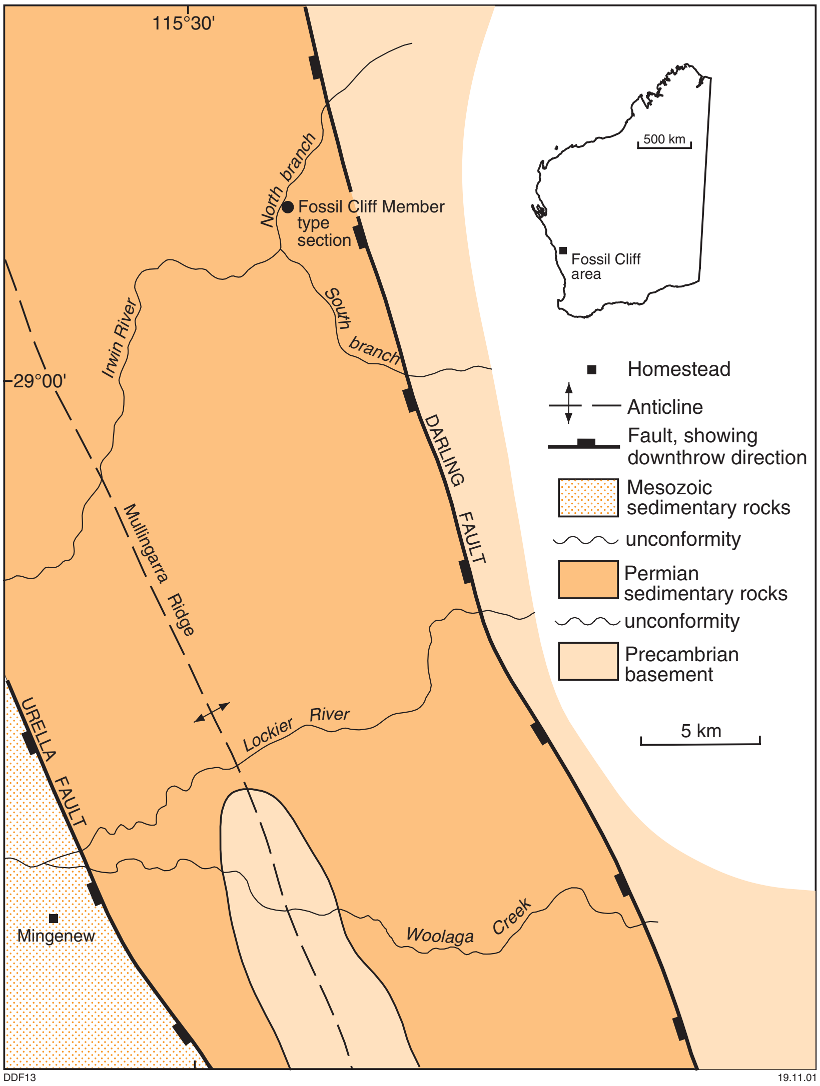

Figure 1. Locality diagram for the Fossil Cliff Member type section

very fine grained, dark-grey to black micaceous mud, which displays thin, planar laminae up to 5 cm apart, but generally about 3–5 mm apart, with bed thicknesses ranging from 20 cm to 4 m. Numerous veinlets of late diagenetic gypsum, subparallel to bedding planes, are present throughout the shale facies in addition to bands of jarosite formed from the alteration of pyrite during diagenesis.

Table 1. Facies coding scheme used in this paper

Terrigenous facies	
Al	Laminated shale and siltstone
(S/A)b	Bioturbated muddy fine-grained sandstone
Sm	Massive, coarse-grained sandstone
Calcareous facies	
(L/A)bs	Bioturbated, shelly, muddy calcarenite
Lbs	Bioturbated, shelly, indurated calcarenite to wackestone

The sandstone lithofacies (*Sm* and *(S/A)b*) above the third parasequence ranges in composition from quartzwacke to subarkose, and in part has an arenitic composition. This facies is only found overlying the third parasequence, and is presumably conformably overlain by the High Cliff Sandstone. The grainsize of the sandstones increases upward, from muddy fine-grained sandstone (*(S/A)b*) to well-sorted, coarse-grained quartz arenite (*Sm*) at the top of the exposure. Fossil assemblages from this lithofacies include a dwarfed fauna of fragmented bryozoa and agglutinated foraminifera.

The shale and sandstone lithofacies contains a sparse fossil assemblage consisting mainly of small crinoid ossicles, fenestrate bryozoan moulds, the thin-shelled chonetid brachiopod *Neochonetes (Sommeria) pratti*, and agglutinated foraminifera, dominated by *Ammodiscus* and *Hyperammina*. The delicate macrofossils are commonly preserved in the shale as external moulds along bedding planes. In the shaly facies the foraminiferal fauna is diverse, with more than 18 species recognized. They are predominantly agglutinated forms, although rare specimens of the nodosariid foraminifera *Protonodosaria irwinensis* and *Howchinella woodwardi* are also present.

Calcareous facies

Within the calcareous beds of the Fossil Cliff Member, three facies are evident. The first is a friable, buff, muddy calcarenite (*(L/A)bs*) containing an assortment of fragmented and intact bioclasts of varying sizes and shell strengths. The muddy calcarenite beds are generally 10–60 cm thick.

The second calcareous lithofacies is a brown, poorly sorted, friable packstone with 20–40% matrix (*(L/A)bs*). Bioclasts in this facies appear to have undergone very little transportation because fragile components such as bryozoa, crinoid stems, and thin-shelled brachiopods are generally intact. Beds of this facies are 10–30 cm thick and display planar bedding surfaces.

The third calcareous lithofacies is an indurated grey wackestone (*Lbs*) containing bioclasts similar in style and preservation to those of the second facies, with 40–65% matrix. The facies outcrops as distinctly lenticular beds, which extend laterally up to 20 m and are 20 to 50 cm thick.

In the calcareous beds of all parasequences, the fossil assemblage is extremely diverse, with more than

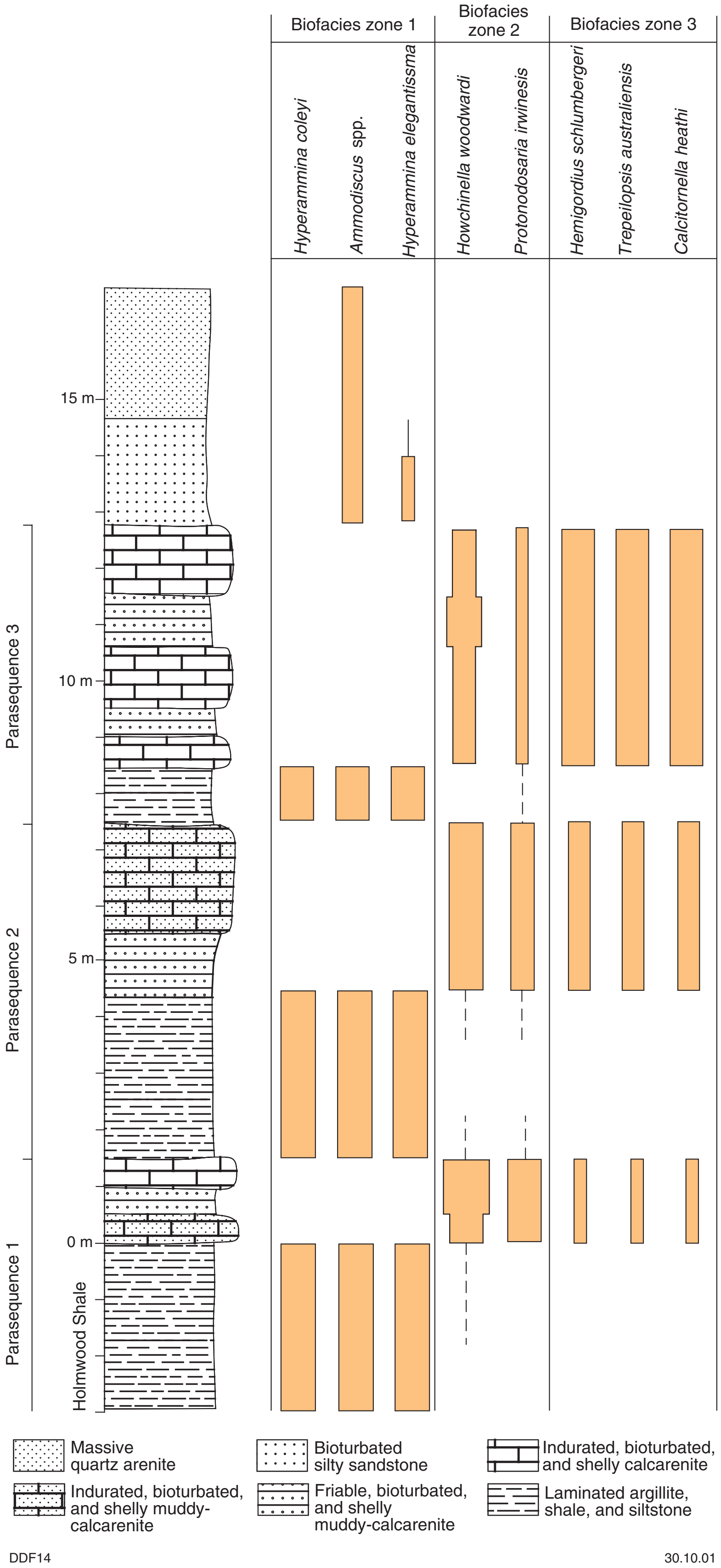

Figure 2. Stratigraphic section of the Fossil Cliff Member at its type locality showing relative abundances of selected species from the three biofacies zones identified

70 species present (Playford et al., 1976). The majority of identified fossils are brachiopods, notably productids and spiriferiids. Other groups present include solitary rugose corals, crinoids, blastoids, bryozoa, bivalves, gastropods, ammonoids, nautiloids, nodosariid and milioliid foraminifers, ostracodes, and rare trilobites. The abundance of the various species and groups in the carbonate beds differs between the parasequences. The significant variations are a decrease in abundance of spiriferiid brachiopods upwards through the member, coinciding with a decrease in the abundance of rugose corals, and an increase in the abundance of species of productid brachiopods upwards through the sequence.

Foraminiferal assemblages within the parasequences

Within the Fossil Cliff Member, the foraminiferal assemblages can be divided into two broad types. The first is an agglutinated foraminiferal assemblage (biofacies zone 1) within the facies *Al*, *Sm*, and *(S/A)b*, and the second is a calcareous assemblage, restricted to the calcareous facies *Lbs* and *(L/A)bs*. The calcareous assemblage can be further subdivided into a calcareous hyaline assemblage (biofacies zone 2) and a calcareous porcellaneous assemblage (biofacies zone 3). These three assemblages broadly correspond to the palaeoecological assemblages listed by Crespin (1958) for the Permian foraminifera of Australia, and their abundances within the member are illustrated in Figure 2. Transitions between the agglutinated and calcareous assemblages are sharp, and strongly controlled by palaeoenvironmental conditions.

Biofacies zone 1

Species within the agglutinated foraminiferal assemblage of biofacies zone 1 (Table 2) include *Ammodiscus nitidus*, *A. multicinctus*, *Hyperammina callytharraensis*, *H. coleyi*, *H. elegans*, *Trochammina subobtusa*, *Thuramminoides sphaeroidalis*, and *Glomospirella nyei*. There is little change in species diversity within the individual beds of lithofacies *Al*, although in lithofacies *(S/A)b* and *Sm* there is a marked decrease in the abundance of slender, tubular genera such as *Hyperammina*, with more robust forms such as *Trochammina subobtusa*, *Ammodiscus nitidus*, *A. multicinctus*, and *Thuramminoides sphaeroidalis* being dominant.

Biofacies zones 2 and 3

The calcareous lithofacies, *Lbs* and *(L/A)bs*, of the Fossil Cliff Member contains a varied fauna of calcareous foraminifera, which are divided into two main biofacies assemblages: the calcareous hyaline assemblage of biofacies zone 2 and the calcareous porcellaneous assemblage of biofacies zone 3 (Table 2). These two biofacies are intermixed, but biofacies zone 2 is the dominant element in the lowermost parasequence and, to a lesser degree, also in the middle parasequence, whereas biofacies zone 3 is dominant in the uppermost parasequence.

The characteristic species of biofacies zone 2 are *Howchinella woodwardi*, *Lunucammina triangularis*, and *Protonodosaria irwinensis*. Within biofacies zone 3 the characteristic species are *Hemigordius schlumbergeri*, *H. voltus*, *Calcitornella heathi*, *C. stephensi*, and *Trepeilopsis australiensis*. Transitions between these two biofacies are gradual, and there is a large degree of intermixing of assemblages within lithofacies *Lbs* and *(L/A)bs*.

Foraminiferal palaeoecology of the Fossil Cliff Member

Foraminifera of the Fossil Cliff Member display two main trends in their distribution. The first is a change based on palaeoenvironmental conditions, from biofacies zone 1 in lithofacies *Al* at the base of each parasequence, to the assemblages dominated by biofacies zone 2 and biofacies zone 3 in the carbonate-rich lithofacies *Lbs* and *(L/A)bs* at the top of each parasequence. The other palaeoecological trend is the dominance of biofacies zone 2 in carbonate beds of the lower parasequences, whereas biofacies zone 3 dominates the calcareous foraminiferal assemblages in the carbonate beds of the uppermost parasequence.

Table 2. Key foraminiferal species from each biofacies zone of the Fossil Cliff Member

Biofacies zone 1	
Hippocrepinella biaperta Crespin, 1958	*?Thuramminoides pusilla* (Parr), 1942
Thuramminoides sphaeroidalis Plummer, 1945	*Teichertina teicherti* (Parr), 1942
Sacammina arenosa (Crespin), 1958	*Hyperammina callytharraensis* Crespin, 1958
Hyperammina coleyi Parr, 1942	*Hyperammina elegans* (Cushman and Waters), 1928
Hyperammina elegantissima Plummer, 1945	*Kechenotiske hadzeli* (Crespin) 1942
Ammodiscus multicinctus Crespin and Parr, 1941	*Ammodiscus nitidus* Parr, 1942
Glomospirella nyei Crespin, 1958	*Ammobaculites woolnoughi* Crespin and Parr, 1941
Trochammina subobtusa Parr, 1942	*Tetrataxis conica* Ehrenberg, 1854
Biofacies zone 2	
Howchinella woodwardi (Howchin), 1895	*Lunucammina triangularis* (Chapman and Howchin), 1905
Protonodosaria irwinensis (Howchin), 1895	*Protonodosaria tereta* (Crespin), 1958
Vervilleina? grayi (Crespin), 1945	
Biofacies zone 3	
Calcitornella elongata Cushman and Waters, 1928	*Calcitornella heathi* Cushman and Waters, 1928
Calcitornella stephensi (Howchin), 1894	*Trepeilopsis australiensis* Crespin, 1958
Hemigordius schlumbergeri (Howchin), 1895	*Hemigordius voltus* Palmieri, 1985

Biofacies zone 1 consists of agglutinated foraminifera that require low amounts of dissolved carbonate in the seawater relative to the calcareous species, and are associated with bryozoa and brachiopod species that are sessile filter-feeders requiring low levels of dissolved oxygen (McKinney and Jackson, 1989). Oxygen levels during deposition of this shale facies were probably dysaerobic, and the substrate was in a reducing environment, with large amounts of terrigenous sediment washed into the area. The presence of intact, delicate fenestrate bryozoa in addition to the thin, delicate test walls of the agglutinated foraminifera, particularly those of the *Hyperammina*, suggests that the water energy was extremely low, with the substrate well below the storm wave base, probably in a protected embayment.

Biofacies zone 2 is found in conjunction with a rich and diverse macrofauna, containing sessile filter-feeding spiriferiid brachiopods and solitary rugose corals. The association of biofacies zone 2 with these faunal elements indicates that oxygen, nutrient, and dissolved carbonate levels in the water were high, the substrate was within the photic zone, and the water turbidity was low. The preservation of many intact specimens of delicate bryozoa, crinoids, and brachiopods suggests that water energy was also low, although there is some fragmentation of the fauna. This may indicate that water levels were generally below wave base, with fragmentation of the fauna on the substrate during infrequent storms.

Biofacies zone 3 dominates the upper parasequence. The species from this assemblage are generally robust and possess thick calcareous tests. They are associated with a rich and diverse macrofauna, which is generally fragmented in nature, lacks sessile filter-feeding groups such as rugose corals and spiriferiid brachiopods, and the brachiopod fauna is dominated by thick-shelled brachiopod species such as *Elivina hoskingae*. The palaeoenvironment of this biofacies is very similar to that of biofacies zone 2, with the exception that the water energy conditions were much higher. This biofacies was probably deposited in a near-shore environment, such as a carbonate shoal.

Conclusions

The two main facies within the Fossil Cliff Member, a faunally impoverished terrigenous-dominated facies and a faunally diverse and abundant calcareous-dominated facies, were deposited during eustatic marine regression. The foraminiferal assemblages within the member closely reflect varying palaeoenvironmental conditions, that is the gradual changes in water depth and energy due to the marine regression and the abrupt change from terrigenous- to calcareous-dominated deposition. The changes from relatively deep-water, dysaerobic deposition to carbonate beds in shallower aerobic conditions, which thicken upwards through the member, probably reflect amelioration of the climate during the Early Permian. This change is possibly associated with eustatic rebound as ice sheets retreated globally (e.g. Miller and Eriksson, 2000).

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High-quality oil-prone source rocks within carbonates of the Silurian Dirk Hartog Group, Gascoyne Platform, Western Australia

by K. A. R. Ghori[1]

Abstract

Geochemical evaluation of core samples from the Silurian Dirk Hartog Group indicates that thin oil-prone shaly to micritic source beds are interbedded within carbonate facies of the Upper Silurian Coburn Formation. These laminated organic-rich source beds are recognized only in those wells in which the Dirk Hartog Group has been fully drilled. Such source beds have fair to excellent hydrocarbon-generating potential and are rich in oil-prone kerogen. Excellent source beds in drillhole Yaringa East 1 (deepening) have an organic richness of up to 7.43% total organic carbon, potential yield (S_1+ S_2) of up to 38.1 mg/g, and hydrogen index of up to 505. Good source beds are also recognized in Coburn 1 and GSWA Woodleigh 2A. Detailed geochemical analyses confirm that oil-prone organic facies are of high quality and were deposited in reducing environments. In Coburn 1, GSWA Woodleigh 2A, and Yaringa East 1 (deepening), the maturity of these source beds ranges from immature to within the early oil-generative window. To the northwest, the Silurian section is more mature as it is buried more deeply, and it is within the peak oil-generative window in Quobba 1 and Pendock 1. For those wells the available geochemical data are based on cuttings and side-wall cores, implying that good oil-source beds may have been missed because continuous core was not available.

KEYWORDS: Petroleum, source rock, geochemistry, Silurian, Dirk Hartog Group, Gascoyne Platform, Western Australia.

Introduction

Many petroleum systems throughout the world were charged by Silurian source beds (Klemme and Ulmishek, 1991), from both siliciclastic- and carbonate-dominated successions. For clastic-dominated rocks, the best examples are organic-rich graptolitic shales of the Lower Silurian succession in north Africa (Boote et al., 1998) and the Middle East (Alsharhan and Nairn, 1997). In the Palaeozoic basins of north Africa, these source beds are considered to have generated 80–90% of the more than 46 billion barrels of oil discovered. An example of source beds in a Silurian carbonate-dominated succession is within Niagaran reefs of the Michigan Basin (North America). The source beds are laminated inter-reef deposits, and are considered to be the primary source rock for oil in the Niagaran reefs, even though they are characterized by relatively low organic richness, of typically 0.3 – 0.6% total organic carbon (TOC; Gardner and Bray, 1984).

This paper documents Silurian source beds within carbonate-dominated rocks of the Southern Carnarvon Basin in Western Australia. The succession is known only from the Gascoyne Platform, where shaly to micritic source beds have excellent to fair hydrocarbon-generating potential, with maturity ranging from immature to within the early oil-generative window.

The stratigraphy, distribution, and lithology of the Silurian Dirk Hartog Group has been discussed in many papers, the most significant of which are Hocking et al. (1987), Gorter et al. (1994), Mory et al. (1998), Mory and Yasin (1998), and Yasin and Mory (1999). The group spans the entire Silurian period, and has been divided into the Ajana, Yaringa, and Coburn Formations (in ascending order; Mory et al., 1998). Lithologically, the group is dominated by shallow-marine dolomitic lithofacies, with evaporitic anhydrite and halite facies and minor siliciclastic lithofacies. These facies probably extended over most of the Gascoyne Platform during the Silurian. They are best studied in the fully cored intervals drilled in GBH 2 by CRA Exploration in 1980, ND 001 and 002 by BHP in 1993, Coburn 1 by Knight Industries in 1997, Woodleigh 2A by the Geological Survey of Western Australia (GSWA) in 1999, and Yaringa East 1 (deepening) by Britannia Gold NL in 2000 (Fig. 1). Other wells in the region contain only short cored intervals, so the

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remainder of these sections can be evaluated only from cuttings and side-wall cores.

Source-rock evaluation

Petroleum source rocks within the Silurian Dirk Hartog Group are here evaluated from 179 TOC, 51 Rock-Eval pyrolysis, eight pyrolysis gas-chromatography (PGC), 11 extract gas-chromatography and mass-spectrometry (GC-MS), and 26 organic petrology analyses of cuttings and core samples. Figure 1 shows the locations of wells from which the Dirk Hartog Group was sampled and analysed, as well as the depth range of the group. Table 1 lists analytical data for TOC and Rock-Eval pyrolysis of core samples having more than 0.5% TOC and 1.0 mg/g pyrolysate yield.

Source-rock richness

Organic richness and pyrolysate yields (S_2) from Rock-Eval pyrolysis are used to identify source rocks.

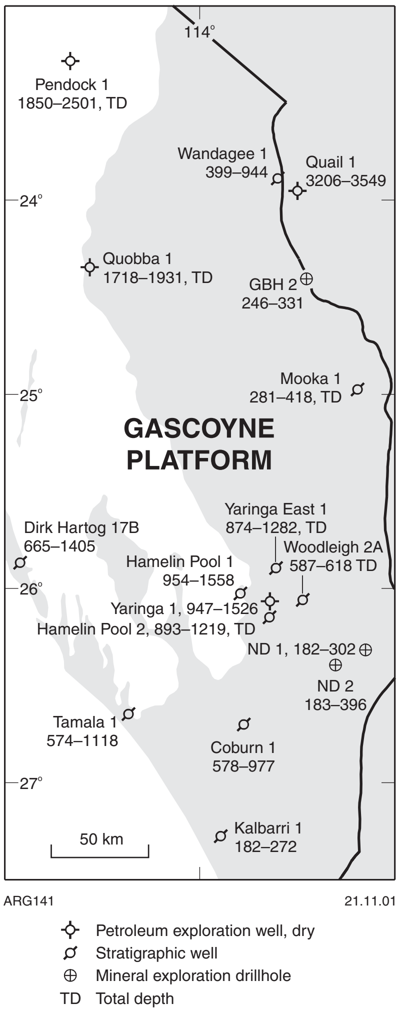

Figure 1. Well locations and depths in metres at which the Dirk Hartog Group was intersected. Shaded area represents land.

Samples with a TOC range of 0.5 to 1.0% and a S_2 yield of 1–5 mg/g of rock are classified as having fair source potential; 1.0 – 2.0% TOC and 5–10 mg/g S_2 as good; 2.0 – 4.0% TOC and 10–20 mg/g S_2 as very good; and more than 4.0% TOC and over 20 mg/g S_2 as excellent (Baskin, 1997). Figure 2a shows the samples with fair to excellent hydrocarbon-generating potential.

The Rock-Eval parameter hydrogen index (HI) is related directly to the atomic hydrogen to carbon ratio (H/C) and indicates the hydrogen-richness of kerogen or organic facies of rocks, whereas T_{max} is a maturity indicator that represents the temperature at which the maximum amount of S_2 hydrocarbons is generated. These parameters (HI and T_{max}) show that the source rocks are rich in oil-prone organic facies of type II kerogen and are immature to early mature (Fig. 2b).

Source-rock quality

Detailed geochemical analyses, including PGC and GC-MS, supplement TOC and Rock-Eval pyrolysis in evaluating source-rock quality, which increases with hydrogen-richness of source-rock organic facies.

Table 1. Total organic carbon (TOC) and Rock-Eval pyrolysis data for core samples having more than 0.5% TOC and 1.0 mg/g pyrolysate yield

Well	*Depth (m)*	*TOC (%)*	*T_{max} (°C)*	*S_1*	*S_2*	*S_3*	*S_1+S_2*	*PI*	*HI*	*OI*	*%Ro*	*Mi*	*Ma*	*R*	*M*
BHP ND 001	191.9	0.70	411	0.16	1.23	0.21	1.39	0.12	176	30	–	–	–	–	–
Coburn 1	606.2	1.23	426	0.86	4.23	0.67	5.09	0.17	344	54	–	–	–	–	–
Coburn 1	623.9	2.06	424	0.86	5.43	0.08	6.29	0.14	264	4	0.65	0.42	0.92	18	Tb
Coburn 1	633.5	0.51	427	0.29	1.36	1.59	1.65	0.18	267	312	–	–	–	–	–
Coburn 1	839.4	0.53	429	0.19	1.05	1.19	1.24	0.15	198	225	–	–	–	–	–
Coburn 1	853.2	0.59	433	0.26	1.30	1.03	1.56	0.17	220	175	–	–	–	–	–
Mooka 1	339.0	0.61	414	0.09	1.25	0.38	1.34	0.07	205	62	0.53	0.45	0.65	5	Dv
Yaringa East 1	967.7	0.67	436	0.31	2.84	0.36	3.15	0.10	424	54	–	–	–	–	–
Yaringa East 1	973.6	1.27	432	0.71	4.98	0.78	5.69	0.12	392	61	–	–	–	–	–
Yaringa East 1	976.2	7.43	428	4.97	33.11	0.40	38.08	0.13	446	5	0.61	0.47	0.82	10	Tb
Yaringa East 1	980.9	0.66	428	0.18	1.64	1.02	1.82	0.10	248	155	–	–	–	–	–
Yaringa East 1	1 066.1	0.69	429	0.31	1.92	0.14	2.23	0.14	278	20	–	–	–	–	–
Yaringa East 1	1 161.0	2.02	424	1.35	5.79	1.42	7.14	0.19	287	70	0.62	–	–	1	Tb
Yaringa East 1	1 185.6	0.62	430	0.30	1.93	1.73	2.23	0.13	311	279	–	–	–	–	–
Yaringa East 1	1 201.6	1.10	433	0.62	5.55	1.25	6.17	0.10	505	114	–	–	–	–	–
Yaringa East 1	1 242.5	0.83	427	0.91	3.13	0.83	4.04	0.23	377	100	–	–	–	–	–
Woodleigh 2A	591.5	1.49	436	0.12	3.82	0.68	3.94	0.03	256	46	–	–	–	–	–
Woodleigh 2A	592.4	2.24	431	0.23	8.22	0.83	8.45	0.03	367	37	0.50	0.40	0.58	28	Dv

NOTES:
Dv = detrovitrinite
HI = hydrogen index
M = maceral
Ma = maximum reflectance
Mi = minimum reflectance
OI = oxygen index
PI = production index
R = number of readings
%Ro = mean reflectance
S_1 = existing hydrocarbons (HC)
S_2 = pyrolytic yield (HC)
S_3 = organic carbon dioxide
S_1 + S_2 = potential yield
Tb = thucholitic bitumen
T_{max} = temperature of maximum pyrolytic yield (S_2)
TOC = total organic carbon

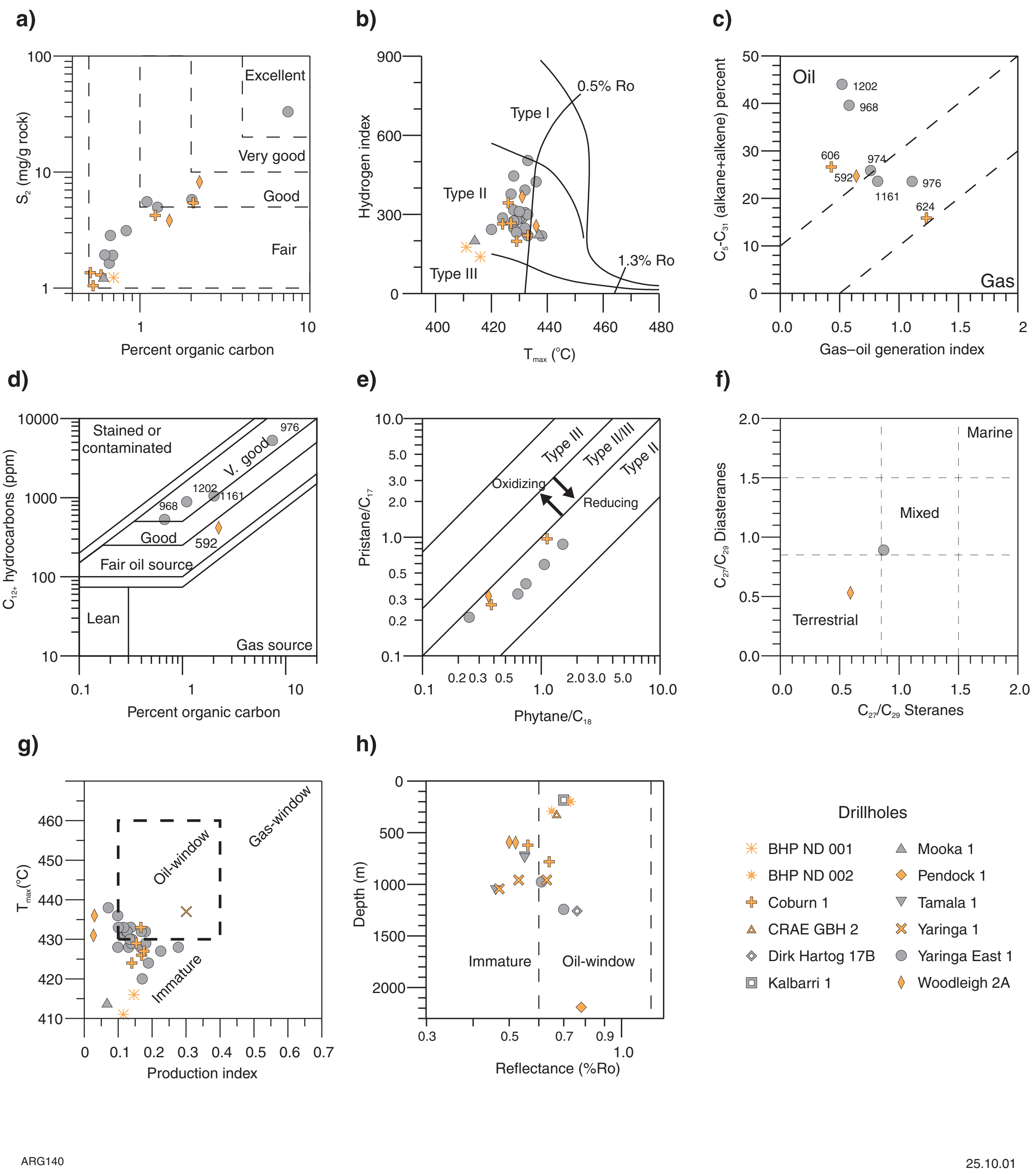

Figure 2. Geochemical interpretative diagrams for the Dirk Hartog Group: a) petroleum-generating potential; b) Rock-Eval kerogen typing; c) pyrolysis gas-chromatography kerogen typing; d) source-rock rating as a function of C_{12+} hydrocarbon yields versus organic richness; e) kerogen type and depositional environment from gas-chromatography biomarkers; f) organic matter type from gas chromatography – mass spectrometry biomarkers; g) maturity from Rock-Eval; h) maturity from organic petrology

Pyrolysis gas-chromatography

Pyrolysis gas-chromatography provides a detailed molecular characterization of kerogen to evaluate its oil- versus gas-generating potential (Larter, 1985). The type and amount of liquid hydrocarbons yielded, and the calculated PGC parameters of gas–oil generation index (GOGI; C_1–C_5/C_{6+}) and C_5–C_{31} saturated (alkanes) and unsaturated (alkenes) hydrocarbons (Fig. 2c), confirm that these source rocks are rich in oil-prone kerogen as indicated by Rock-Eval pyrolysis.

Gas chromatography – mass spectrometry

Extract concentration, composition, and the distribution of biomarker alkanes can be used to evaluate source richness, quality, maturity, and environment of deposition. However, caution is required in interpretation because these parameters also depend on maturity and the organic facies present (Peters and Moldowan, 1993). The Gascoyne Platform samples have a high yield of heavy hydrocarbons (C_{12+}) as a function of their organic richness and maturity, and are rated as fair to very good oil-prone source rocks (Fig. 2d). The organic-rich sample (2.24% TOC) from 592.4 m in GSWA Woodleigh 2A is rated as a fair source rock because it is the least mature among the analysed samples, and thus has the lowest heavy hydrocarbons (C_{12+}) yield as a function of its low maturity.

Biomarkers identified by GC and GC–MS of the saturated hydrocarbons are indicators of organic facies, depositional environment, thermal maturation, and biodegradation, and also can be used for source-rock characterization. For the Dirk Hartog Group, GC biomarker parameters include pristane to phytane values of 0.80 – 1.33, pristane to n-C_{17} of 0.21 – 0.97, and phytane to n-C_{18} of 0.25 – 1.52. These parameters indicate that the oil-prone organic facies were deposited in a reducing environment. Low pristane to phytane ratios in source rocks typically indicate reducing conditions as observed in the group, whereas the pristane/n-C_{17} and phytane/n-C_{18} values indicate oil-prone organic facies with type II kerogen (Fig. 2e). The GC–MS biomarkers for samples from GSWA Woodleigh 2A and Yaringa East 1 (deepening) indicate that the organic matter is terrestrial and mixed terrestrial to marine, respectively (Fig. 2f).

Source-rock maturity

Rock-Eval and organic petrology data indicate that maturation ranges from immature to within the early oil-generative window (Fig. 2g,h). The maturity of the Dirk Hartog Group increases northward, probably due to increasingly deeper burial; it was intersected at 182 m in the southernmost well (Kalbarri 1) and at 1850 m in the northernmost well (Pendock 1; Fig. 1). The source beds in Yaringa East 1 (deepening), for example, are more deeply buried compared to source beds in Coburn 1 and Woodleigh 2A, and are noticeably more mature (Table 1).

Discussion

Excellent to good oil-prone source rocks identified in the Dirk Hartog Group, although thin, are significant in evaluating the prospectivity of the region. The carbonate succession contains fine-grained, laminated to banded, shaly to micritic, organic-rich source beds up to a metre thick. In comparison, shaly beds within the more clastic parts of the Dirk Hartog Group are poor in organic matter. To date, Silurian source beds in the region have been recognized only in fully cored wells, because identification of source rocks is more difficult in carbonate-dominated facies than in clastic-dominated facies. The organic-rich beds indicate euxinic conditions during deposition, either through restricted water circulation or by vertical stratification of the water column. Globally, there are many effective source rocks in carbonate-dominated facies of Silurian and Devonian age (Palacas, 1984; Gardner and Bray, 1984; Powell, 1984). Previous GSWA studies have also documented the deposition of thin but excellent source beds within the carbonate-dominated facies of the Devonian Gneudna Formation from GSWA Gneudna 1 and Barrabiddy 1A (Ghori, 1998, 1999).

The recognition of excellent to good oil-prone source beds within carbonate-dominated rather than clastic-dominated facies should influence exploration strategies within the region as well as directing future source-rock studies to such facies.

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Assembly of a composite granite intrusion at a releasing bend in an active Archaean shear zone

by R. H. Smithies[1] and D. C. Champion[2]

Abstract

The Wallareenya extensional jog developed between c. 2955 and 2940 Ma at a releasing bend in the northeast-trending Tabba Tabba Shear Zone, in the Archaean Pilbara Craton of northwestern Australia. The extensional jog, or pull-apart, formed during transtensional movement along the shear zone, and was simultaneously filled by a sequence of magmas ranging in composition from gabbro to monzogranite. Magmas were emplaced through fractures that broadly conform to Riedal R1 and R2, and P fracture directions and segment the area into diamond-shaped blocks. Some of these fractures formed conduits that were used by up to five magma generations. Space for emplacement was created primarily through active extension within the evolving jog, and the emplacement age of the magmas decreases systematically westwards, tracking a paralleled migration in the main focus of extension. Away from fractures and magma conduits, horizontal sheeting shows that the magmas spread out laterally at suitable horizons such as the contact with overlying metasedimentary country rocks.

KEYWORDS: Pilbara, Western Australia, igneous intrusion, emplacement mechanism, Archaean

Introduction

A close spatial relationship has been recognized between granitic rocks and crustal-scale strike-slip shear zones and fault systems that are thought to act both as migration pathways and sites of magma emplacement (Hutton, 1988; D'Lemos et al., 1992; McNulty et al., 1996). Dilational domains, such as extensional jogs, or pull-apart structures, en echelon P-shear arrays, tension gashes, extensional duplexes, and fault splays have all been indicated as potential emplacement sites within such shear zones and fault systems (Speer et al., 1994; McNulty et al., 1996). Emplacement into these sites is thought to be passive, with simultaneous dilation and magma filling (Brown, 1994), with other processes such as ballooning by magma flow and stoping playing a local and less important role. However, the specific process by which space for magma emplacement is created is commonly obscured through a lack of preserved growth history (McNulty et al., 1996).

This study documents an Archaean composite intrusion that was emplaced into an extensional jog at a releasing bend of the crustal-scale Tabba Tabba Shear Zone, in northwestern Australia (Fig. 1). This well-exposed region has undergone only minor deformation after the development of the shear zone. A combination of geochronological studies (Nelson, 2000, 2001) and well-constrained field relationships permits an evaluation of the interrelated structural and magmatic history of the extensional jog, including magma emplacement mechanisms.

Geological setting

The Tabba Tabba Shear Zone forms the southern margin of the eastern part of the Archaean Mallina Basin and separates that basin from older crust to the southeast (Fig. 1). The east-northeasterly trending basin is one of the youngest components of the Pilbara granite–greenstone terrain and developed as an intracontinental rift basin through at least three depositional cycles or basin-forming events between c. 2970 and 2935 Ma (Smithies et al., 1999, 2001).

Preserved basin margins are either unconformities or fault zones. The northeast-trending Tabba Tabba Shear Zone can be traced for approximately 100 km, but becomes increasingly obscure, both in outcrop and in its geophysical expression, to the southwest, where it appears to terminate into a series of splays within the rocks of the Mallina Basin.

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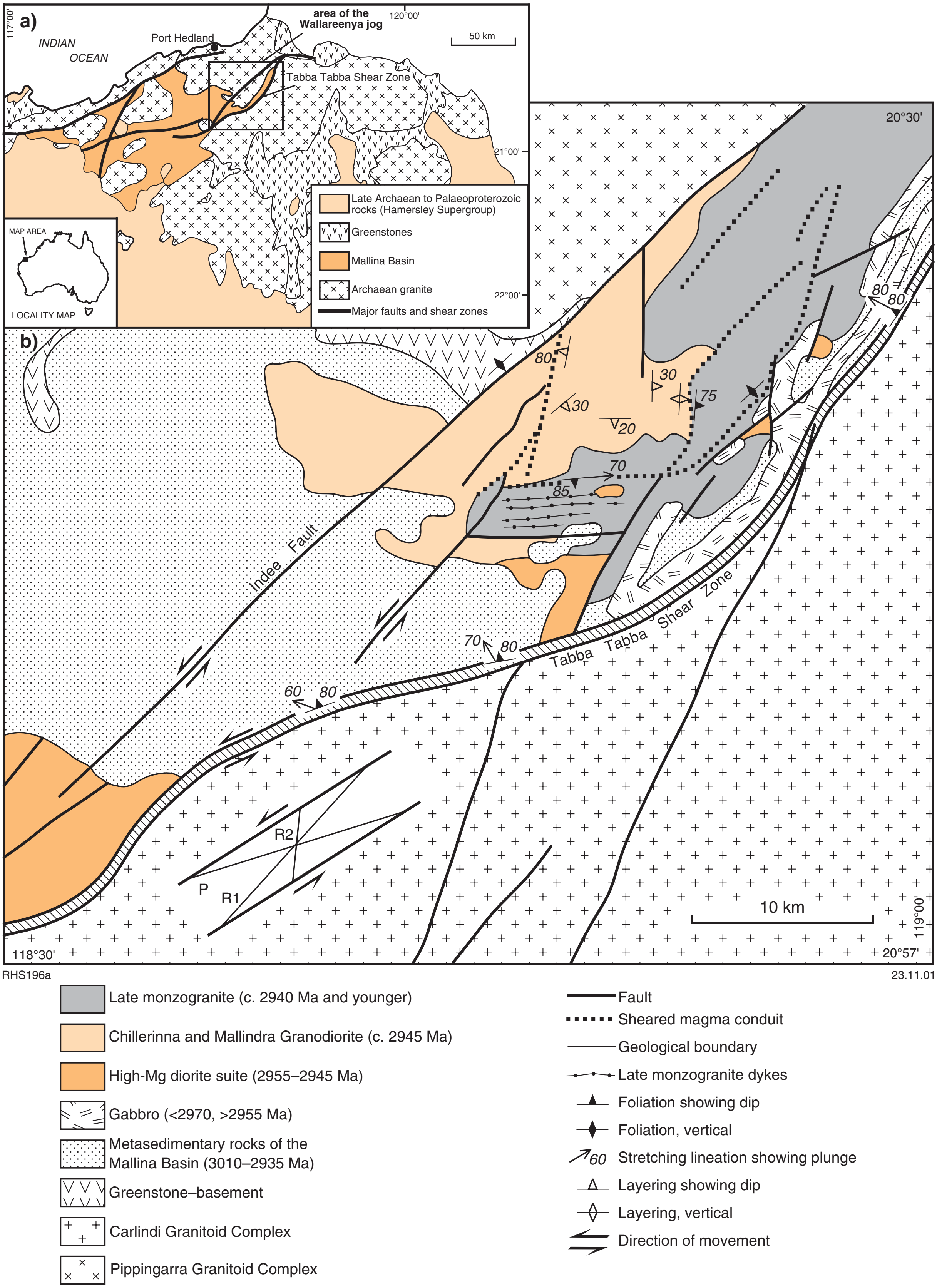

Figure 1. a) Simplified geological map of the Pilbara Craton, showing the area of the Wallareenya jog; b) Geological map of the Wallareenya area, showing the major feature of the Wallareenya jog and summary structural data. Common fracture orientations within an idealized brittle layer are also shown

Between c. 2955 and c. 2935 Ma the emplacement of locally voluminous intrusions in and marginal to the Mallina Basin was influenced by fault or shear zones or both (Smithies and Champion, 2000). Magma compositions changed significantly and systematically throughout this period from gabbroic to dioritic and grano-dioritic to granitic (Smithies and Champion, 2000). Stress regimes associated with the developing basin also changed throughout this period, from renewed extension during the 2950–2935 Ma depositional phase, to north–south compression and folding, which began at about c. 2935 Ma. The full range of this magmatism is present in the Wallareenya area (Fig. 1), adjacent to a bend in the Tabba Tabba Shear Zone.

Tabba Tabba Shear Zone

In the eastern part of the Mallina Basin, the Tabba Tabba Shear Zone forms a northeast-trending and steeply northwest dipping zone up to 3 km wide (Fig. 1). It comprises a belt of strongly foliated clastic rocks, chert, banded iron-formation, granitoids, and ultramafic to mafic intrusive and extrusive rocks, with an anastomosing system of locally mylonitized rock. The shear zone is distinctly sinusoidal in plan view, and stretching lineations, rotated phenocrysts, and S–C fabrics show that the latest major movement was dominantly normal (northwest-side down), but with a significant sinistral component. This movement reflects a generally transtensional regime, which has been correlated with the c. 2950–2935 Ma depositional phase of the Mallina Basin (Smithies et al., 2001).

Normal and sinistral movement along the sinusoidal shear zones caused extension at releasing bends (i.e. an extensional jog or pull-apart structure), and these areas appear to have been exploited by intruding magmas. Intrusive rocks account for approximately two-thirds of the exposed area within the Wallareenya extensional jog. These rocks are well exposed and detailed mapping provides a clear picture of the large-scale fault structures relating to this jog (Fig. 1). The extensional jog comprises an extensively faulted zone up to 15 km wide between the Tabba Tabba Shear Zone and the northeast-trending Indee Fault. The well-developed pattern of faults and dykes within the jog broadly conforms to Riedal R1 and R2, and P fracture directions, segmenting the area into diamond-shaped blocks, each roughly parallel to the overall orientation of the jog. The development of strong internal post-full crystallization fabrics within the granites is restricted to zones that parallel fracture planes; generally, the rocks are only weakly deformed or show well-developed magmatic foliations, consistent with passive emplacement. In the section below we outline the magmatic evolution of the Wallareenya jog.

Early gabbro

The earliest intrusive rocks within the Wallareenya jog form elongate bodies of gabbro. Although not directly dated, they intruded younger than 2970 Ma siliciclastic rocks of the Mallina Basin and were intruded by rocks of the 2955–2945 Ma Pilbara high-Mg diorite suite. The gabbro is exposed adjacent to the Tabba Tabba Shear Zone, in the southeastern part of the jog. The two elongate bodies continue northeastward, subparallel to the shear zone (Fig. 1). The gabbro outcrop forms what appears to be two consecutive doubly plunging folds. However, this structure actually resulted from the structurally controlled emplacement of the gabbro into northeast and east-northeast fractures that mark the earliest recognizable stages in the development of the Wallareenya jog.

Pilbara high-Mg diorite suite

Rocks of the Pilbara high-Mg diorite suite intrude into and to the west of the gabbro (Fig. 1). One of the diorites has been dated at 2954 ± 4 Ma (Nelson, 2000), consistent with the age of the suite elsewhere, which has been well constrained to between c. 2955 and c. 2945 Ma (Smithies and Champion, 2000). In the Wallareenya area, intrusions within the high-Mg diorite suite range from diorite to tonalite and granodiorite, and appear to have used some of the same fractures along which the gabbro intruded. West and south of the Wallareenya jog, this suite forms a linear belt of subvolcanic plutons that parallels the axis of the Mallina Basin for about 150 km. This linear pattern of intrusions suggests that the transport and emplacement of magmas within this belt was structurally controlled, probably by early basin-forming faults in the basement.

Chillerinna Granodiorite

The biotite–hornblende granodiorite to monzogranite phases of the Chillerina Granodiorite were emplaced into the Wallareenya jog at c. 2945 Ma (two samples dated at 2946 ± 3 and 2945 ± 2 Ma; Nelson, 2001). Closely related to these rocks in both composition and age are hornblende–biotite gabbro to granodiorite and tonalite intrusions collectively referred to here as the Mallindra Granodiorite. The Chillerina and Mallindra Granodiorites outcrop west of the early gabbro and the high-Mg diorite suite (Fig. 1). Both contain abundant evidence for structural controls on emplacement, in particular, shear zones that were active during (and after) emplacement.

In the central-western part of the granodiorite body, plagioclase porphyritic granodiorite has been affected by north-northeasterly trending faulting. Away from the fault, plagioclase alignment defines a magmatic flow-foliation that parallels the fault plane, suggesting that this structure may have controlled magma emplacement. Closer to the fault, this foliation is progressively overprinted by a post-magmatic (post-full crystallization) schistosity that also parallels the fault plane.

In the central portion of the Chillerinna Granodiorite, large pendants of metasedimentary rocks belonging to the Mallina Basin show that only the roof of the pluton is exposed. Importantly, while large roof-pendants are preserved, metasedimentary xenoliths are not abundant, suggesting that stoping was not the primary means of creating space for the intruding magmas.

Throughout the central portion of the Chillerinna Granodiorite, the granodiorite has been intruded, on a

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Figure 2. a) Layering or banding produced by intrusion of leucocratic monzogranite into granodiorite. The scale of layering varies within a single outcrop from centimetre to millimetre scale (lens cap is ~5 cm in diameter); b) Finer scale layering than that shown in (a). Here, the layering has been chaotically folded; however, neither monzogranite or granodiorite shows significant mineral elongation or flattening, or other evidence for significant deformation in the solid state (lens cap2 is ~5 cm in diameter)

centimetre to millimetre scale, by sheets of coarse-grained and locally K-feldspar porphyritic leucocratic biotite monzogranite, with locally entrained schlieric wisps of host granodiorite (Fig. 2a). Sensitive high-resolution ion microprobe (SHRIMP) U–Pb dating of zircon (Nelson, 2001) indicates that the monzogranite (2940 ± 2 Ma) is only marginally younger than the granodiorite (2945 ± 2 Ma). These sheets collectively form up to 40% of the outcrop, producing a conspicuous layering. This layering is locally chaotically folded (Fig. 2b), but neither rock shows evidence for strong solid-state deformation, and so the folding almost certainly reflects synmagmatic movements within the magma chamber. More typically, the layering dips gently (<30°) but does not follow any regional or local pattern of deformation (Fig. 1). It possibly parallels an undulating upper contact between the granodiorite and its metasedimentary host rocks.

Along the eastern margin of the Chillerinna Granodiorite, the granodiorite–monzogranite layering steepens into a near-vertically dipping shear zone (Fig. 1). The trend of this shear zone varies from north to northeast, conforming to common fracture sets within the Wallareenya jog. Deformation within the shear is heterogeneous. Many areas are characterized by a well-developed schistosity, with a steep (>70°) stretching lineation that indicates a predominant vertical component of movement. However, the steeply dipping layering is locally only weakly deformed and preserves a magmatic fabric produced by flow-attenuated schlieren of granodiorite in monzogranite. In some unstrained zones within the shear zone, weakly to undeformed, but flow-foliated, monzogranite contains abundant xenoliths derived from numerous distinct phases of rocks of the high-Mg diorite suite and the Chillerinna Granodiorite. In a single outcrop, up to five individual magma batches can be recognized, sometimes including xenoliths in xenoliths and both sheared and unsheared varieties. We suggest that this shear zone is a magma conduit that was repeatedly exploited during evolution of the jog.

Late monzogranite

Highly leucocratic and variably K-feldspar porphyritic monzogranite has been intruded throughout the Wallareenya jog, crosscutting all previous lithologies (Fig. 1). SHRIMP U–Pb zircon ages range from 2940 ± 3 to 2928 ± 6 Ma (Nelson, 2001). The Petermarer Monzogranite is the largest and most homogeneous body, comprising massive to strongly flow-foliated monzogranite that is petrographically and chemically very similar to the monzogranite sheets intruding the central portion of the Chillerinna Granodiorite. Southeast of the Chillerinna and Mallindra Granodiorites, the late monzogranites form a composite intrusion of fine- to medium-grained rocks, locally containing abundant xenoliths of gabbro, granodiorite, monzogranite, and metasedimentary rock.

There are sheared magma conduits similar to the one described from the Chillerinna Granodiorite. Again, these shears are at or near the contacts between discrete intrusive bodies, with dominantly east-northeasterly and northeasterly trending orientations. In the southern part of the Wallareenya jog, fine-grained monzogranite also forms a series of east-northeasterly trending dykes.

Discussion

The present expression of the Tabba Tabba Shear Zone is the result of movement that postdated the main (2970–2955 Ma) depositional phase of the Mallina Basin. The relationship between the development of the Wallareenya jog and the emplacement history of magmas indicates that the shear zone was active, at least periodically, from before 2955 to c. 2945 Ma. Dating of a strongly foliated late monzogranite (Nelson, 2001) that has intruded the south-eastern edge of the Tabba Tabba Shear Zone extends the period of activity to at least 2940 ± 3 Ma. This period coincides with the latest depositional event within the Mallina Basin, estimated to have occurred between 2950 and 2935 Ma, based on the ages of detrital zircons and the age of syntectonic granite intrusion into the western parts of the Mallina Basin. The presence of gabbro and high-Mg diorite shows that the Tabba Tabba Shear Zone provides a control on the migration and emplacement of mantle-derived magmas (e.g. Smithies and Champion, 2000) and is of crustal scale.

The Wallareenya jog is a dilational jog or pull-apart structure that formed at a releasing bend in the Tabba Tabba Shear Zone during transtensional movement defined by north-block-down and sinistral displacement. The diamond-shaped jog comprises a remarkably continuous and well-developed mosaic of smaller, northeast-orientated diamond-shaped segments, defined by a network of faults, dykes, and sheared magma conduits that conform to Riedal R1 and R2, and P fracture directions (Fig. 1). The developing jog provides a mechanism that is interpreted to have controlled the emplacement of magmas, and can account for the distinct westward temporal migration in the emplacement age of magmas from <2970–2955 Ma gabbro to the 2955–2945 Ma high-Mg diorite suite to the c. 2945 Ma Chillerinna Granodiorite (Fig. 3). This relationship records a progressive westward migration in the main focus of extension within the jog, culminating in the development of the Indee Fault, and provides evidence that active extension within the jog provided the primary mechanism for creating space for simultaneous, passive magma emplacement. There is no evidence that processes such as stoping provided significant space for magma emplacement.

Magma conduits preserved within the Wallareenya jog have been used by several (up to five) separate magma batches, and have also been active zones of deformation throughout this multiple intrusive history. The clearest evidence for this is the presence of multi-generation xenolith suites, including xenoliths in xenoliths, showing a range in the degree of post-full crystallization deformation. Conduits that include xenoliths of gabbro, high-Mg diorite, Chillerinna Granodiorite, and late monzogranite have been exploited by migrating magma, at least periodically, for up to 15 m.y.

The Wallareenya jog is a well-exposed example of fracture-controlled emplacement of magmas into dilational zones related to major active shear zones. The pronounced and gently dipping layering produced by multiple sheeting of the Chillerinna Granodiorite by slightly younger monzogranite indicates that the magmas spread out laterally from these near-vertical conduits to be emplaced as sheet complexes at suitable horizons, such as the contact between the granodiorite and overlying metasedimentary rocks.

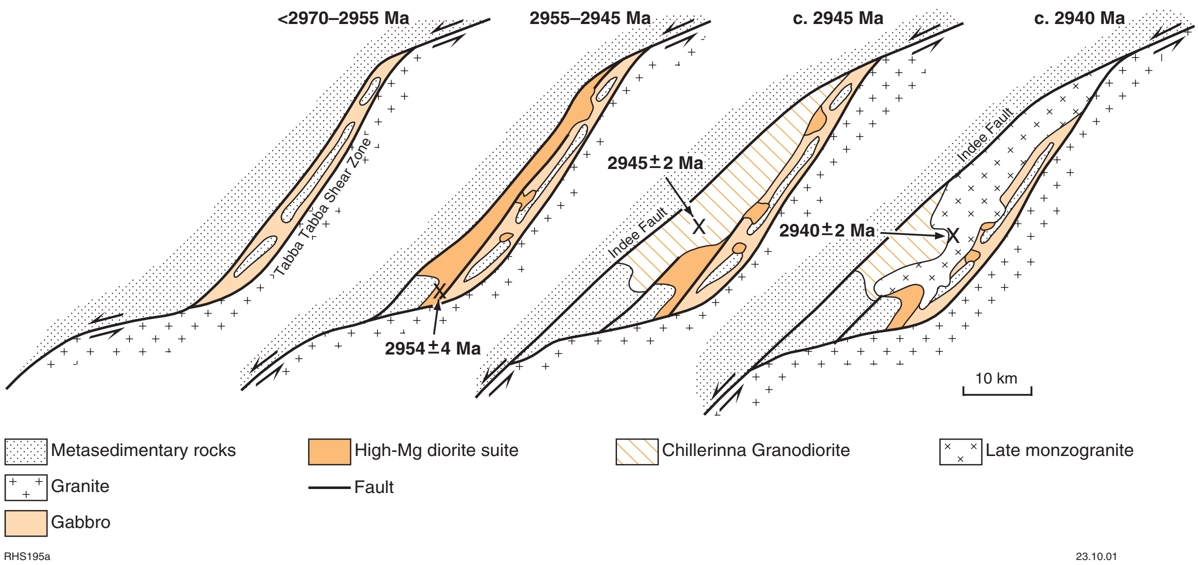

Figure 3. Sketch showing the interpreted geological evolution of the Wallareenya jog

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New occurrences of 'strings of beads' in the Bangemall Supergroup: a potential biostratigraphic marker horizon

by K. Grey[1], I. R. Williams[1], D. McB. Martin[1], M. A. Fedonkin[2], J. G. Gehling[3], B. N. Runnegar[4], and E. L. Yochelson[5]

Abstract

Enigmatic bedding-plane markings, commonly referred to as 'strings of beads', were initially described from three localities in the Mesoproterozoic Stag Arrow Formation of the Manganese Group, Bangemall Supergroup. They were compared to similar structures in the Belt Supergroup, Montana, USA, that were recently named *Horodyskia moniliformis*. The 'beads' have since been discovered at more localities in the upper Bangemall Supergroup (Collier and Manganese Groups). They are both abundant and geographically widespread and appear to be narrowly constrained stratigraphically. Despite uncertainties surrounding their biological affinities, they appear to be a significant biostratigraphic marker.

KEYWORDS: Bangemall Supergroup, Collier Group, Manganese Group, Stag Arrow Formation, Backdoor Formation, biostratigraphy, problematica, enigmatic fossils, 'strings of beads', Proterozoic

Introduction

The 'strings of beads' structures are enigmatic fossils first discovered in Western Australia by I. R. Williams in 1985 in the Mesoproterozoic Stag Arrow Formation of the Manganese Group (Bangemall Supergroup). Grey and Williams (1990) described the structures from three localities on the ROBERTSON[6] 1:250 000 sheet (Fig. 1; Table 1). They compared them to the 'strings of beads' earlier described from the Belt Supergroup, Montana, USA (Horodyski, 1982). In 1990, I. R. Williams and K. Grey discovered several new localities containing 'strings of beads' in the Backdoor Formation of the Collier Group, on the COLLIER, MOUNT EGERTON, and TUREE CREEK sheets (Fig. 1; Table 1).

In August 2000, further field studies were carried out by the authors (except K. Grey) at the known localities to try to establish the palaeobiological affinities of the beads and determine the extent of their similarity to *Horodyskia moniliformis* from the Belt Supergroup of Montana. Subsequent investigation by D. Martin has shown that the beads are abundant in the area around localities 7 and 8 (Fig. 1). The new localities show that the beads are present in a wider range of palaeoenvironments than previously recorded, and add considerably to interpretations of the morphology of the structures. The documented sites now extend over a distance of about 450 km, from southeast of Balfour Downs Homestead to west of Pingandy Creek Homestead, and confirm that the beads are abundant and appear to be restricted stratigraphically.

Geological setting and age

The stratigraphy of the Bangemall Supergroup, which consists of a number of groups, some of which may be coeval, is currently being reviewed. A revised subdivision into a basal Edmund Group and unconformably overlying Collier Group has been established on the EDMUND sheet (Martin et al., 1999). The 'strings of beads' structures are in the lower part of the Backdoor Formation of the basal Collier Group and in the Stag Arrow Formation towards the base of the Manganese Group. Lithostratigraphic correlations between the Collier and Manganese Groups are

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

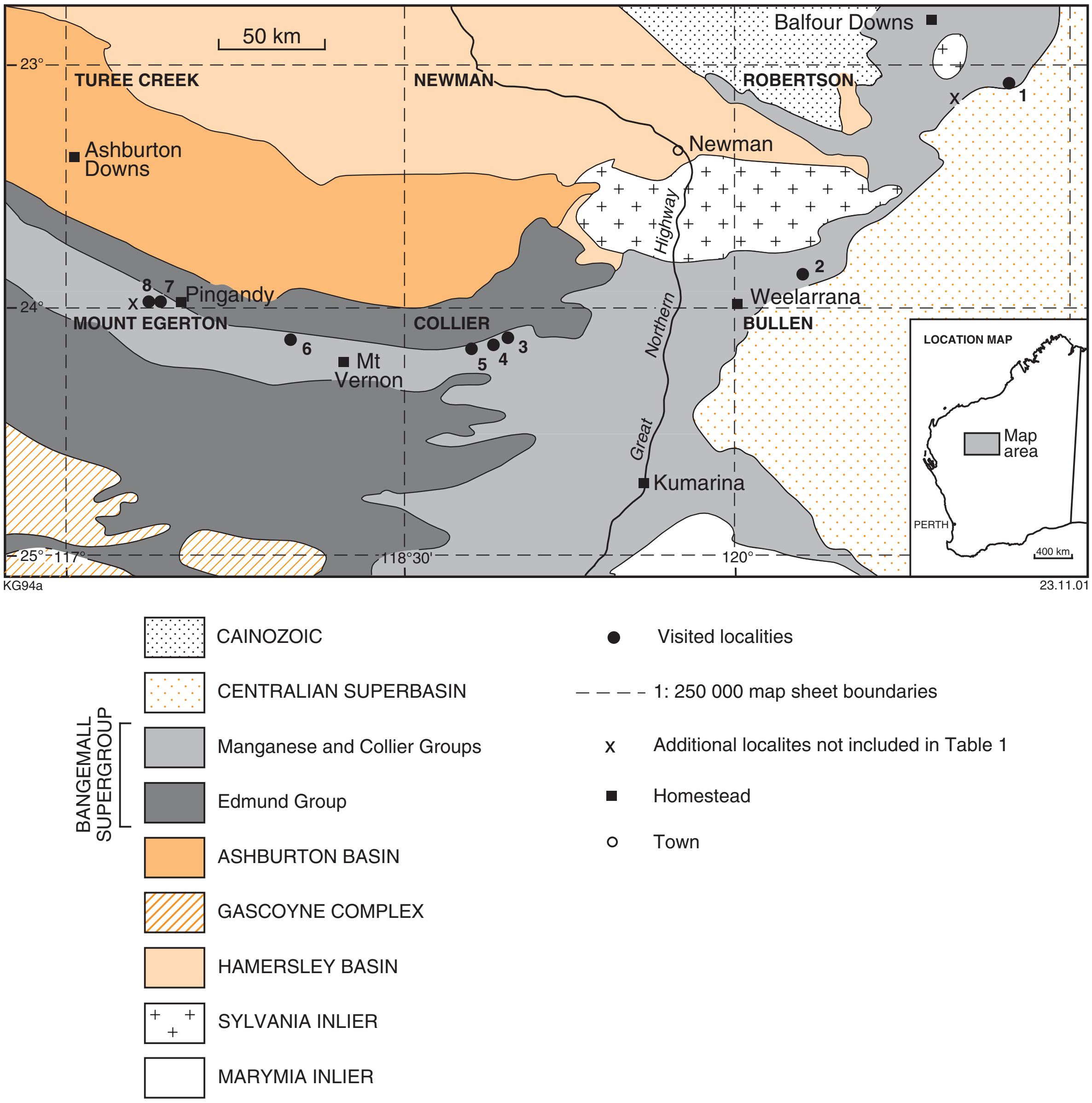


Figure 1. 'Strings of beads' localities in the Bangemall Supergroup, Western Australia (after Martin et al., 1999). Details are presented in Table 1

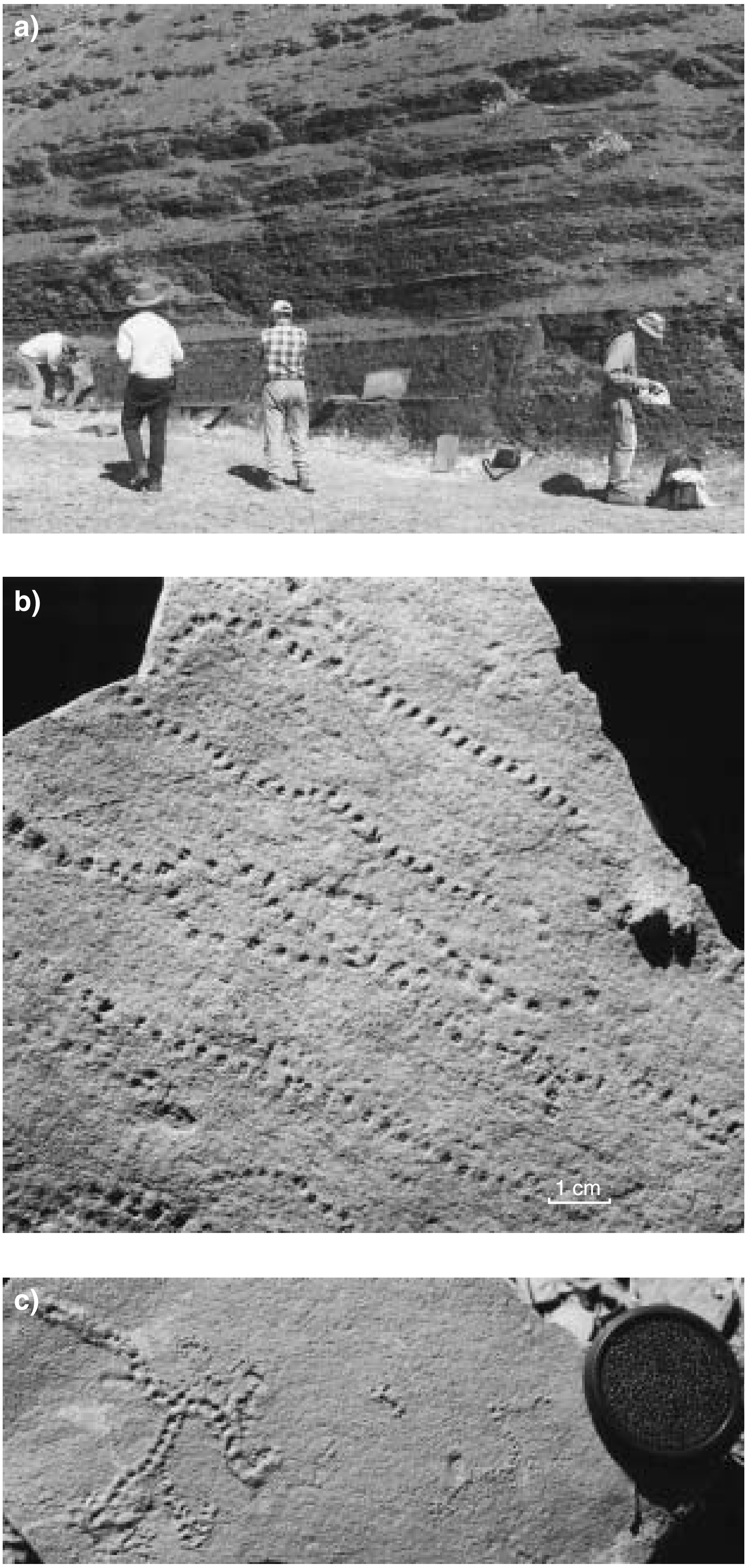
hampered by a lack of continuous outcrop, but partial stratigraphic equivalence between the Backdoor and Stag Arrow Formations has been suggested (Williams and Tyler, 1991). The presence and lateral continuity of 'strings of beads' in the Backdoor and Stag Arrow Formations suggests that this correlation warrants closer scrutiny, and that the 'bead' horizon may be an important biostratigraphic marker linking the two groups.

The 'bead' localities are all at about the same relative stratigraphic level with respect to the base of the Collier and Manganese Groups, and on COLLIER lie below and above a distinctive stromatolitic carbonate. The structures are in interbedded fine-grained sandstone and sandy siltstone with interbedded shales (Fig. 2a) that reflect energy regimes ranging from quiet water to high energy currents. Individual tabular sandstone beds are massive to normally graded with locally ripple-laminated tops. Rare tool marks (flute and groove casts) are associated with beads at some localities. Wrinkle marks are also common on the upper surface of many sandstone beds.

Constraints on the ages of the Collier and Manganese Groups are poor, but have been significantly improved by recent sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon and baddeleyite dating of the Collier Group, suggesting that the 'strings of beads' structures are between c. 1211 and 1070 m.y. old (Martin and Thorne, 2001). The Western Australian examples are therefore probably younger than those in the Belt Supergroup of Montana.

Table 1. Details of 'strings of beads' localities shown in Figure 1

Locality (Fig. 1)	*Map sheet 1:250 000*	*Position*	*Remarks*
1	ROBERTSON SF 51-13	Prolific 'strings of beads' are well exposed along a 3 km, southeasterly trending ridge, 8 km south-southwest of Millari Bore; particularly at 23°04'33"S, 121°11'34"E; 23°04'33"S, 121°11'48"E; and 23°05'08"S, 121°11'53"E	Assigned to the Stag Arrow Formation of the Manganese Group (Williams and Tyler, 1991), and described in Grey and Williams (1990); the 'strings of beads' are mainly on lower bedding-plane surfaces of thinly bedded, fine- to very fine grained, brown-weathering, grey sandstone interbedded with shale and siltstone; some thicker bedded (4–5 cm) ripple-marked sandstone also has beads preserved on the top surface both in the ripple troughs and oblique to the crests of the ripple marks; distribution of beads ranges from fairly linear and roughly parallel (current controlled) to random, arcuate and semi-circular forms (still-water conditions); possible branching forms identified; tool marks or current structures generally absent from the lower bedding-plane surfaces on which the 'strings of beads' are located
2	ROBERTSON SF 51-13	Sparsely scattered to locally abundant 'strings of beads' on a low rubble-strewn, flat-topped rise west and northwest of a claypan, 9.5 km bearing 139° from Mundiwindi; at 23°51'42"S, 120°18'09"E; and 23°51'30"S, 120°18'06"E	Assigned to the Stag Arrow Formation of the Manganese Group (Williams and Tyler, 1991), and described in Grey and Williams (1990); the 'strings of beads' are on weathered, flaggy, red-brown, fine-grained sandstone, commonly not in situ; linear, arcuate, and branching forms present; tool marks and current structures are common; some gutter casts have beads impressed on the base of the casts
3	COLLIER SG 50-4	Scattered and locally abundant 'strings of beads' on rubble- strewn flats and in situ on adjacent, benched northwest-facing, hillside 4.2 km bearing 212° from Boundary Bore; 24°08'28"S, 118°58'56"E; a small area of prolific beads is also located 1.3 km west of this locality at 24°08'31"S, 118°58'13"E	Assigned to the Backdoor Formation of the Collier Group (Martin et al., 1999); 'strings of beads' on lower bedding-plane surfaces of thin, fine-grained, green-grey sandstone and siltstone interbedded with greenish-grey shale; succession overlain by purple-grey stromatolitic dolomite; scattered beads are also in interbedded grey-green siltstone and calcareous shale overlying the stromatolitic dolomite unit; the small area to the west is notable for the prolific beads on the lower bedding-plane surfaces of very thin bedded, dark-grey-brown sandstone interbedded with shale; this horizon lies below the stromatolitic dolomite unit
4	COLLIER SG 50-4	Prolific 'strings of beads' are located in a 10 m cliff on the western side of a north-flowing sandy creek, 6.2 km bearing 230° from Boundary Bore at 24°08'30"S, 118°57'19"E; a second locality, lying 400 m and to the south also on the west bank, 24°07'46"S, 118°55'10"E, contains abundant beads	Assigned to the Backdoor Formation of the Collier Group (Martin et al., 1999); prolific 'strings of beads' are on the lower bedding-plane surfaces of thin, greyish-green fine-grained sandstone beds in laminated shale and siltstone. The irregular spaced sandstone beds are commonly wrinkle marked on the upper surface; beads are mainly large, linear and roughly parallel (current controlled); tool marks are sparse; this clastic succession is overlain by a stromatolitic dolomite unit. The abundant 'bead' locality, 400 m to the south, directly underlies the dolomite unit
5	COLLIER SG 50-4	Abundant 'strings of beads' on western side of an abrupt hill in gullies above a sandy creek, 16.6 km bearing 086° from Peterson Bore; on southern side of track at 24°09'16"S, 118°51'22"E	Assigned to the Backdoor Formation of the Collier Group (Martin et al., 1999); several horizons located with prolific to abundant beads in brown-weathering khaki greenish-grey sandstone interbedded with shale and siltstone; overlain by grey-violet stromatolitic dolomite; sparse beads in siliceous and calcareous shale and siltstone overlying the dolomite unit
6	MOUNT EGERTON SG 50-3	Sparse 'strings of beads' in flaggy rubble at base of low hill, 2.5 km bearing 350° from Mount Vernon and 1 km west of the Meekatharra – Ashburton Downs road at 24°06'09"S, 118°01'38"E	Assigned to the Backdoor Formation of the Collier Group (Martin et al., 1999); sparse beads on red-brown to grey-brown, flaggy, fine-grained sandstone; poor preservation, rubbly outcrop
7	TUREE CREEK SF 50-15	Sparse 'strings of beads' located in several areas north and south of the Mount Augustus – Pingandy road; around 11.2 km bearing 291° from Pingandy Homestead; 23°57'42"S, 117°24'51"E; and 23°57'29"S, 117°24'23"E	Assigned to the Backdoor Formation of the Collier Group (Martin et al., 1999); sparse beads are scattered over a wide area in rubbly, flaggy, dark red-brown weathered, fine-grained sandstone; some 'elephant-skin' texture (algal mat) on top of sandstone beds
8	TUREE CREEK SF 50-15	Prolific 'strings of beads' along a small gully 50 m north of the Mount Augustus – Pingandy road, 12 km bearing 290° from Pingandy Homestead; 23°57'29"S, 117°24'23"E	Assigned to the Backdoor Formation of the Collier Group (Martin et al., 1999); prolific beads on slabby and flaggy, dark grey-brown to red-brown, fine-grained sandstone, interbedded with siltstone and shale; some sandstone shows graded bedding; random arcuate distribution, branching forms; quiet water conditions; some tool marks



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Description of the 'strings of beads' structures

The Bangemall Supergroup 'strings of beads' are commonly present as impressions on the undersurface of successive 2–6 cm-thick sandstone beds (Fig. 2b,c). They are commonly separated by a few millimetres of siltstone (now largely eroded). Preservation on the undersurface is common, but only rare impressions have been observed on the bedding plane itself. At one locality the structures are present in at least 30 m of section.

The 'strings of beads' consist of impressions of 3 to 30 beads, in strings from 1 to 7 cm long (Grey and Williams, 1990). Bead diameter ranges from 0.5 to 4 mm. Impressions are up to 1 mm deep and typically between 1 and 5 mm apart. Parameters are consistent on any one string. The strings vary from linear subparallel (Fig. 2b) to arcuate or semicircular (Fig. 2c) and their orientation appears dependent on current strength. Detailed discussions of morphological variation and statistical analyses were presented by Grey and Williams (1990). Beads from the new localities are similar to those already described, although size ranges are probably greater.

Discussion

The 'strings of beads' fossils are of considerable interest for evolutionary palaeobiology. Grey and Williams (1990) discussed the probable biological origin of the structures, and evaluated a range of possible origins. They suggested a likely metaphytic origin, possibly as megascopic algae with affinities to the Phaeophyceae (the brown algae or seaweeds), but did not formally name the structures.

Figure 2. Illustrations of 'strings of beads' fossils: a) examining the 'strings of beads' in thin interbedded sandstone and shales at locality 4; b) typical 'strings of beads' showing subparallel alignment on lower bedding plane surface at locality 1; c) 'strings of beads' showing random, sinuous orientation with beads impressed in soft sediment, locality 8

Horodyski (1982) was uncertain of the origin of the highly comparable Belt Supergroup structures. Other possible origins for the structures have been discussed. Fedonkin and Runnegar (1992) considered the Montana and Western Australian structures to be dubiofossils. Hofmann (1992) thought they were pseudofossils, comparing them to structures formed at the tips of evaporite veins in the McArthur Basin in Queensland, but there are no traces of evaporites in the Western Australian formations, and the beads have quite a different form from the structures referred to by Hofmann. Fedonkin et al. (1994) suggested that they were formed by a string of polyp-like creatures.

After studying the Montana 'strings of beads', Yochelson and Fedonkin (2000) concluded that they were fossils, and named them *Horodyskia moniliformis*. This species is present in the Appekunny Formation, which is older than 1443 ± 7 Ma based on SHRIMP U–Pb dating of zircons in the Purcell Lava (Evans et al., 2000).

K. Grey still favours an interpretation of the structures as metaphytes, possibly seaweed (Grey and Williams, 1990). M. Fedonkin and E. Yochelson favour an interpretation as metazoans, but other possibilities such as a microbial (prokaryotic) origin (B. Runnegar) require exploration. The size and complexity of these structures suggests that they were multicellular with well-developed tissue differentiation.

Conclusions

If an animal rather than plant origin can be demonstrated for the 'strings of beads', this would place animal evolution at least 700 m.y. earlier than current unequivocal traces (between about 550 and 600 Ma) and would overturn thinking about evolutionary pathways. A few recent models of molecular clocks predict a very early origin for the metazoans (Wray et al., 1996; Bromham et al., 1998), which is close to the age of the Bangemall fossils. The biostratigraphic potential of these structures also requires more detailed study. If, as it appears at present, the beads are extremely abundant but restricted in stratigraphic distribution, this makes them a valuable stratigraphic marker for rocks that are otherwise difficult to date and correlate. This is of particular significance for the revision of the Bangemall Supergroup currently being undertaken by the Geological Survey of Western Australia (Martin et al., 1999; Martin and Thorne, 2001).

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Our thanks to Alan Marshall for pointing out 'bead' localities near Pingandy Homestead.

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Cycle types in carbonate platform facies, Devonian reef complexes, Canning Basin, Western Australia

by R. M. Hocking[1] and P. E. Playford[2]

Abstract

Two principal types of metre-scale depositional cycles, 2 to 12 m thick, can be recognized in reef-flat and back-reef carbonates of the Devonian reef complexes of the northern Canning Basin, Western Australia. Subaqueous infill cycles consist, ideally, of a silty lithofacies overlain by various stromatoporoid lithofacies and capped by fenestral limestone, and contain little or no signs of emergence or subaerial terrigenous progradation. They record infill from relatively quiet, oxygenated water a few metres deep through progressively shallower, more agitated water to shallow subtidal or intertidal flats on which cryptalgal mats thrived. Subaqueous infill to subaerial progradation cycles record moderate- to high-energy subtidal deposition, on stromatoporoid bioherms and in subtidal channels (stromatoporoid limestone and sandstone), followed first by shallow subtidal to ?intertidal deposition (*Amphipora* limestone and fenestral limestone), then by prograding intertidal and supratidal terrigenous deposits (fenestral sandstone). Large-scale stacking patterns can be discerned in places, and repeat the shallowing-upward pattern, but with a longer periodicity spanning four to six cycles. Metre-scale cycles are clearly short term, but are not dated and constrained well enough to favour either short-term orbital forcing or repeated tectonic episodes as the controlling mechanism for cyclicity.

KEYWORDS: Devonian, reef complexes, Canning Basin, stratigraphy, carbonates

Introduction

Reef complexes are spectacularly exposed in Middle and Upper Devonian (Givetian–Famennian) rocks along the northern margin of the Canning Basin in Western Australia (Fig. 1). Platform, marginal-slope, and basinal facies are exposed (Playford, 1980; Playford and Hocking, 1998; Playford et al., 1989, 1999), with associated subaerial (alluvial fan) to deep-marine (basin floor) conglomerates. The reef-flat and back-reef facies are commonly characterized by metre-scale cyclic deposition, with cycles between about 2 and 10 m thick. Two principal types of cycles are present: subaqueous infill cycles, and subaqueous infill to subaerial progradation cycles. Wholly subaqueous, limestone-dominated, shallowing-upward cycles record subaqueous aggradation, or infill, on the platform. Mixed carbonate–clastic cycles of the second type were formed by subaqueous infill followed by subaerial progradation. Recognition of the first cycle type is based primarily on measured sections in the lower Pillara Limestone (Givetian–Frasnian) in the southeast Lennard Shelf and in the Famennian Nullara Limestone, whereas the second type is recognized in the upper Pillara Limestone (Frasnian) in the northwest Lennard Shelf (Fig. 1). Conglomerate-dominated subaqueous to subaerial cycles are an extension of the second cycle type that are present in a specific localized tectonic setting in part of the Sparke Range, in the southeast Lennard Shelf, and are not considered further here.

Subaqueous infill cycles

Subaqueous infill cycles (Fig. 2) contain little or no signs of emergence or subaerial terrigenous progradation. Each cycle records infill from relatively quiet, oxygenated water of a few metres depth (terrigenous lithofacies), through progressively shallower, more agitated water (various stromatoporoid lithofacies), to shallow subtidal or intertidal flats on which cryptalgal mats thrived (fenestral lithofacies). The thin-bedded cap at the top of some cycles is interpreted as the transgressive drowning phase prior to the re-establishment of deep-water conditions in the next cycle. Cycles are 2 to 6 m thick, with an average thickness of 3.5 m. Figure 2 shows an

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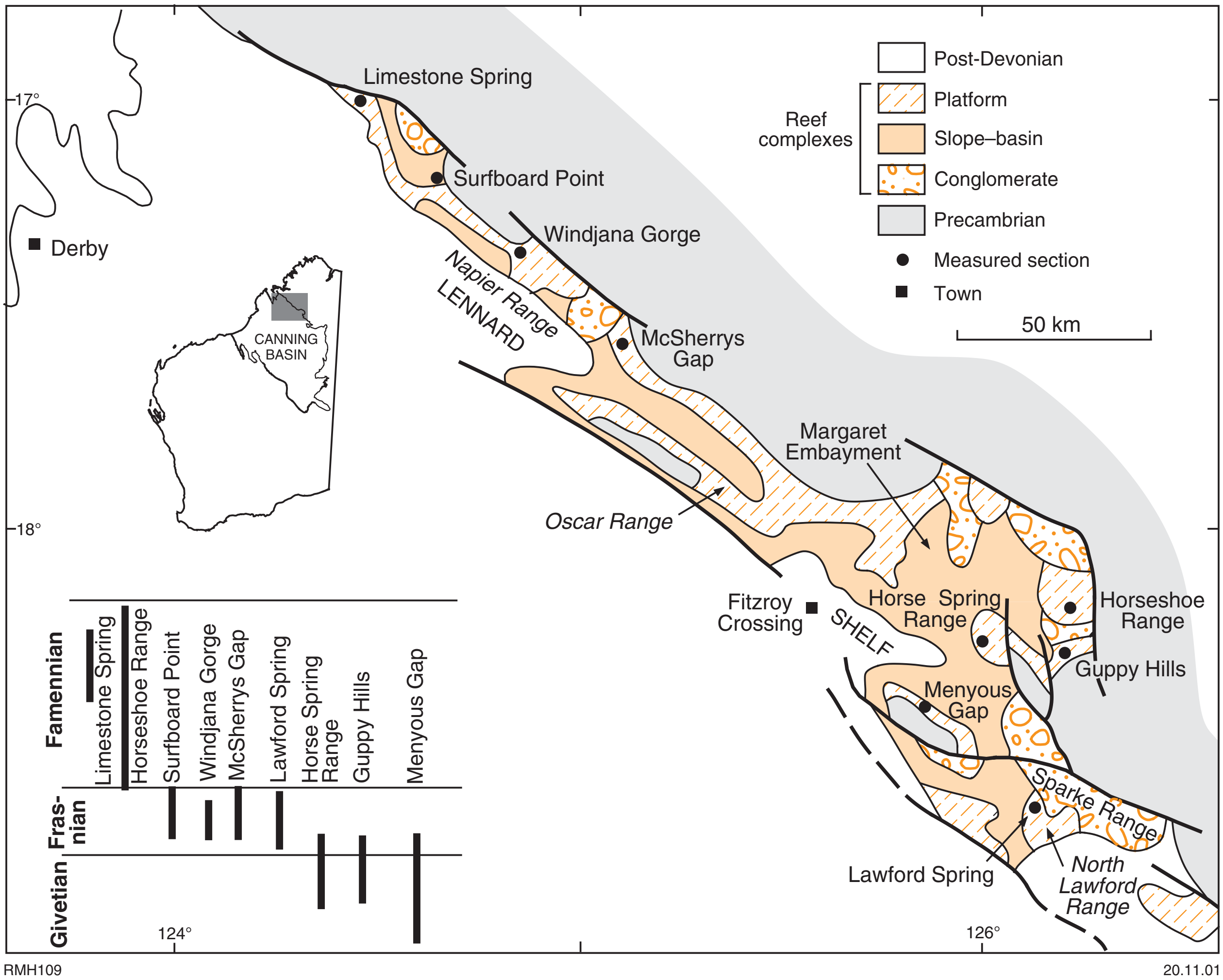

Figure 1. Location of Devonian reef complexes and measured sections, and approximate age relationships of measured sections

ideal cycle, based largely on sections near Horse Spring and through Menyous Gap. Jell and Brownlaw (2000) described these cycles, from the same measured sections. The platform-margin cycles of Webb and Brownlaw (2000) grade laterally into these cycles. We interpret most 'cycles' less than two metres thick as local banks or mounds rather than externally driven cycles, because the stromatoporoid limestones that cap the 'cycles' cannot be traced laterally for more than a few tens of metres.

Subaqueous cycles are present in the lower Pillara Limestone in the southeast Lennard Shelf, in the uppermost parts of the Pillara Limestone in the central Lennard Shelf around McSherrys Gap and Windjana Gorge, and in the Nullara Limestone in the Horseshoe, Oscar, and Napier ranges (Fig. 1). Terrigenous influx in areas such as the Margaret Embayment commonly masks this type of cycle. The cycles described by Read (1973) from Menyous Gap and by Brownlaw et al. (1996) from Guppy Hills are of this type.

Variations from the ideal complete cycle tend to occur as groups of cycles, reflecting longer term controls over accommodation than those applicable to individual cycles. Where the basal siltstone lithofacies is present, cycles commonly shallow up to *Stachyodes* or *Amphipora* limestones and do not have a fenestral cap. Conversely, where well-developed, thick, fenestral limestone units are present, the basal siltstone and tabular-stromatoporoid limestone lithofacies are commonly absent. This may reflect medium- to long-term deeper and shallower areas, on which short-term metre-scale cyclicity was superimposed.

Stromatoporoids are absent in Famennian cycles. Oolitic and oncoid limestones are present in similar positions to stromatoporoid limestones in Givetian and Frasnian cycles, and there is far more cyanobacterial binding apparent. Fenestral limestones and tepee-like deformation are more abundant than in Frasnian platform facies, perhaps reflecting wider and shallower platform areas in the Famennian.

Subaqueous infill – subaerial progradation cycles

Cycles that show subaqueous infill followed by subaerial progradation

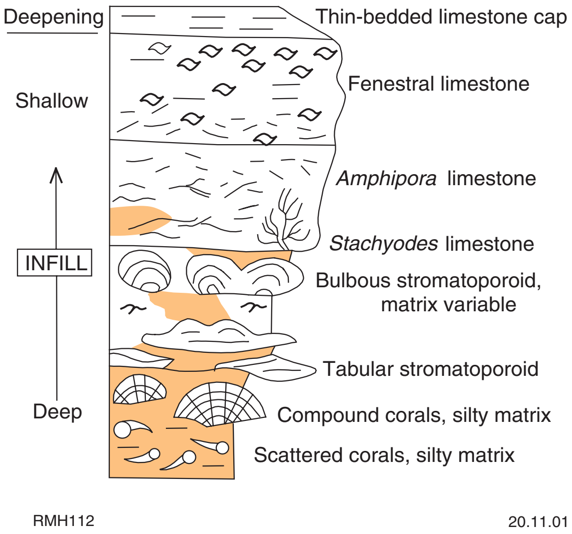

Figure 2. Ideal subaqueous cycle, Pillara Limestone. Cycle thickness 2 to 6 m, average about 3.5 m. Shading indicates terrigenous sediment; dashed lines indicate bedding; see Figure 4 for legend

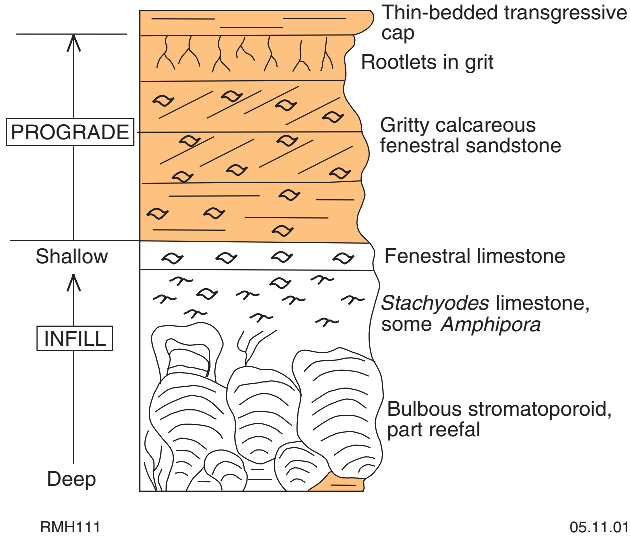

Figure 3. Ideal subaqueous–subaerial cycle, Pillara Limestone. Cycle thickness 2 to 12 m, average about 4 m. Shading indicates terrigenous sediment; dashed lines indicate bedding; see Figure 4 for legend

(Fig. 3) are common in the upper Pillara Limestone in the central to northwest Napier Range. These are the cycles recognized and briefly described by Playford (1980) and Playford et al. (1989). Each cycle records moderate- to high-energy subtidal deposition on stromatoporoid mounds and in subtidal channels (stromatoporoid limestone and sandstone), followed first by shallow subtidal to intertidal deposition (*Amphipora* limestone where present, and fenestral limestone), then by prograding intertidal and supratidal terrigenous deposits (fenestral sandstone and sparsely bioturbated sandstone, locally with recognizable rootlets). The thin-bedded caps on some cycles represent the transgressive drowning phase, and herald the start of the next cycle. Cycles are 2 to 12 m thick (average about 4 m), and vary in lithology more than the subaqueous cycles.

Cross-bedded sandstone is commonly present at the base of cycles instead of stromatoporoid limestone. Moderate sorting, doubly draped foresets, wrinkly toesets, and stromatoporoid and shelly debris indicate that these sandstone units are tidal channel and bar deposits, deposited at shallow-subtidal depths between stromatoporoid mounds and in areas where terrigenous influx was sufficient to inhibit stromatoporoid development. Some tidal channels and bars are clearly erosively based, and significantly affect average cycle thickness. One large lateral-accretion surface on the side of a tidal bar in the Surfboard Point (Fig. 1) section is 8 m thick. This lateral gradation is similar to that noted by Adams and Grotzinger (1996) from the Cambrian of California, where parasequences commonly displayed facies changes when traced laterally over hundreds of metres. On the Lennard Shelf, many parasequence (cycle) boundaries and vertical boundaries between major facies can be followed for several kilometres on the ground or on 1:25 000-scale aerial photographs, and thus appear more laterally persistent than the boundaries of Adams and Grotzinger (1996).

Poorly sorted, gritty sandstone, commonly with a calcareous cement and a fenestral texture, is present in the upper parts of cycles, above stromatoporoid and fenestral limestone. This sandstone was deposited in intertidal and supratidal conditions by fluvially dominated channels and sheetflood processes. Rootlets and possible soils, highlighted by clay-filled or sand-filled tubes, branching subvertical fenestrae, and diffuse mottled textures suggest supratidal conditions. Evaporite pseudomorphs have not been found.

Cycle stacking patterns (large-scale cycles)

In each section, some cycle boundaries are clearly more significant than others. In places a repetitive pattern can be discerned. They mark larger scale packages of metre-scale cycles, into large-scale cycles. Recognition of these large-scale cycles is more subjective and tentative than for metre-scale cycles because of their size and because the results of other long-term changes in sediment influx and tectonic activity mask the large-scale cyclicity.

At Surfboard Point, McSherrys Gap, and the northern Lawford Range (Fig. 1), large-scale cycle-stacking patterns can be seen in the upper Pillara Limestone. They follow a general pattern of gradual shallowing spanning several metre-scale cycles, followed by abrupt deepening to the next large-scale unit. Regular, repeated, large-scale cycles are most readily recognized near the east end of Windjana Gorge in the upper Pillara Limestone (Figs 4 and 5). Here, the metre-scale cycles are arranged into sets of four to six cycles. The sets are 20 to 30 m thick. The metre-scale cycles grade from limestone-dominated cycles at the base of the cycle set (large-scale cycle) to sandstone-dominated cycles at the top. There is an abrupt shift from sandstone-dominated

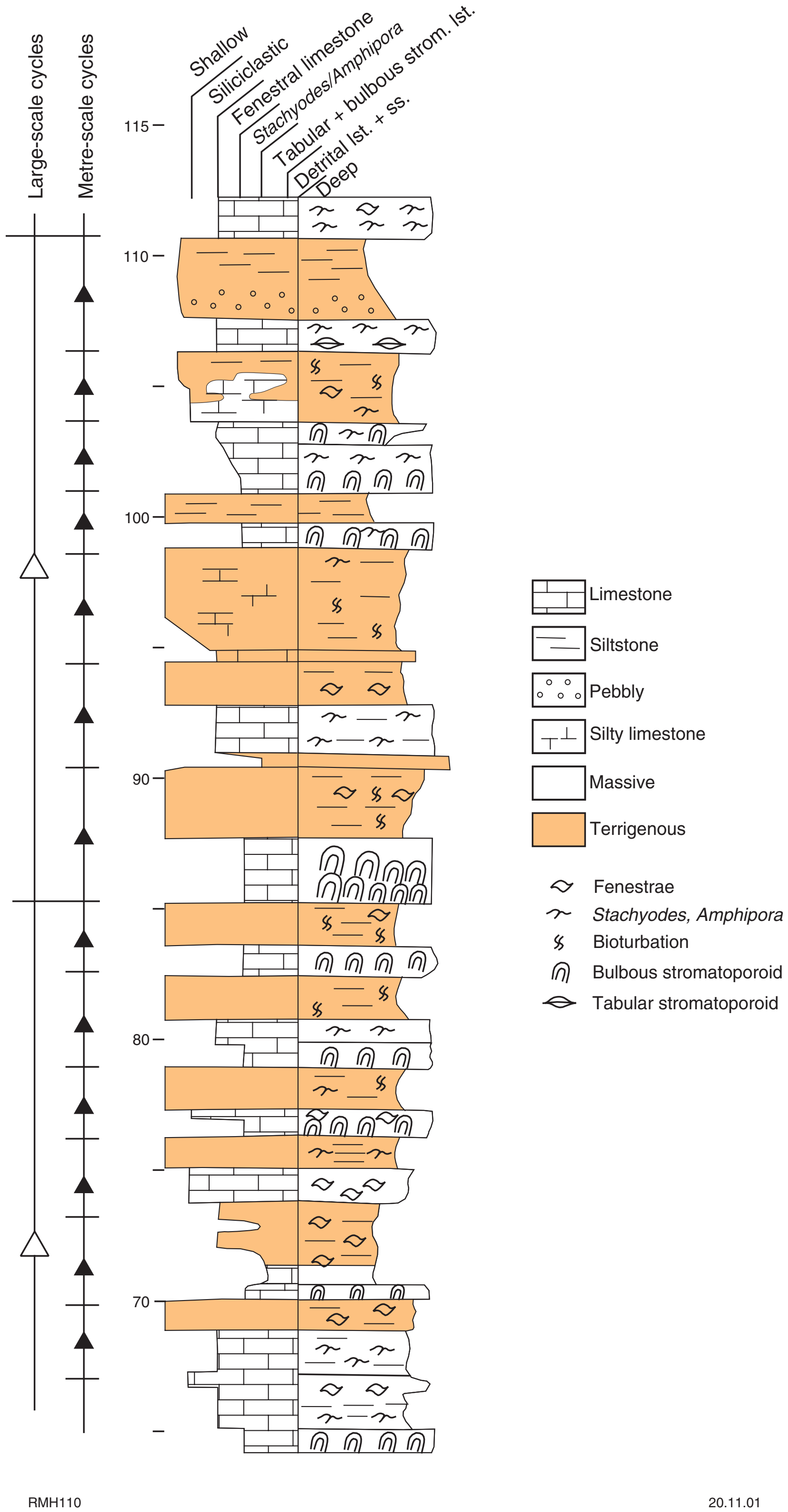

Figure 4. Partial measured section, near east end of Windjana Gorge, showing metre-scale cycles and cycle stacking patterns. Section located at approximately AMG 708200E, 8074200N, upwards in gorge from location shown as Mingun (fishing rock) on Playford and Hocking (1998). Thickness is from full measured section extending from about AMG 708700E, 8074200N over saddle at Malambeea (wait-a-while); lst. = limestone, ss. = sandstone, strom. = stromatolite

below to limestone-dominated above at the boundary between each large-scale cycle, so they are similar to, but of larger scale than, normal subaqueous–subaerial metre-scale cycles from Windjana Gorge. Both metre-scale and large-scale cycles record a pattern of gradual shallowing of the depositional environment through infill, followed by abrupt deepening.

Sections through the lower Pillara Limestone do not show large-scale stacking patterns to the same degree as those in the upper Pillara Limestone. Groups of cycles are apparent in Guppy Hills in aerial views (Fig. 6), but these are not obvious in a section through the western end of the hills, except as a broad alternation of groups of deeper water facies and shallower water facies. In Menyous Gap, there are broad trends in lithofacies abundance (and thus comparative water depth) through the section, but stacking patterns involving several metre-scale cycles are not obvious.

Controls on cyclicity

Both metre-scale cycles and large-scale cycles are the product of repeated relative sea-level fluctuations, with shallowing-upward phases separated by abrupt deepenings. Greenstone conditions (Read, 1995) can be inferred from the relatively small variations in bathymetry throughout the cyclic succession. The carbonate-dominated, lower parts of metre-scale cycles are interpreted as the products of deposition in transgressive to early-highstand conditions, when accommodation was high and carbonate productivity was highest, leading to rapid stromatoporoid, oolith, and oncoid growth . Terrigenous material was either trapped along the basin margin or, if silty, carried to deeper areas to form the coral-bearing terrigenous siltstone lithofacies at the base of some cycles. As accommodation decreased, platform areas shallowed markedly, and terrigenous progradation or cryptalgal mat development (or both; forming fenestral limestone) began. During and after the late-highstand period, platform areas became choked by cryptalgal mats, which formed widespread,

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Figure 5. Aerial view of subaqueous–subaerial metre-scale cycles, east end of Windjana Gorge. Resistant beds are columnar and subspherical stromatoporoid limestone. Large-scale cyclicity is not apparent in this photo

commonly thick, fenestral limestone bodies. In areas of terrigenous influx, sands and gravels prograded over the platform. The subsequent return to deeper water conditions is poorly preserved except as local thin-bedded limestones. The large-scale cycles also reflect gradual infill with lessening accommodation and (where terrigenous influx was sufficient) increasing progradation, followed by rapid drowning.

The cause of the cyclicity in the platform carbonates is equivocal. Orbital forcing (Milankovich cyclicity; Fischer and Bottjer, 1991; De Boer and Smith, 1994; House and Gale, 1995) influences deposition over wavelengths of 20 to 25 ka (precession), 41 ka (obliquity), 100 ka (short-term eccentricity) and 400 ka (long-term eccentricity). To tie the metre-scale and large-scale cycles of the platform facies to these mechanisms requires both precise control on the age of the sections, in terms of biostratigraphic age, and precise correlation of the biostratigraphy to absolute age (chronostratigraphy). The errors implicit in estimates of the age and duration of each section render a choice of either precession or obliquity for metre-scale cycles very subjective, given that platform facies are poorly dated compared to the marginal-slope facies. Consequently, estimates of cycle duration such as those of Jell and Brownlaw (2000) are not attempted here.

A tectonic control over cyclicity is possible. The Lennard Shelf lies along the northern margin of the Canning Basin, adjacent to the King Leopold Orogen, and in the southeast abuts the southern end of the Halls Creek Orogen. In the Devonian, the Lennard Shelf was in an intracratonic, west-opening extensional setting (Baillie et al., 1994; Hocking and Preston, 1998). Faults extend from the Halls Creek Orogen into the Devonian succession in the Sparke Range area, and Devonian movement is established in the Margaret Embayment area by intra-Devonian angular unconformities, as well as in the Ord Basin to the northeast (Thorne and Tyler, 1996). A tectonic control would have to act very regularly over the length of the Lennard Shelf, about 500 km, on a 5 to 10 m scale, by repeated episodic step-wise subsidence (jerky subsidence).

Jerky subsidence as a possible control on cyclicity was debated by Hardie et al. (1991) and Read et al. (1991). Hardie et al. (1991) noted that major earthquakes (M_s 8 to 9) should have a frequency in the same range as Milankovich cyclicity, and can drop areas 100 to 200 km wide by several hundreds of kilometres long (the size of the Lennard Shelf), by 2 to 4 m. The controlling mechanism would be periodic fault movements due to release of tension as a threshold was reached.

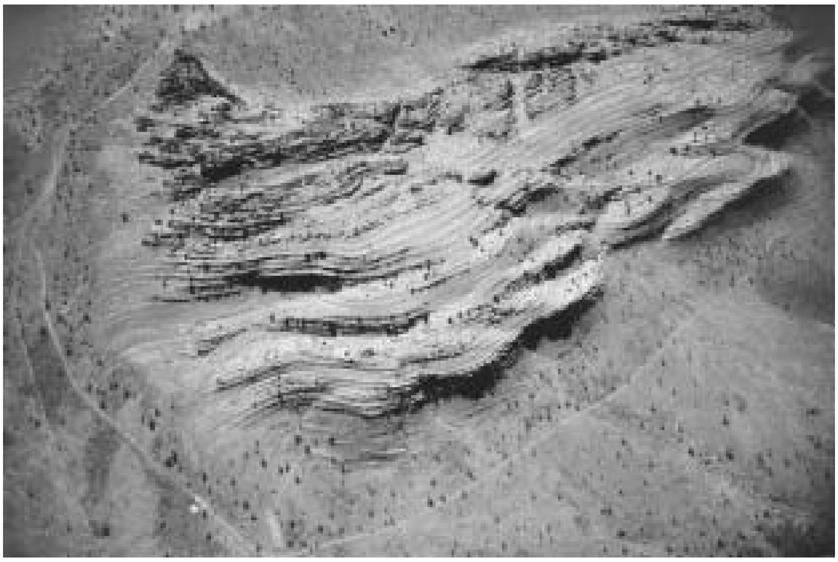

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Figure 6. Aerial view, west end of Guppy Hills looking east. Groups of cycles can be seen here, but are not obvious on the ground

Earthquakes are far more common on compressional margins than extensional margins (Isacks et al., 1968; Condie, 1997), so it is reasonable to assume repeated major earthquakes should also be more common in a compressional setting rather than an extensional setting such as the Devonian Lennard Shelf. However, Read et al. (1991) noted that the established earthquake record is very brief geologically, so these comments and those of Hardie et al. (1991) are largely conjectural. Additionally, there should be abundant smaller earthquakes triggering collapse of unstable sediments in any setting with repeated major earthquakes. The smaller earthquakes may be reflected in the debris-flow deposits characteristic of the marginal-slope facies (Playford, 1984; George et al., 1994), leaving larger earthquakes as a trigger for metre-scale cyclicity as a distinct possibility in the extensional setting of the Lennard Shelf.

Acknowledgements

Four of the sections were measured with Scott Brownlaw, and extended discussions with him then and over the following five years are gratefully acknowledged. Scott contributed to the ideas and conclusions here, but may not necessarily agree with all of them. Annette George first noted the stacking patterns at Windjana Gorge, from Malambeea.

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Program review

SUBPROGRAM 3102: MINERAL AND PETROLEUM RESOURCE STUDIES

SUBPROGRAM 3103: REGIONAL GEOSCIENCE MAPPING

SUBPROGRAM 3104: SCIENTIFIC, TECHNICAL, AND FIELD SUPPORT

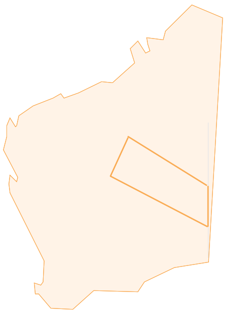
SUBPROGRAM 3105: GEOSCIENCE EDITING AND PUBLISHING

SUBPROGRAM 3106: GEOSCIENTIFIC AND EXPLORATION INFORMATION

SUBPROGRAM 3107: INVENTORY OF ABANDONED MINE SITES

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 2000–01

The main activities during 2000–01 were the compilation of the Vines 1 well completion report, and Reports on Hydrocarbons of the Western Australian Officer Basin, the Stratigraphy of the Western Australian Officer Basin, and the Gibson area, and compilation of data for other Reports in progress. These manuscripts contain details of significant improvements in the understanding of potential Neoproterozoic petroleum systems of the Officer Basin.

Additional fieldwork in the Gibson area (Fig. 1) was completed and will contribute to future revisions of the RUNTON* 1:250 000 geological map. Improved understanding of the stratigraphy of this remote region of the Officer Basin will also contribute to the selection of a drilling locality for a stratigraphic test in the Gibson area of the Officer Basin.

Team members co-authored a paper entitled 'Permian–Carboniferous tectono-stratigraphic evolution and petroleum potential of the northern Canning Basin, Western Australia', which was published in the AAPG Bulletin.

* Capitalized names refer to standard map sheets.

2000–01 publications and products

Report 77: 'Basin development and petroleum exploration potential of the Lennis area, Officer Basin, Western Australia'.

Future work

Compilation of analytical data, core descriptions, and geophysical logs, together with preliminary interpretations, will be published in the Vines 1 well completion report. Following completion of fieldwork in the Gibson area, Reports on the exploration potential of the Gibson and Waigen areas will be published. Additional planned publications are: 'A review of the stratigraphy of the Officer Basin, Western Australia', and a Report on 'Hydrocarbons and petroleum systems of the Officer Basin, Western Australia'. In order to promote the work of GSWA, and in particular the results of the petroleum initiatives project, external publications and presentations for the APPEA Conference and the Western Australian Basins Symposium III Conference are in preparation.

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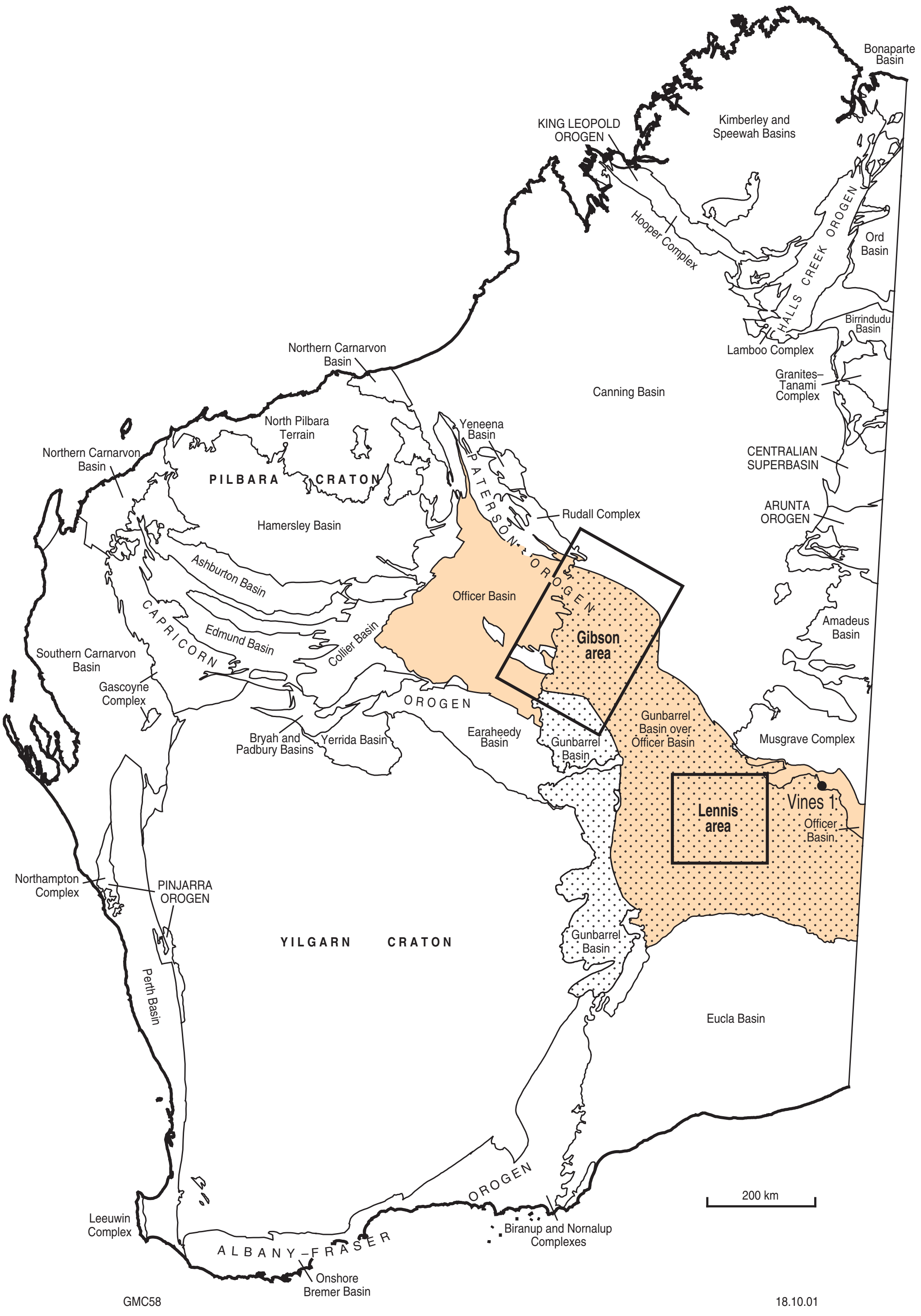
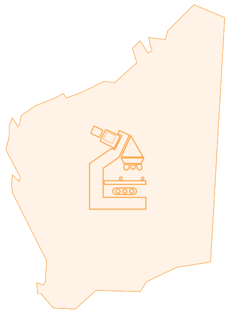


Figure 1. Location of the Interior Basins petroleum initiatives project

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 2000–01

Biostratigraphic correlation in the western Officer Basin (in support of the Interior Basins petroleum initiatives program) continues to be a major focus for GSWA palaeontological studies. Studies of stromatolites from RUNTON are in progress, and indicate that at least some carbonates are about 800–700 m.y. old. Palynology studies of Vines 1 drillcore identified acritarch species ranging in age from about 800–700 Ma, together with ones from upper Neoproterozoic – lower Cambrian rocks. All specimens are badly fragmented and degraded, and both groups are present throughout the drillcore, indicating that the assemblages are extensively reworked. They indicate that the age of deposition is probably younger than earliest Cambrian.

Several papers on broad aspects of Neoproterozoic correlation were published or submitted for publication. New species names must be published and proposed correlations established across a wide geographical area before zonation schemes can be applied. With this in mind, AGSO funded preparation of a monograph describing terminal Neoproterozoic (Ediacarian) palynomorphs in Australia. This project was undertaken as part of the AGSO initiative to validate key zones used in resource and exploration studies through its Virtual Centre for Economic Micropalaeontology and Palynology (VCEMP).

The task of cataloguing and maintaining the fossil collection continued. The major emphasis this year has been on reorganizing the storage of specimens. This should allow easier access and prepare for the transfer of the collection on completion of the new core library. Work continued on the development of a palaeontology database and on capturing and entering data.

Requests for palaeontological information remained at a high level. Many correspondents (ranging from research scientists to tourists) asked about visiting the 3.5 Ga (early Archaean) stromatolites in the Pilbara or living stromatolites at Shark Bay or Lake Clifton. In the last twelve months several overseas research groups, especially ones associated with NASA Astrobiology projects, examined Pilbara localities that show evidence of ancient life. Some localities are vulnerable to overcollecting, and access details are supplied only if we are convinced that removal of material is justified on scientific grounds. We are currently trying to identify a site that might be suitable for general access so that visitors from a range of backgrounds can examine the fossil evidence. A web page is being developed to answer frequently asked questions relating to fossil sites in Western Australia. It will provide information about the need to protect sites from casual or commercial collecting, the remoteness of the locations, land-access issues, and laws relating to exporting fossil specimens. The 'ancientfossils' page on the MPR website, which describes the 3.5 Ga-old stromatolites, receives more than 200 hits per day, and many requests have been received seeking permission to use some of the illustrations. The site has been incorporated in several teaching packages.

Output from the Biostratigraphy and palaeontological services section was either as publications, or in the form of data used by other geologists in preparing their products. Four conference presentations (on Neoproterozoic palaeomagnetism, Mesoproterozoic and Neoproterozoic stratigraphic revisions, Warrawoona Group stromatolites, and the Officer Basin petroleum potential) contained contributions from the section. Two papers were published, two are in press, and one more is in an advanced stage of preparation. These are:

- Record 2000/16: 'Revised lithostratigraphy for Proterozoic rocks in the Earaheedy Basin and nearby areas';
- 'Mesoproterozoic stratigraphy in the Oldham Inlier, Little Sandy Desert, central Western Australia' (in the GSWA Annual Review 1999–2000);
- 'Cherts of the Palaeoproterozoic Yerrida Basin, Western Australia, a rift-related hot spring environment' (in Precambrian Research);
- 'Ediacarian palynology of Australia' (in the Memoirs of the Australasian Association of Palaeontologists);
- Record 2001/18: 'GSWA Vines 1 well completion report, Waigen area, Officer Basin, Western Australia'.

Future work

Work on the palaeontology collection and database will continue throughout 2001–02. Further work on a lithostratigraphic revision of the western Officer Basin and on Neoproterozoic stromatolite and palynological correlation is also planned.

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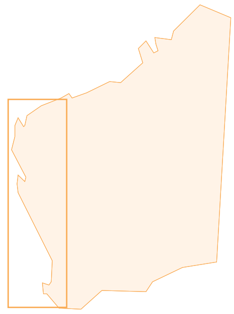
Western Margin petroleum initiatives project



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 2000–01

The main activities during the year were the preparation of reports and external papers on the Southern Carnarvon Basin, with the completion of two major reports on the Woodleigh impact structure.

Work has commenced on compiling reports on the leads and prospects of the northern Perth Basin and the structure of the western Gascoyne Platform – Edel Terrace, and a Bulletin on the evolution and petroleum potential of the Southern Carnarvon Basin synthesizing previously published GSWA reports.

Three stratigraphic wells (Fig. 2), Boologooro 1, Edaggee 1, and Yinni 1, focusing on the Cretaceous section in the Southern Carnarvon Basin, were drilled in May 2001 with the cooperation of the University of Western Australia, which will oversee micropalaeontological studies of this material.

Papers were published this year on probable biogenic gas within the Peedamullah Shelf (PESA Journal), and a reply to comments on the Woodleigh structure (Earth and Planetary Science Letters).

Promotional booths containing displays of major products from the Western Margin and Interior Basins project teams were prepared for the 2000 AAPG International Conference (Bali), 2001 APPEA Conference (Hobart), GSWA 2001 open day, and the 2001 AAPG Conference (Denver).

2000–01 publications and products

Report 73: ‘Petroleum geology of the Peedamullah Shelf and Onslow Terrace, Northern Carnarvon Basin, Western Australia’;

Report 75: ‘Geology and petroleum potential of the Abrolhos Sub-basin, Western Australia’;

Report 79: ‘The geophysical interpretation of the Woodleigh impact structure, Southern Carnarvon Basin, Western Australia’.

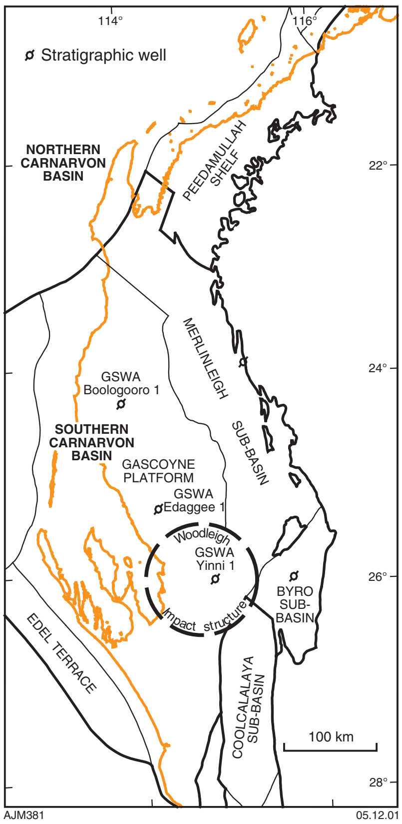


Figure 2. The northern part of the Western Margin petroleum initiatives project area, showing the location of the three drillholes drilled in 2001

Future work

Due for completion in 2001–02 are reports on prospects and leads in the northern onshore Perth Basin, and the hydrocarbon potential of the western Gascoyne Platform – Edel Terrace. In addition, preparation of a Bulletin on the evolution and petroleum potential of the Southern Carnarvon Basin will continue into 2002–03. Contributions to the Western Australian Basins Symposium (September 2002) are also planned, as well as other external papers promoting the prospectivity of the region.

The only new data to be acquired during 2001–02 will be analyses of existing core, mainly from Boologooro 1, Edaggee 1, and Yinni 1.

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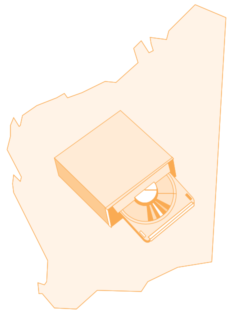
Resource assessment and geoscientific advice

Resource studies and MINEDEX database

Objectives: *To maintain a detailed inventory of the State's identified mineral resources, monitor mining and exploration activities, and provide advice on mineral resources, mineral exploration, and potential for mine development. To promote development of industrial minerals in Western Australia by the systematic documentation of industrial mineral occurrences and production of reports on industrial mineral commodities, and to provide advice concerning industrial mineral resources to industry, government, and the public. All these functions are supported through MINEDEX, the Department's mines and mineral deposits information database.*



Highlights and activities 2000–01

A position paper overviewing exploration and development in Western Australia during 1999 and 2000 was prepared and used at the Prospectors and Developers Association of Canada (PDAC) in Toronto to promote the prospectivity of Western Australia.

Total mineral exploration expenditure (excluding petroleum) in Western Australia rose slightly in 2000–01 after a three-year period of substantial falls in exploration activity. Exploration expenditure rose by an estimated 6.3% ($26.2 million) from $415.0 million to $441.2 million (estimated) in 2000–01. The recovery was led by renewed interest in the still-dominant gold sector and continued strength in iron ore, but which were partly offset by further falls in exploration for base metals, nickel–cobalt, diamonds, heavy mineral sands, and 'other minerals'. Overall, exploration activity is showing signs of stabilizing at around this level, which is comparable to the recession in 1990–91. Despite the rapid decline in mineral exploration expenditure over the previous three years, the proportion of Australian mineral-exploration expenditure spent within Western Australia continues to remain very high (59% for 2000–01) and is only slightly down from the record level of 62% in 1998–99.

In 2000–01, ongoing data capture into MPR's mines and mineral deposits information (MINEDEX) database formed a significant part of the function of this section, together with advice to a wide range of customers. A web front-end to portions of the data in MINEDEX (projects, sites, locations, tenements, resources, notices of intent, and site operators) was designed and mostly implemented, with release to the public in early 2001–02. MINEDEX data were up-to-date in June 2001. Mines and mineral deposits stored in MINEDEX were used to produce the 'Western Australia atlas of mineral deposits and petroleum fields 2001'. This continues to be one of the most popular publications of the Geological Survey of Western Australia, and a revised edition was published in 2000–01.

MINEDEX is also used as an inventory of mineral resources. Gold resources (measured and indicated) increased for the eighth year in succession, despite continued high levels of production and a previous three-year fall in gold exploration expenditure. The rise results from continued exploration successes in recent years, initial resource estimates for major discoveries such as the Thunderbox and Belleisle deposits, and the continued trend to near-mine (brownfields) exploration. Near-mine exploration is proving successful in the short-term, but the industry will not survive on that type of success alone. Low levels of grassroots (greenfields) exploration remains a concern. This issue is to be researched further during 2001–02, with analysis of the data from Form 5 of the Mining Act.

The boom in nickel exploration during the mid- to late 1990s is showing signs of slowing down, with exploration expenditure falling during 2000–01 and with a drop in the estimated measured and indicated resources. The drop in resources is mostly from a rise in the cut-off grade (from 0.5% Ni up to 0.8% Ni) for some of the major lateritic nickel projects, due to falling world nickel prices. Resources of diamonds have increased following another upgrade of resources at Argyle, whereas resource estimates of the other major commodities (iron ore, heavy mineral sands, and bauxite) changed little during 2000–01.

A report on the geology and mineral resources of the Southern Cross – Esperance region was prepared in 1999–2000 and formed part of the joint Federal–State–industry regional minerals study looking at possible development and infrastructure scenarios within the region for the next ten years. During 2000–01, this report was revised and updated, and will be released as a GSWA Record.

Released during the year was an updated map 'Iron ore deposits of the Pilbara region', but this time the map was accompanied by an extensive digital dataset on CD.

For industrial minerals, the main projects completed during 2000–01 included preparation of a final draft commodity Bulletin on construction industry and speciality clays (attapulgite and bentonite–saponite), and a first draft of a commodity Bulletin on high-grade silica in Western Australia.

2000–01 publications and products

Record 2000/14: 'Geology and mineral resources of the Mid West Region' (including map and digital dataset);

'Mineral exploration and development in Western Australia in 1999 and 2000';

'Western Australia atlas of mineral deposits and petroleum fields 2001';

Iron ore deposits of the Pilbara region (1:50 000; including digital dataset).

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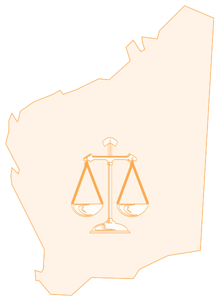
Geoscientific advice relating to exploration



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

Highlights and activities 2000–01

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

Exploration performance on 2068 mineral tenements (Table 1) was reviewed during 2000–01 (1446 in 1999–2000) as part of the assessment of applications for exemption from expenditure conditions, applications for extension of term of exploration licences, applications for retention licences, applications for special prospecting licences, and applications for Ministerial consent to dealings in exploration licences during their first year of tenure.

The number of applications for exemption from expenditure received by the Department during 2000–01 has increased by about 12% to 6671, reflecting current economic conditions (especially difficulties in raising capital for exploration). Referral of such applications to the Geological Survey for geological advice has increased slightly to 24% of the total applications (from about 22% in 1999–2000). Most referrals are in respect to applications under Section 102(2)(e)

Table 1. Tenement reviews

Geological advice provided	*Number of tenements*					
	1995–96	*1996–97*	*1997–98*	*1998–99*	*1999–2000*	*2000–01*
Expenditure exemption	3 004	458	821	580	1 287	1 569
Extension of term of exploration licences	353	186	27	48	82	394
Dealings in first-year exploration licences	36	58	21	27	7	75
Iron-ore authorization (exploration licences)	na	6	13	9	22	16
Iron-ore drop offs (exploration licences)	na	13	10	27	22	2
Retention licence applications	na	na	5	3	3	6
Special prospecting licence applications	na	na	11	14	1	4
Other	na	na	48	65	22	2
Total	**3 393**	**721**	**956**	**773**	**1 446**	**2 068**

NOTE: na not available

and (f) (i.e. that the tenement contains a deposit that is currently subeconomic or contains ore required for future operations). Exemption applications recommended for refusal are referred if they require the assessment of work programs that have been lodged as part of a company's submission. The number of exemption applications refused has fallen to 5% of the total in 2000–01 (7% in 1999–2001).

The increase in referrals of applications for extension of term for exploration licences is due to more applications being received where previous conditions of the licences were not met. In these cases, extensions of term may still be granted if reasons acceptable under Regulation 23AB can be demonstrated (i.e. significant mineralization has been discovered or new geological concepts are being applied).

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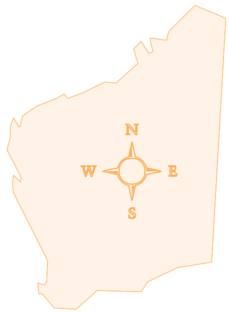
Regional mineralization mapping

Objectives: *To enhance perceived prospectivity for precious metals, base metals, ferro-alloys, and diamonds, and to encourage mineral exploration within the State, 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 hard-copy reports and maps, together with GIS-compatible databases on CD-ROMs.*



Highlights and activities 2000–01

During the year, one data package on the east Pilbara was prepared for publication (to be released in early 2001–02). Compilation of databases and digitizing of spatial data was in progress for the north Kimberley and the west Kimberley. Updated CD-ROMs using data from the latest WAMEX releases since 1998 were in progress for three earlier projects (Bangemall Basin, southwest Western Australia, and north Eastern Goldfields; Fig. 3).

Each data package contains a Report that synthesizes information on the mineral prospectivity of an area, a CD, and a 1:500 000 map that shows mineral occurrences, mineralization styles, commodity groups, and geology. The CD-ROM in 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); TENGRAPH (extract of Departmental database with mining tenements and holders); geology (solid and regolith); Landsat images; aeromagnetic data; radiometric data; gravity data; and topographic and cultural features.

Future work

A data package for the east Pilbara area (Report 81) will be released in 2001. Two data packages for the north Kimberley area and the Arunta–Musgrave area are planned for release in mid-2002. Two data packages for the west Kimberley and Canning areas are planned for release in late 2002. Compilation and digitizing of spatial data will continue for mineral occurrences and mineral exploration activities for the north Kimberley and west Kimberley areas, and will commence for the Arunta–Musgrave and Canning areas (Fig. 3).

Compilation and digitizing of additional spatial data will also be completed for an update of mineral occurrences and mineral exploration activities for the west Pilbara, using data from the latest WAMEX releases since 1999. The new digital data will be released on an updated CD-ROM in 2002.

A poster on the Geology and mineralization of the Pilbara Craton (at 1:500 000 scale) is to be prepared for the 4th International Archaean Symposium held in September 2001.

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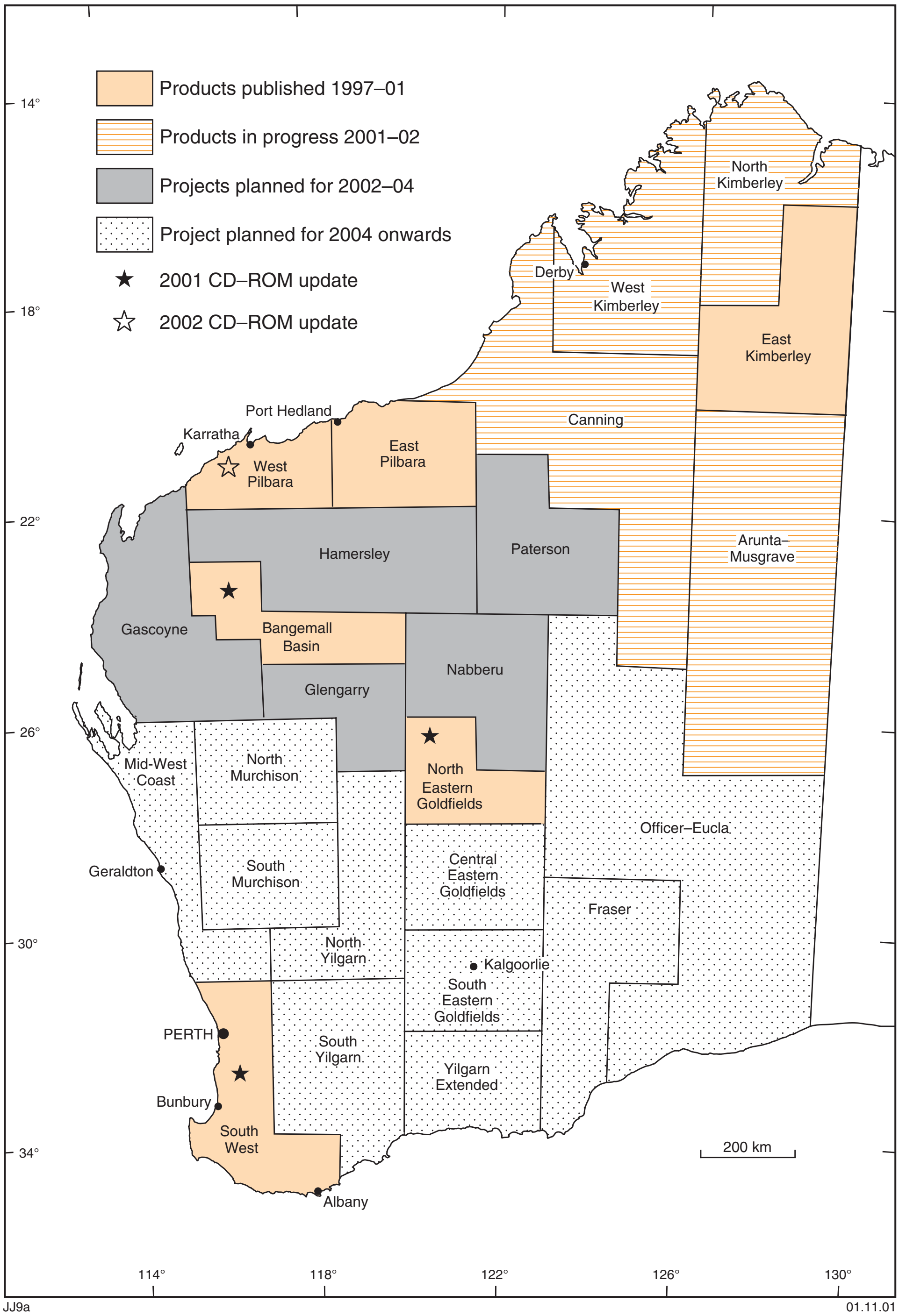

Figure 3. Progress of regional mineralization mapping projects

Urban and development areas geological mapping

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 hard-copy 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 2000–01

The regolith–landform mapping system was combined with an appraisal of potential for extracting basic raw materials to form the basis of the published maps and reports. Regolith–landform resources mapping involved the systematic collection of surface and near-surface material properties, and landform properties and patterns. Field data were added to the WAROX database, which continued to be tested in both the field and office. Map compilation in the field used 1-m and 0.5-m resolution orthophotographs and high-resolution digital elevation models, resulting in products with a high degree of spatial integrity. ArcView GIS software was used by the mapping geologists as the primary map-compilation tool, and the process of digital compilation was continually refined through the year.

Field mapping was completed for the Karridale–Tooker and Leeuwin 1:50 000 map sheets (Fig. 4) in 2000. An orientation survey of the Kalgoorlie area was completed in 2001, and mapping then commenced on the Kalgoorlie and Boulder 1:50 000 sheets.

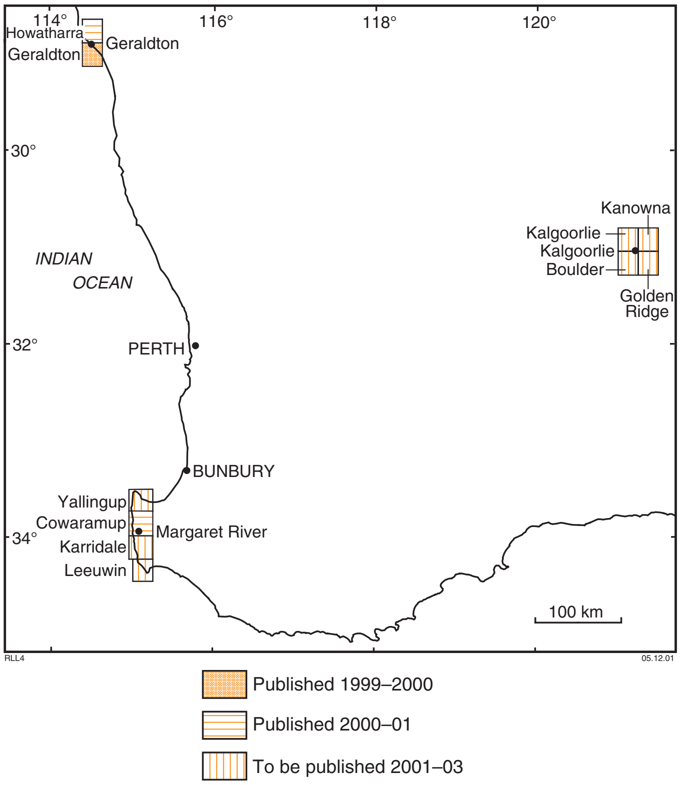

Figure 4. Progress of urban and development areas geological mapping

2000–01 publications and products

Record 2000/18: ‘Regolith–landform resources of the Cowaramup–Mentelle 1:50 000 sheet’ (including map and CD-ROM);

Record 2001/17: ‘Regolith–landform resources of the Howatharra 1:50 000 sheet’ (including map and CD-ROM).

Future work

The Karridale–Tooker and Leeuwin regolith–landform resources maps, report and CD-ROM will be published in 2001–02. Digital remastering and revisionary fieldwork will be completed on Yallingup in early 2002, leading to completion of a Cape-to-Cape dataset for this part of the South West Region.

The Kalgoorlie–Boulder regolith–landform resources maps, report and CD-ROM will be completed in 2001–02, and will have an increased emphasis on mineral resource data. Fieldwork for the Kanowna and Golden Ridge 1:50 000 sheets will commence in 2002.

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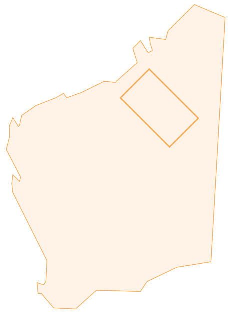
Subprogram 3103
REGIONAL GEOSCIENCE MAPPING

Lennard Shelf project



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

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

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

Seven maps of the outcrop belt, at scales of 1:250 000, 1:100 000, 1:50 000, and 1:25 000, and a Report on the subsurface geology, have been published.

Highlights and activities 2000–01

Fieldwork during the past year has concentrated mainly on the Permian–Devonian unconformity and Upper Devonian karst associated with major sequence boundaries in the reef complexes. The Lower Permian unconformity is a subglacial karst surface, with associated glacial pavements. Karst features include extensive caves, karst-corridor networks, major solution dolines, and collapse breccias. The study of the Permian–Carboniferous glaciation has also been extended to include other areas in various parts of the State, principally in the Pilbara Craton, Carnarvon Basin, and Perth Basin.

A major manuscript on exhalative mineralization and associated stromatolites in the Devonian reef complexes, by Phillip Playford and Malcolm Wallace, has been accepted for publication in Economic Geology.

Future work

Work will continue on the preparation of further relevant papers and a Bulletin dealing with the geology of the reef complexes. A field excursion for the International Palaeontological Congress will be conducted in the area during 2002.

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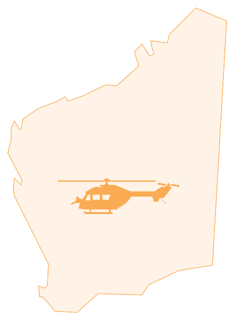
Regional regolith and geochemical mapping



Objective: *To determine the distribution and composition of surface material (regolith) over parts of Western Australia, and present these data as maps and digital datafiles to the mineral exploration industry.*

Twenty 1:250 000 map sheets have been covered since 1993 in the regional regolith and geochemical mapping project (Fig. 5).

Highlights and activities 2000–01

Maps and Explanatory Notes were published for the WINNING POOL – MINILYA and BYRO map sheets at 1:250 000 scale in 2000–01 (Fig. 5), and gravity was measured at each sampling site. Regolith sampling was completed on the NICHOLLS

1:100 000-scale map sheet, centred on an area of barite-hosted mineralization in part of the Officer Basin.

The interpretation of regolith mapping and geochemistry continues to be enhanced by the use of gravity collected during the regolith sampling program. A greater understanding of three-dimensional processes affecting the chemistry of regolith on WINNING POOL – MINILYA has been gained following the incorporation of information on regional structures. Combined gravity and regolith geochemical data has indicated the possibility of platinum-group element mineralization associated with ultramafic rocks on BYRO, and further indicated the mineralization potential of Phanerozoic sedimentary rocks to the west of the Narryer Terrane.

A talk highlighting the importance of combining regolith geochemistry with gravity was given at the GSWA open day in March 2001, and the scope and application of the GSWA's regional regolith geochemistry and gravity program was the focus of a trade display and talk presented at the 20th International Geochemical Exploration Symposium in Santiago in May 2001.

Regolith chemistry on the NICHOLLS 1:100 000-scale map sheet has included a comparison of a total analytical approach versus a partial extraction approach, in order to determine the best analytical protocols for exploration in sand-dominated terrains.

The GSWA regolith classification scheme continues to be widely used throughout the organization, with the scheme published as a GSWA Record and formally released at the GSWA open day in March 2001.

As part of an ongoing interest in expanding the regional geochemical database of Western Australia, GSWA acquired in excess of 300 000 soil and lag samples from WMC Resources Ltd collected over greenstones of the Yilgarn Craton and part of the Paterson Orogen.

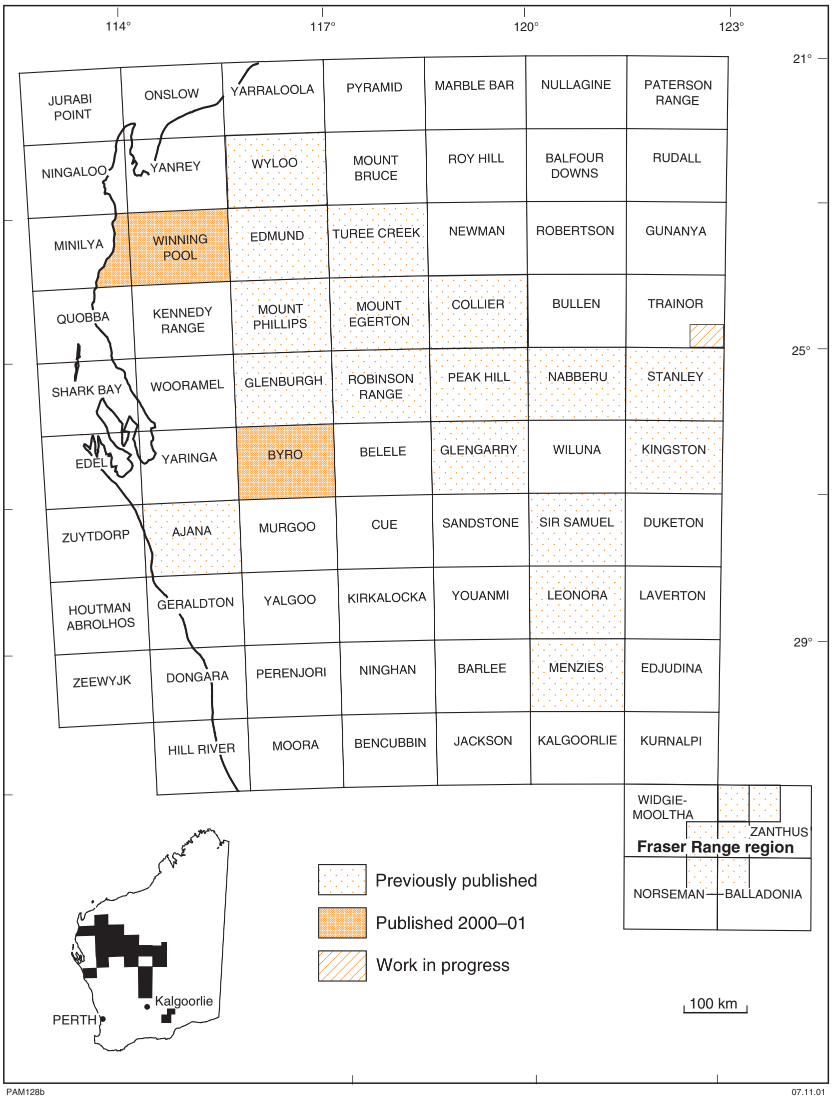


Figure 5. Progress of the regional regolith and geochemical mapping program

2000–01 publications and products

Explanatory Notes, maps, and digital data for WINNING POOL – MINILYA and BYRO;

Record 2001/4: 'A classification system for regolith in Western Australia';

Digital data (CD version) for the Fraser Range region.

Future work

During 2001–02, GSWA will release a regolith map, Explanatory Notes, and a digital dataset for the NICHOLLS 1:100 000 map sheet. Discussions will be held with relevant parties to gain access for the GSWA's regolith geochemistry and gravity program to areas in the eastern Kimberley region. As a member of the Cooperative Research Centre for Landscape Environments and Mineral Exploration (phase 2), GSWA intends to collect and subsequently analyse broadly spaced regolith samples over parts of the Yilgarn Craton, with the aim of producing a craton-wide geochemical map of surface deposits.

A program of compiling a State regolith map at 1:500 000 scale will commence, with the capture of data for the southern part of the State. This map will complement the State geology coverage at the same scale and provide valuable information on the distribution of transported regolith and regolith formed in situ.

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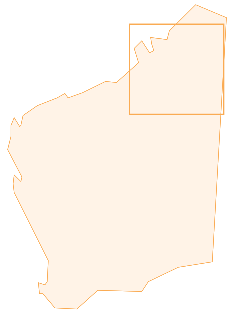
King Leopold and Halls Creek Orogens project



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 2000–01

Two papers were published in the Journal of the Geological Society of London: 'Geochronological constraints on tectonic models for Australian Palaeoproterozoic high-K granites' and 'High- and low-K granites and adakites at a Palaeoproterozoic plate boundary in northwestern Australia'.

I. M. Tyler presented a paper entitled 'Palaeoproterozoic plate collision in northern Australia: the Halls Creek Orogen' at the joint Geological Society of America and Geological Society of London meeting 'Earth System Processes' in June 2001. AGSO released a bulletin entitled 'Geology and economic potential of the Palaeoproterozoic layered mafic–ultramafic intrusions in the East Kimberley, Western Australia' to which we contributed.

Future work

During 2001–02, 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 the DIXON and TURKEY CREEK 1:100 000 map sheets (Fig. 6) will commence.

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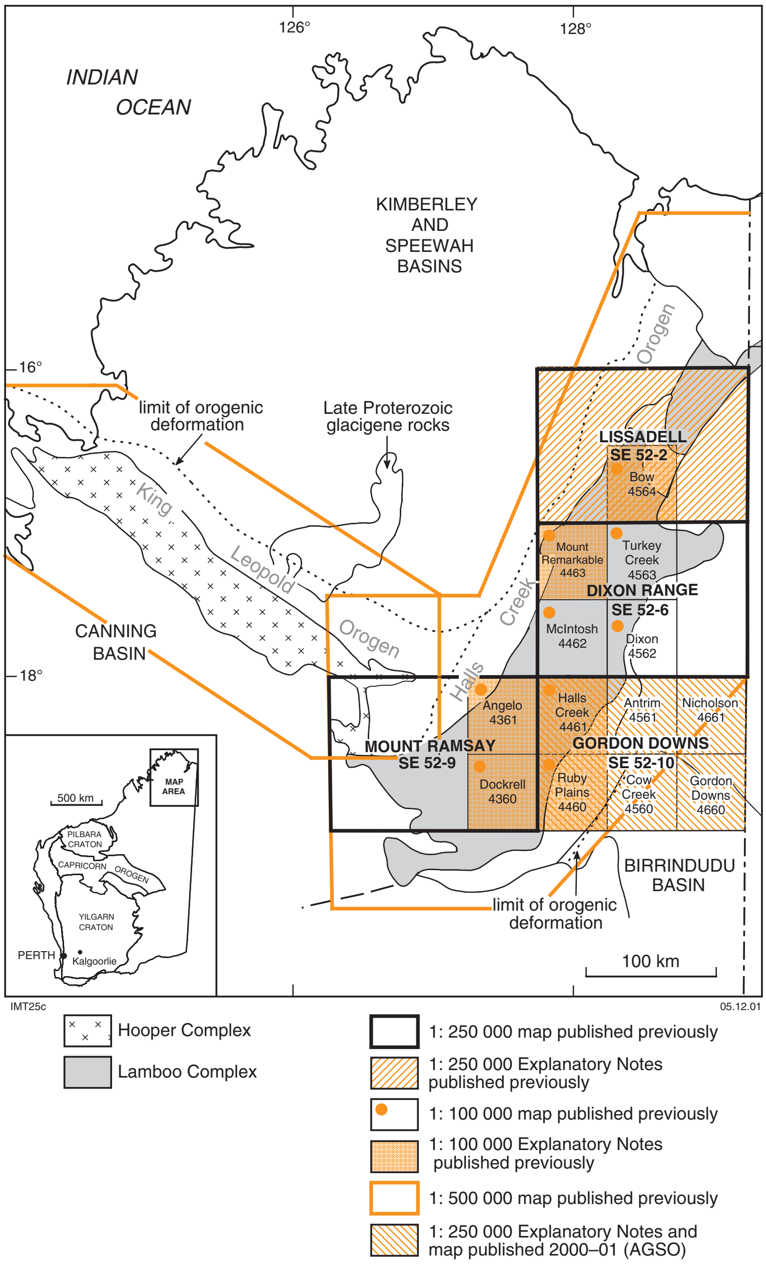
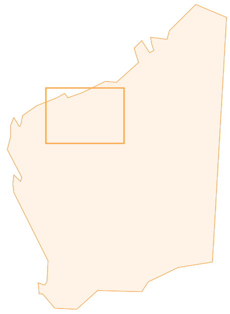


Figure 6. Progress of geological mapping across the King Leopold and Halls Creek Orogens

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. Over its ten year history the project will have resulted in the detailed remapping of a 70 000 km^2 area, publication of 28 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 Pilbara project. All published maps will be accompanied by Explanatory Notes that describe all aspects of the geology of individual sheets, whereas a number of GSWA Reports and papers in international journals will present both regional syntheses and the results of specialized research.

Highlights and activities 2000–01

In 2000–01, geological mapping was completed on the White Springs, Mount Edgar, Pardoo, and De Grey 1:100 000 maps, and commenced on the Yilgalong, Hooley, and Nullagine 1:100 000 maps. Mapping continued on the Eastern Creek, Marble Bar, and Carlindie sheets. This is a National Geoscience Mapping Accord (NGMA) project with AGSO, which contributed to the mapping and publication of the Wallaringa and Wodgina 1:100 000 sheets. Results of the project were the subject of public presentations at the GSWA 2001 open day in March 2001.

New information was obtained on the structural development of Archaean greenstone belts in the East Pilbara Granite–Greenstone Terrane (EPGGT), and this was presented orally at GSWA 2001. The new interpretation, based on field observations during the 1:100 000-scale mapping program, explains the structural environment of epigenetic gold mineralization over a large part of the east Pilbara. The interpretation also provides strong support for the existing diapiric tectonic model for the dome-and-syncline structures of the east Pilbara. Other highlights included the recognition of hydrothermal chert veins and dykes beneath many of the major sedimentary chert units of the east Pilbara. Evidence is accumulating to suggest that the distribution of stromatolites in the c. 3490–3430 Ma cherts of the Warrawoona Group may have been at least partly controlled by the locations of hydrothermal vents. This possibility has implications for the evolution of early life on Earth, and is now being examined by several research groups.

New SHRIMP U–Pb zircon geochronology, combined with new Sm–Nd isotopic data, has supported the interpretation that the c. 3650–2850 Ma EPGGT is separated from the c. 3270–2920 Ma West Pilbara Granite–Greenstone Terrane (which contains evidence of c. 3480–3300 Ma crust) by a belt of Archaean crust that is entirely younger than c. 3200 Ma. The younger crust is interpreted to have formed in a northeast-trending rift zone after separation of the two terranes, probably after c. 3270 Ma.

2000–01 publications and products

Satirist 1:100 000 Explanatory Notes;

Dampier 1:100 000 Explanatory Notes;

Warrawagine 1:100 000 Explanatory Notes;

Satirist 1:100 000 map sheet;

Preston 1:100 000 map sheet;

Wallaringa 1:100 000 map sheet;

Dampier – Barrow Island 1:250 000 map sheet.

Future work

The 2001–02 year will see the publication of the Wodgina, White Springs, Tambourah, Eastern Creek, Pardoo, De Grey, Split Rock, Hooley, and Cooya Pooya 1:100 000 maps, the Yarrie 1:250 000 map, and the Mallina Basin 1:250 000 special map. Explanatory Notes for the Roebourne 1:100 000 map, and the Roebourne 1:250 000 map will be published. Field guides on the east Pilbara and west Pilbara will be published as part of the 4th International Archaean Symposium held in Perth in 2001. Mapping will be completed for the Hooley, Carlindie, Coongan, and Eastern Creek 1:100 000 maps, and on the Port Hedland 1:250 000 sheet area. Recent 1:100 000 mapping will be used to complete compilation of a new Pyramid 1:250 000 map, which will be published in 2002–03. Field mapping for the Marble Bar, Yilgalong, and Nullagine 1:100 000 sheets, and for the Marble Bar and Nullagine 1:250 000 sheets, will be completed in 2002–03.

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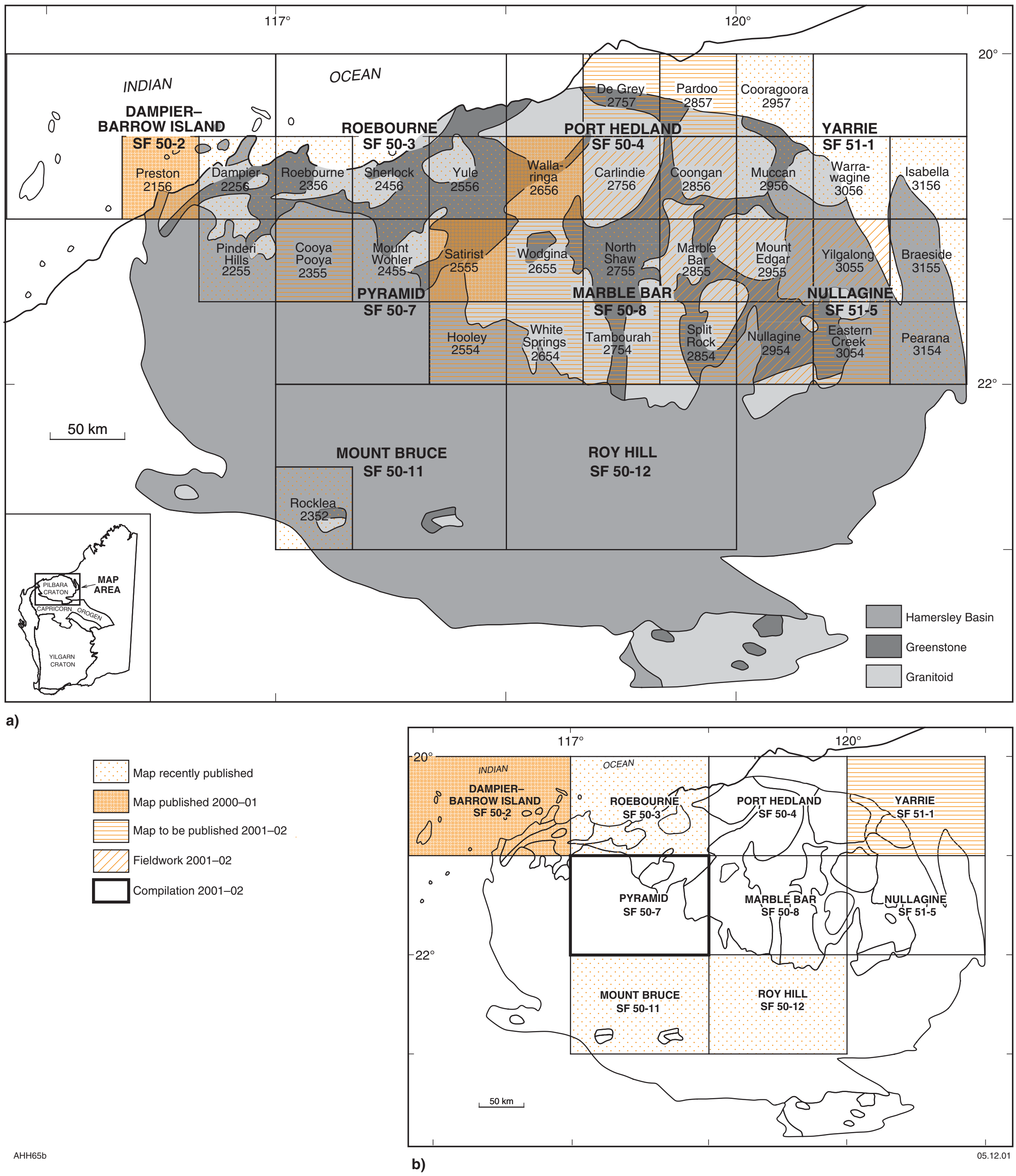
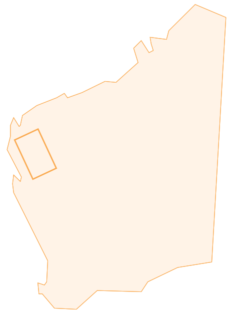


Figure 7. Progress of regional mapping in the Pilbara Craton

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 2000–01

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 the 2000 field season, two Honours students (based at Curtin University of Technology) from the Tectonics Special Research Centre mapped part of the CANDOLLE 1:100 000 sheet area. For the 2001 field season, two cooperative studies with students (based at Curtin University of Technology) from the Tectonic Special Research Centre commenced. Two Honours students remapped part of the MOUNT PHILLIPS 1:100 000 sheet area, and fieldwork for a PhD study by S. A. Occhipinti on ‘The tectonothermal evolution of the southern Capricorn Orogen’ began on the GLENBURGH 1:250 000 sheet area. As part of this study, samples from shear zones are being processed for Ar–Ar geochronology.

Compilation for a 2nd edition ROBINSON RANGE 1:250 000 map sheet was completed and writing of the accompanying Explanatory Notes commenced. GSWA staff completed a guide to accompany the excursion to the Narryer Terrane and southern Gascoyne Complex, as part of the 4th International Archaean Symposium held in Perth in September 2001. S. A. Occhipinti and S. Sheppard also submitted an extended abstract ‘Stuck between two cratons — latest Archaean crust in the Gascoyne Complex’ for the symposium.

S. A. Occhipinti presented a paper ‘Links between regional-scale deformation and granite generation: the Yarlarweelor Gneiss Complex, Western Australia’ at the Specialist Group in Tectonics and Structural Geology Conference at Ulverstone, Tasmania. At the GSWA 2001 open day in March 2001, S. Sheppard presented a paper ‘The tectonic setting of granites in the southern Gascoyne Complex’.

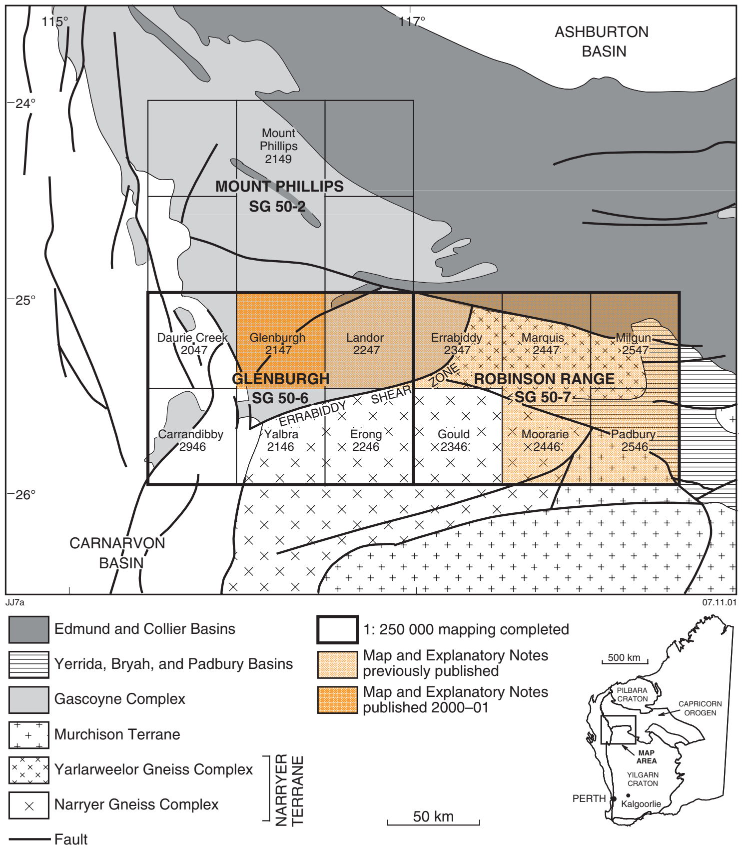


Figure 8. Progress of geological mapping for the southern Gascoyne Complex project

2000–01 publications and products

GLENBURGH 1:100 000 Explanatory Notes;

GLENBURGH 1:100 000 map sheet.

Future work

Compilation for a 2nd edition GLENBURGH 1:250 000 map sheet will commence during 2001–02. Explanatory Notes for the 2nd edition ROBINSON RANGE 1:250 000 map sheet will also be written during this period.

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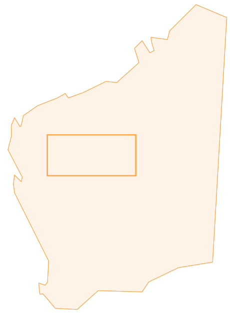
Bangemall Supergroup project



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, blind, sediment-hosted base-metal orebodies. The Bangemall Supergroup also has a history of minor gold and phosphate production.

Highlights and activities 2000–01

Fieldwork on the northwestern outcrop of the Bangemall Supergroup during 2000–01 has involved detailed mapping in the EDMUND and KENNETH RANGE 1:100 000 map sheet areas (Fig. 9). On EDMUND, sandstone from the Kiangi Creek Formation was sampled for provenance studies, and geochronological and geochemical sampling of the Gascoyne Complex was carried out. Perth-based activities have included the compilation of geological data for EDMUND and analysis of field data.

Remapping of the Bangemall Supergroup on EDMUND and KENNETH RANGE has resulted in significant advances in the understanding of this important stratigraphic unit. This work has confirmed the presence of an unconformity between the Edmund and Collier Groups and also suggests an unconformity may be present at the base of the Kiangi Creek Formation.

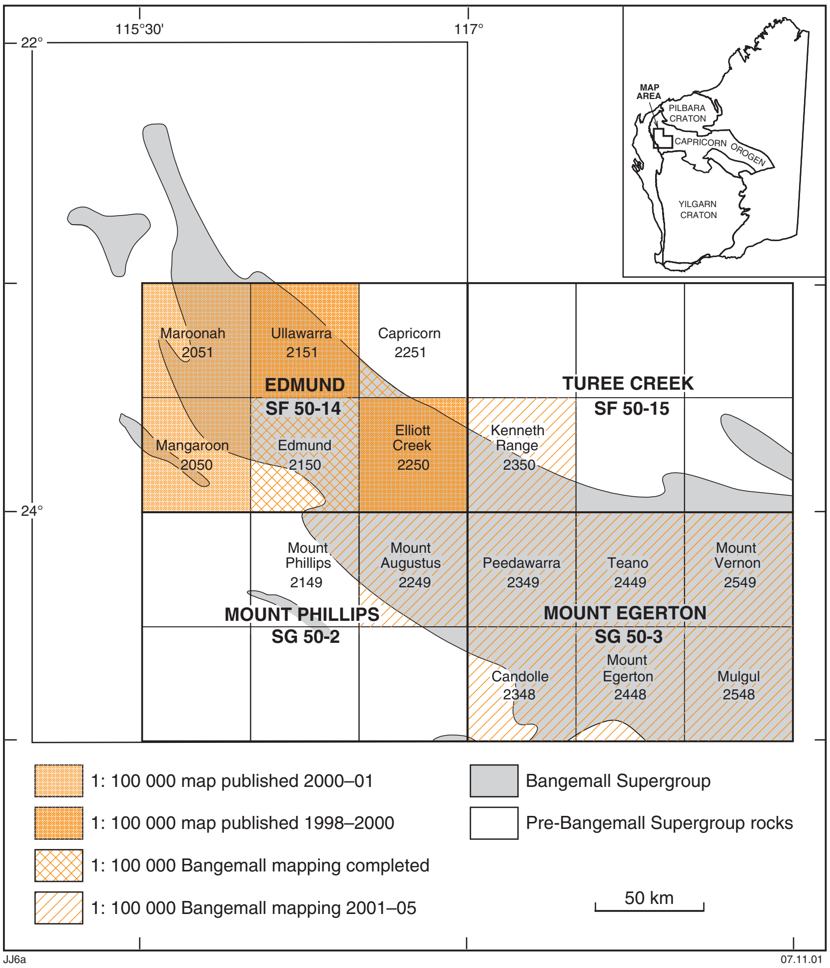


Figure 9. Progress of geological mapping for the Bangemall Supergroup project

Constraints on the relative age of the Bangemall Supergroup have been significantly improved by SHRIMP U–Pb dating of both detrital zircons, carried out in collaboration with P. Cawood and A. Nemchin of Curtin University of Technology, and of dolerite intrusions, in collaboration with M. Wingate of the University of Western Australia. The Edmund Group is older than the c. 1465 Ma dolerite sills that intrude it, and is probably younger than the 1619 Ma Discretion Granite in the Gascoyne Complex. Dolerite sills that intrude both the Edmund and Collier Groups constrain the minimum age of the Collier Group to c. 1070 Ma. Detrital zircons from the Bangemall Supergroup constrain a maximum age of c. 1200 Ma for the Backdoor Formation, suggesting a minimum 250 m.y. gap between the Edmund and Collier Groups. Deformation of the Bangemall Supergroup during the Edmundian Orogeny is younger than the

c. 1070 Ma sills, but older than the crosscutting 755 Ma Mundine Well dyke swarm.

A paper entitled 'Another Jillawarra-style sub-basin in the Bangemall Supergroup — implications for mineral prospectivity' was published in the GSWA Annual Review for 1999–2000.

2000–01 publications and products

Mangaroon 1:100 000 preliminary release map sheet;

Maroonah 1:100 000 preliminary release map sheet.

Future work

Mapping of Bangemall Supergroup rocks on Kenneth Range, Capricorn Formation rocks on Capricorn, and Gascoyne Complex rocks on Maroonah is to be completed during the 2001–02 field season. Principal objectives are to complete geological mapping of Capricorn Orogen rocks on the Edmund 1:250 000 map sheet, to further test and implement the revised stratigraphy for the Bangemall Supergroup on Kenneth Range, and to identify and sample suitable targets for U–Pb zircon geochronology, provenance studies, and geochemistry.

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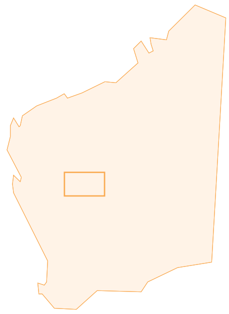
Earaheedy Basin project



Objective: *To increase geoscientific knowledge of the Earaheedy Basin, one of the Capricorn Orogen's Proterozoic tectonic units, 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 on the Earaheedy Basin project commenced in 1997 and in 1998–99 three 1:100 000-scale maps were published (Fairbairn, Nabberu, and Merrie; Fig. 10). This initial work resulted in a revision of the existing lithostratigraphy, and in 1999–2000 four new 1:100 000-scale geological maps were published (Methwin, Granite Peak, Earaheedy, and Rhodes). In addition to continued revision of the lithostratigraphy, an understanding of the geodynamic evolution of the basin posed a challenge that was rendered particularly difficult by the paucity of precise geochronological constraints. Continuing fieldwork, and new geochronological data obtained during 2000–01 from the Earaheedy Basin, nearby terranes, and other projects (Gascoyne and Bangemall), has provided an insight as to the geodynamic evolution of the basin, within the framework of the Capricorn Orogen. Fieldwork in the Earaheedy Basin has, of necessity, overflowed onto adjacent terranes to the north, resulting in the recognition of a new Mesoproterozoic igneous province (Glenayle and Prenti Dolerites), which has potential for Ni and platinum-group element (PGE) mineralization.

Highlights and activities 2000–01

The Palaeoproterozoic Earaheedy Basin in Western Australia contains the Earaheedy Group, and lies at the eastern end of the Capricorn Orogen. Geological mapping carried out during the past four years has led to a revision of the stratigraphy, the development of a new model for basin evolution, and a better understanding of the origin of known mineralization and the potential for undiscovered mineral resources. Collaborative work with researchers from Curtin University of Technology and the Australian National University has also better constrained tectonic and timing relationships between the Earaheedy Basin and the Capricorn Orogen.

The c. 1.9 – 1.8 Ga Earaheedy Basin lies at the easternmost end of the Capricorn Orogen and unconformably overlies rocks of the Yilgarn Craton, Yerrida Basin, and possibly the Bryah Basin. The Earaheedy Basin developed in a passive margin setting, and was much larger than its present-day exposure, extending further to the southwest, to the north, and to the east, where it is masked by the overlying Mesoproterozoic Collier and Officer Basins. The Earaheedy Basin is characterized by a 5 km-thick package of shallow-marine clastic and chemical sedimentary rocks, the Earaheedy Group, which is divided into two subgroups, each representing a different phase

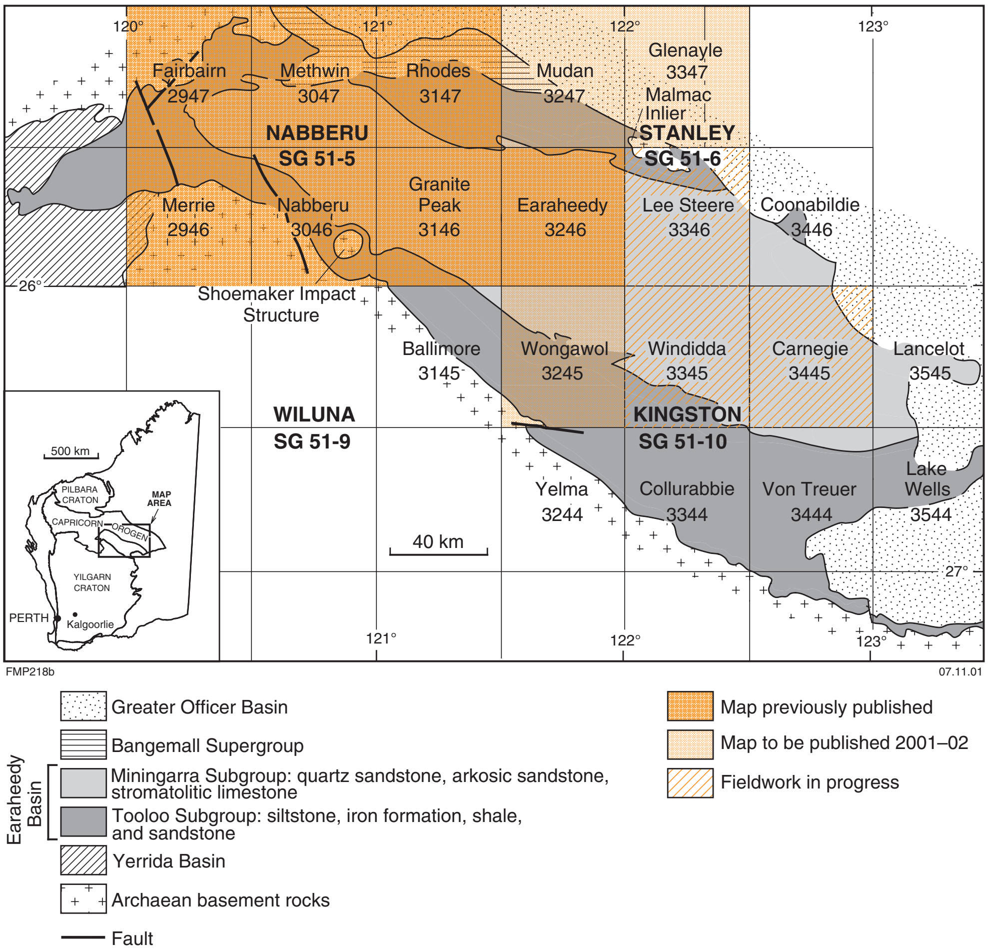


Figure 10. Progress of geological mapping for the Earaheedy Basin project

in the geodynamic history of the basin. There was no known igneous activity in the Earaheedy Basin during deposition of the group.

In addition to the potential for iron ore within the Frere Formation, known mineralization in the Earaheedy Basin includes Mississippi Valley-type Pb–Zn–Cu deposits in the Sweetwaters Well Member, near the Shoemaker Impact Structure, and the large (>200 Mt) Magellan Pb deposit, which is spatially associated with the unconformity between outliers of the Yelma Formation and the Yerrida Group in the Yerrida Basin. Minor stratiform Mn and Fe oxides, with anomalous abundances of Cu, Ba, and Pb, are present within the shale units of the Karri Karri Member and Wongawol Formation. These areas are coincident with widespread regolith geochemical anomalies that are spatially associated with dolerite intrusions. Gold mineralization is present in the Stanley Fold Belt (a zone of deformation along the presently exposed northern margin of the Earaheedy Group), where it is hosted by mylonite and quartz veins.

The Earaheedy project also includes mapping and the study of rocks from adjacent tectonic units such as the Edmund and Collier Basins (Mesoproterozoic) and the Officer Basin (Neoproterozoic), and mafic igneous rocks (Glenayle and Prenti Dolerites). The Glenayle Dolerite intrudes units of the Officer Basin (Sunbeam Group) and Collier Basin (Collier and ?Salvation Groups), and may be part of a large igneous province with potential for Ni and PGE mineralization. This potential is confirmed by regolith geochemical anomalies.

GSWA's work in the area throughout the year included geological mapping, and geochemical and mineralization studies of Earaheedy Group rocks and adjacent mafic igneous rocks. During the year field geological mapping was completed for GLENAYLE and WONGAWOL, and was commenced for the LEE STEERE, WINDIDDA, and CARNEGIE 1:100 000 map sheets. A comprehensive study linking bedrock geology and regolith geochemistry was also completed, and a paper presented at the 20th International Geochemical Exploration Symposium held in Chile. The revised stratigraphy of the Earaheedy Group was published in the GSWA Annual Review 1999–2000, together with two other papers on Mesoproterozoic stratigraphy and mineralization. An article on auriferous barite in the Quadrio Lake area (Officer Basin) was published in the Prospect magazine. Two other publications were compiled for publication in external journals, and two papers were presented at the 15th Australian Geological Convention in Sydney in July 2000.

2000–01 publications and products

Record 2000/16: 'Revised lithostratigraphy for Proterozoic rocks in the Earaheedy Basin and nearby areas';

FAIRBAIRN 1:100 000 Explanatory Notes;

EARAHEEDY 1:100 000 Explanatory Notes.

Future work

Work planned for 2001–02 includes field mapping for the LEE STEERE, CARNEGIE, and WINDIDDA 1:100 000 map sheets, and compilation of the 2nd edition 1:250 000 geological map of NABBERU. Field mapping will commence for VON TREUER and COLLURABIE in 2002. There will be a continuation of studies of the basin tectonics and associated mineralization, publication of the MUDAN, GLENAYLE, and WONGAWOL 1:100 000 maps, and the Explanatory Notes for METHWIN, NABBERU – GRANITE PEAK, and RHODES will be completed. Report 82 on the Shoemaker Impact Structure will be finalized.

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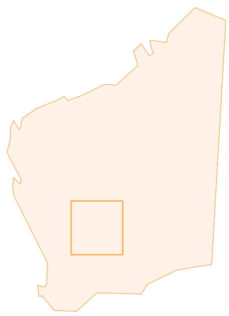
East Yilgarn project

Objective: *To increase geoscientific knowledge of the East Yilgarn terrane by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps, GIS-based seamless geological databases, 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 eastern two-thirds of the Yilgarn Craton and contains the highly mineralized Eastern Goldfields and Southern Cross Granite–Greenstone Terranes (Fig. 11). The Yilgarn Craton, with its extensive areas of Archaean granitoid and greenstone belts, hosts numerous world-class gold and nickel deposits. The project embodies the Kalgoorlie regional office, the Joe Lord Core Library, and the Eastern Goldfields.

Highlights and activities 2000–01

The Joe Lord Core Library was officially opened on 17 July 2000 by the Premier of Western Australia, the Hon. Richard Court MLA, and the then Minister of Mines, the Hon. Norman Moore MLC. The core library is part of the new facility in Kalgoorlie–Boulder that also houses a geoscientific information centre and an operational base for projects in the region. This new facility is an important asset to the mining and exploration industry in the Eastern Goldfields. With support from the mining industry, collection of historical or heritage drillcore has commenced. A number of significant holes have been acquired, including 'KD1' — the discovery hole for the nickel sulfide mineralization at Kambalda, and 'WWD3' — a very long hole drilled to test for a deep western repetition of the Golden Mile.

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. It also provides access to the WAMEX open-file database, GSWA publications, GSWA digital information, and past mining-tenement plans. The Kalgoorlie office is also the operational base for field geological staff involved in the Eastern Goldfields regional mapping projects. Staff involved in the development of an inventory of abandoned mine sites in the Kalgoorlie region, and the urban and development areas geology team mapping the KALGOORLIE 1:50 000 sheet also use the Kalgoorlie office as their operational base.

Good cooperative relationships have continued to be maintained with the Western Australian School of Mines (WASM) and AGSO, and the Kalgoorlie office has also been involved with the local branch of the Australasian Institute of Mining and Metallurgy (AusIMM). Kalgoorlie staff participated in the organization of a JORC (Joint Ore Reserve Committee) workshop.

In October 2000, a combined GSWA and AGSO open day was again held in Kalgoorlie. In addition to the posters and displays, a series of talks was presented on the recent activities of GSWA and AGSO in the Yilgarn Craton.

During the year, the second phase of the development of the GIS-based seamless East Yilgarn digital geoscience database was completed. This second phase covers an area from Cunyu to Cosmo Newbery and incorporates seamless digital coverage of eighteen 1:100 000 geological outcrop maps. The themes included in the database are 1:100 000 outcrop geology and structures, mineral location and

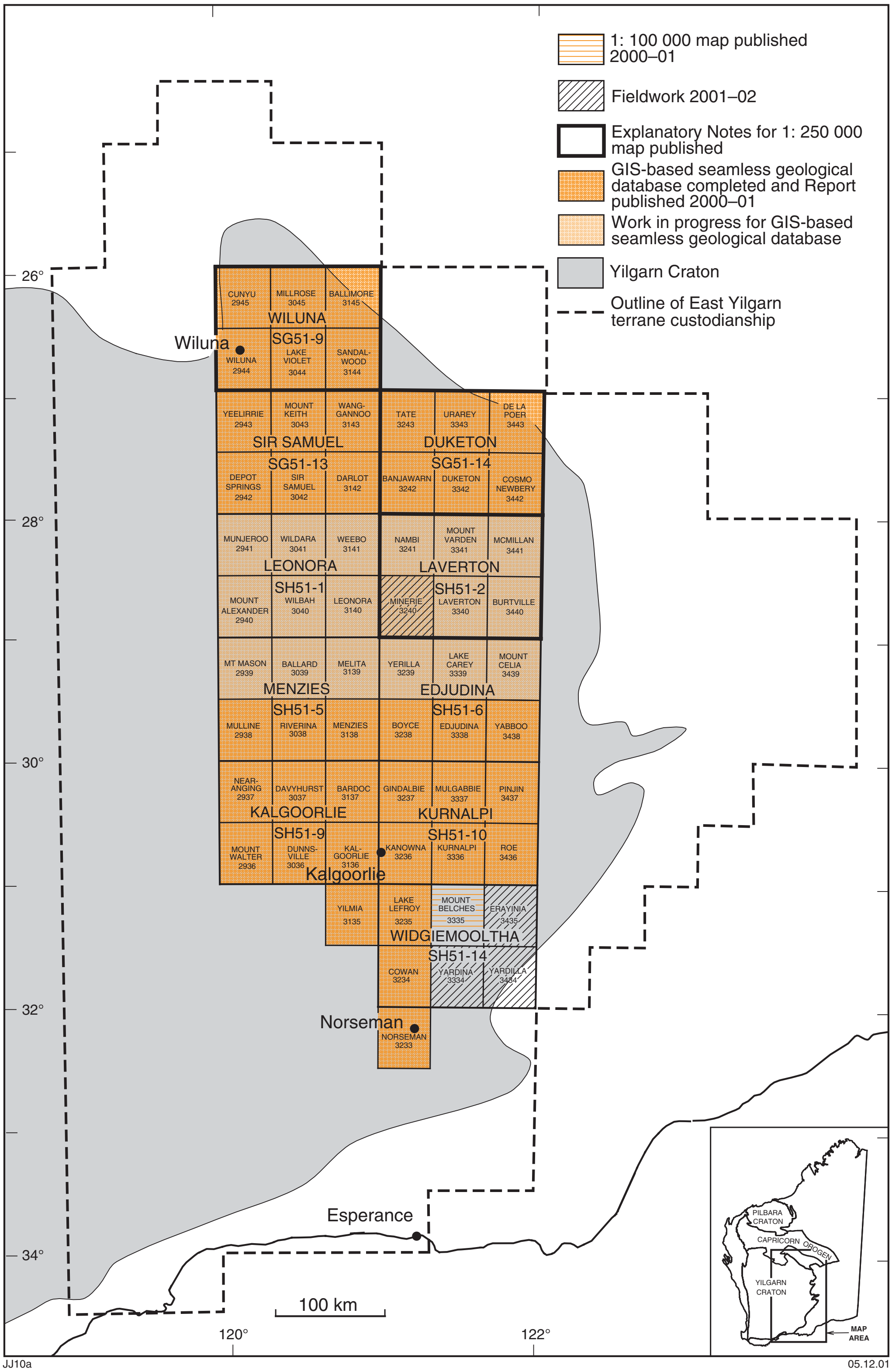


Figure 11. Progress of geological mapping in the east Yilgarn region and progress towards the GIS-based seamless digital database

resource data (MINEDEX), tenement and geographic information (TENGRAPH), Landsat images, aeromagnetic coverage, and 1:500 000 interpretative geology. The data is supplied in a number of computer formats suitable for computer software, including ArcInfo, ArcView, and MapInfo.

A spin-off of the seamless digital database has been the development of RoxMAP.WA — a facility to produce hard-copy maps of any part of the area covered by the database. In November 2000, RoxMAP.WA was awarded a High Commendation in the Innovation category of the Premier's Awards for Excellence in Public Sector Management. RoxMAP.WA is available in the Kalgoorlie regional office and in Mineral House, Perth.

Fieldwork has commenced for the third phase of the GIS-based seamless digital geoscience database. 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.

2000–01 publications and products

LAVERTON 1:250 000 Explanatory Notes;

DUKETON 1:250 000 Explanatory Notes;

WILUNA 1:250 000 Explanatory Notes;

MOUNT BELCHES 1:100 000 map sheet;

Report 78: 'East Yilgarn Geoscience Database, 1:100 000 geology Menzies to Norseman — an explanatory note';

Report 83: 'East Yilgarn Geoscience Database, 1:100 000 geology of the north Eastern Goldfields Province — an explanatory note'.

Future work

Development of the East Yilgarn Geoscience Database will continue, with the release of the Leonora–Laverton 1:100 000 digital geological data package and Report.

GSWA Records on metamorphism in the Kalgoorlie region, and whole-rock geochemical data for the Gordons area, and a mineral occurrence dataset for the WOOLGANGIE and YILMIA 1:100 000 map sheets, will be completed in 2001–02.

Fieldwork will commence on the MINERIE, ERAYINIA, YARDINA, and YARDILLA 1:100 000 sheets, and a draft Report will be completed on gold mineralization in the Edjudina–Kurnalpi–Kanowna area.

Acquisition of drillcore for the Joe Lord Core Library will continue and a Record will be published on the selection criteria used for drillcore collection.

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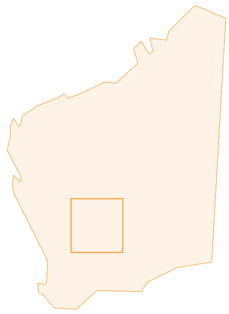
Central Yilgarn (Southern Cross) project



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 five 1:100 000 sheets have been published to date (JOHNSTON RANGE, LAKE GILES, JACKSON, BARLEE, and BUNGALBIN).

Highlights and activities 2000–01

In 2000–01, fieldwork and compilation of the EVERETT CREEK and RICHARDSON 1:100 000 sheets was completed, and field mapping on the ATLEY 1:100 000 sheet began. Further fieldwork was carried out on the MENZIES 1:250 000 sheet, and this sheet is currently being compiled (Fig. 12).

During 2000–01, 12 new SHRIMP U–Pb isotopic ages were acquired and published, and a further 16 samples were collected for analysis. A composite dataset providing aeromagnetic coverage of the SANDSTONE 1:250 000 sheet was acquired for use in field mapping programs, and for public-domain release. Other activities included the preparation of a comprehensive excursion guide to the central Yilgarn for the 4th International Archaean Symposium, the completion and publication of an external paper on the structural evolution of the Marda–Diemals region, and the preparation of a paper for external publication describing stratigraphic correlations in the Marda–Diemals greenstone belt.

The proposed stratigraphy for the Marda–Diemals greenstone belt

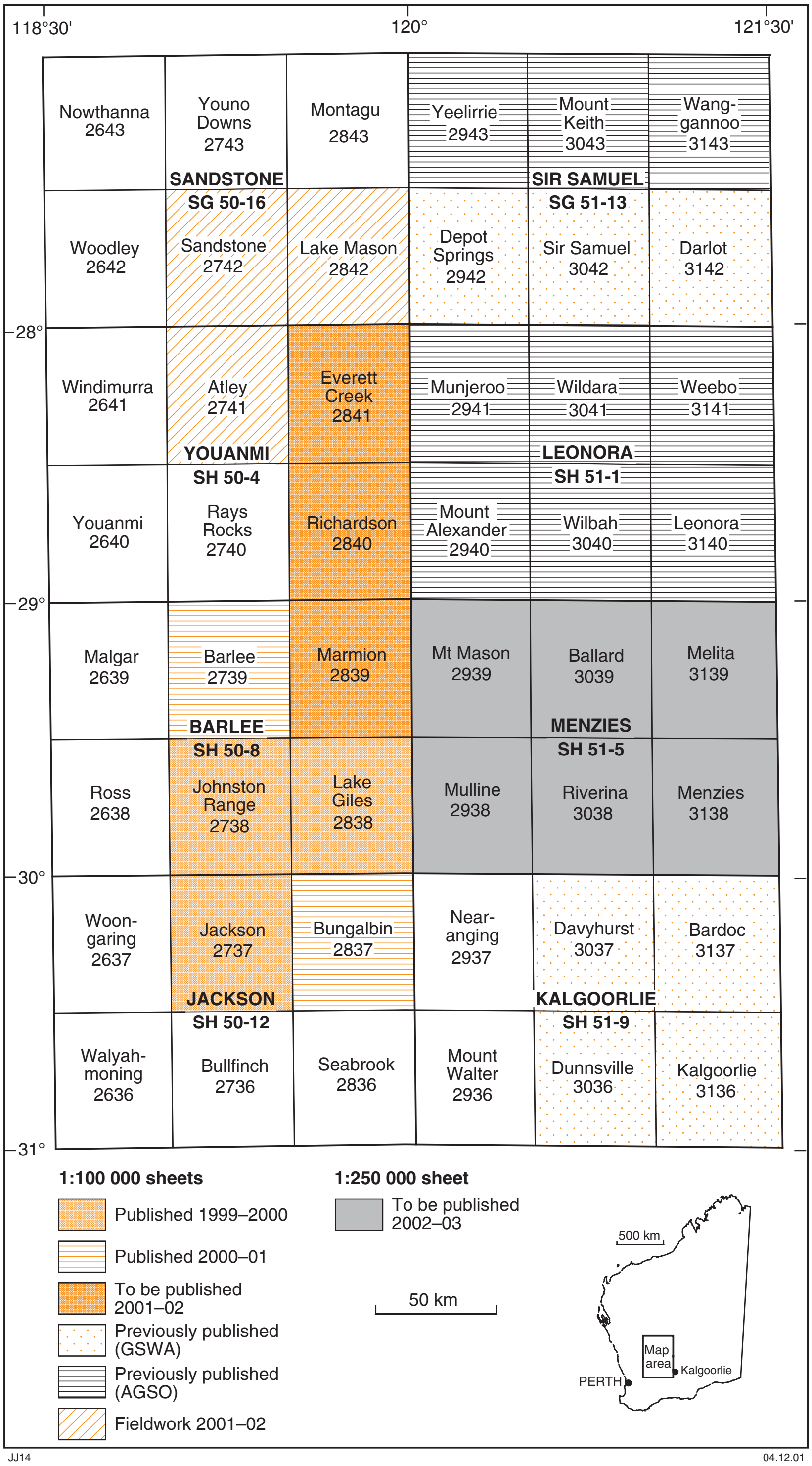


Figure 12. Progress of geological mapping for the central Yilgarn (Southern Cross) project

comprises a lower and an upper greenstone succession. The lower greenstone succession contains three associations, with the regional correlation based on the middle association. This association is marked by several units of banded iron-formation, and forms a prominent feature on aeromagnetic images. The upper and lower associations are characterized by abundant mafic rocks. The age of the lower greenstone succession is poorly constrained at c. 3.0 Ga.

The upper greenstone succession in the Marda–Diemals greenstone belt comprises the calc-alkaline c. 2.73 Ga Marda Complex, and clastic sedimentary rocks of the Diemals Formation that have a maximum depositional age of c. 2.73 Ga. The upper succession, which has a faulted and locally unconformable contact with the lower succession, appears to have been emplaced in an overall compressional regime.

2000–01 publications and products

Johnston Range 1:100 000 Explanatory Notes;

Lake Giles 1:100 000 Explanatory Notes;

Barlee 1:100 000 map sheet;

Bungalbin 1:100 000 map sheet.

Future work

The Marmion, Everett Creek, and Richardson 1:100 000 map sheets will be published in 2001–02. Fieldwork on the Atley 1:100 000 sheet will be completed in 2001–02, and work will commence on the Sandstone and Lake Mason 1:100 000 sheets. Compilation of the 2nd edition Menzies 1:250 000 sheet will be completed, and this map will be released the following year. Explanatory Notes will be completed for the Jackson and Everett Creek 1:100 000 sheets, and draft Explanatory Notes will be written for the Bungalbin 1:100 000 sheet.

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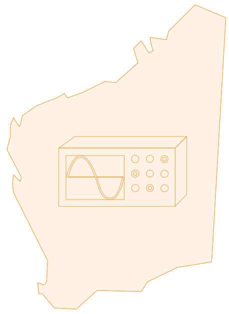
Subprogram 3104 SCIENTIFIC, TECHNICAL, AND FIELD SUPPORT

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 2000–01

Almost 70 samples were dated by the SHRIMP U–Pb zircon, baddeleyite, and monazite techniques, with typical precision of ± 6 Ma, for incorporation into GSWA geological maps and projects. Samples included dolerites from the Edmund and Collier Basins (Bangemall Supergroup), granitic and volcanic rocks from the Gascoyne, Pilbara, and Southern Cross regions, and sedimentary rocks from the Edmund, Collier, Earaheedy, and Yeneena Basins. GSWA Record 2001/2 will document all results from the geochronology work undertaken during calendar year 2000.

During the year, efficient new laboratory procedures for the isolation of baddeleyite were successfully implemented. Improvements were also made to the data-processing software for clearer presentation in Record 2001/2 of analytical data obtained from sedimentary rock samples. Assessment of the Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICPMS) technique for Hf isotopic and reconnaissance U–Pb provenance investigations is in progress. New photomicrography equipment is currently being assessed that may enable the publication of digital images of the minerals analysed for geochronology on CD. These could then be released with the annual GSWA geochronology Record.

Future work

Further sampling is planned for the Pilbara, Southern Cross, and Bangemall regions before the end of 2001–02.

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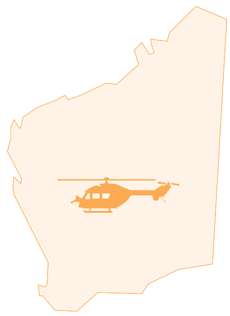
Geophysics



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

During 2000–01, GSWA and AGSO contracted Kevron Geophysics to acquire approximately 30 000 line km of new 400-m magnetic and radiometric data over the SANDSTONE 1:250 000 sheet area. The new data were merged with 40 000 line km of older private company data that were purchased in conjunction with AGSO to provide complete coverage of the sheet area at survey line spacings from 200 to 400 m. The located and gridded data were made available for public access, and 1:250 000 radiometric and magnetic images of the map sheet area were released.

Magnetic and radiometric data and imagery, from a multiclient regional airborne dataset covering 60 000 km^2 in the Bangemall–Gascoyne region, have been made available for public access. The region includes MOUNT PHILLIPS and parts of the EDMUND, MOUNT EGERTON, COLLIER, GLENBURGH, and ROBINSON RANGE 1:250 000 sheet areas. The release follows negotiations with Fugro Airborne Surveys to acquire joint ownership and copyright of the data (1999–2000).

Three 1:500 000-scale series airborne magnetic maps, from variable line spaced data (200–500 m), were released during 2000–01. These were image maps of the Bangemall–Gascoyne region, Yandal greenstone belt and adjacent areas, and the Earaheedy Basin.

In June 2001, GSWA and AGSO released the 'Gravity anomaly map of Western Australia', a Statewide summary of data held in the National Gravity Database at AGSO. The map incorporates results from the latest surveys that were undertaken by AGSO and GSWA, and previously confidential company data. It forms a companion product to the 'Geological map of Western Australia' released by GSWA in 1998 and the 'Magnetic anomaly map of Western Australia' released in 2000.

Airborne geophysical survey register and data repository

During 2000–01, 82 new airborne survey datasets, containing approximately 510 000 line km of various magnetic, radiometric, digital elevation, and electromagnetic data, were received for inclusion in the web-available Minerals and Energy Airborne Geophysical Information eXchange (MAGIX) data repository. About 2.4 million line km of private data from almost 439 surveys are now held in the repository.

Most of the companies submitting data have agreed to make public the location and basic specifications of their surveys; this information is available through a graphical interface on the Department's web-site (www.mpr.wa.gov.au).

Regional gravity surveys

GSWA continued its helicopter-assisted regional geochemistry and gravity survey program, with one field program during 2000–01 over the BYRO 1:250 000 sheet area. A total of 1273 gravity readings were taken on an irregular 4-km grid using La Coste and Romberg gravity meters (on loan from AGSO). Height control to an accuracy of 0.5 m was achieved with the use of differential GPS receivers in the survey helicopters.

2000–01 publications and products

Record 2000/19: 'Gravity data — Kingston and Stanley 1:250 000 sheets, Western Australia';

Record 2001/3: 'Gravity data — Winning Pool – Minilya 1:250 000 sheets, Western Australia';

Gravity anomaly map of Western Australia;

BYRO gravity image;

MOUNT PHILLIPS total magnetic intensity image;

SANDSTONE total magnetic intensity image;

Bangemall–Gascoyne region total magnetic intensity image;

Yandal greenstone belt total magnetic intensity image;

Earaheedy Basin total magnetic intensity image;

MOUNT PHILLIPS ternary radiometric image;

SANDSTONE ternary radiometric image;

SANDSTONE airborne geophysics dataset;

BARLEE–JACKSON airborne geophysics dataset;

Bangemall airborne geophysics dataset.

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Carlisle operations

Objectives:

- *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 core library facilities in both Perth and Kalgoorlie to service the needs of industry and GSWA*
- *To ensure quality laboratory services for the preparation of samples for geochronology and other laboratory requirements*
- *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*

The Carlisle operations team provides a wide range of support services to geoscientists, including vehicles, equipment, field assistants, and laboratory services. Construction of the new Kalgoorlie J. H. (Joe) Lord Core Library and Operational Base was completed in June 2000, and was officially opened by the Premier, the Hon. Richard Court MLA, on 17 July 2000. Four hundred pallets of carefully selected historical core have been collected from the Eastern Goldfields and already archived in the new facility. Funding for the construction of an 8800-pallet core storage facility to be built at Carlisle has been approved and construction will commence in February 2002. The project will be completed by the end of 2002 and, in conjunction with the Kalgoorlie facility, will provide storage for more than 11 000 pallets. This facility will provide industry with the most advanced system of drillcore storage in Australia and accommodate sufficient storage for the next 15 years.

The trend of increased demand for public access to local core storage facilities at Dianella, Carlisle, and Star Street storage has continued to grow. During the year, 167 visitors spent 980 hours viewing core and cuttings, and took 1857 samples for further analysis. More than 500 sets of cuttings and 550 pallets of mineral exploration core were accessioned into the collection during the year. Forty pallets of rock-pulp samples were also collected and archived for future analysis.

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.

The Geological Survey's laboratory at Carlisle continued to maintain its focus on the preparation of samples for geochronological analysis by SHRIMP. A total of 82 samples were processed for SHRIMP analysis for the year. In addition to this work, laboratory staff were responsible for the supervision and quality control of 1036 thin and polished thin sections, and 57 polished rock surfaces were prepared by external contract service providers.

Provision of most field assistants by an employment agency continues to allow flexibility in meeting short-term needs for field staff at short notice.

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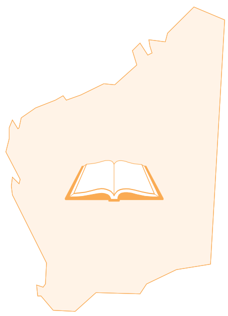
Subprogram 3105
GEOSCIENCE EDITING AND PUBLISHING

Publications and promotion

Objectives:

- *To provide a quality and timely editing and publishing service for geoscientific manuscripts and maps produced by Geological Survey geoscientists*
- *To promote GSWA products and services through displays, advertising, and other promotional events*
- *To monitor product sales and develop marketing strategies to ensure products are reaching the appropriate market*
- *To provide information and advice for the general public on all aspects of Western Australian geology*



Editing and publishing

During 2000–01, a total of thirty-eight manuscripts were edited, illustrated, and published (Appendix, p. 118).

Explanatory Notes to accompany published maps continued to dominate our manuscript output. Of the thirty-eight manuscripts published for the year, fourteen were Explanatory Notes. The remainder included one major Bulletin (on the Fortescue Group), six substantial Reports, eleven Records, the GSWA Annual Review, and several miscellaneous publications. An increasing number of Geological Survey publications are now being provided with digital datasets enclosed. In 2000–01 seventeen such packages were released, mostly on CD-ROM in GIS format, and several with self-loading viewing software. The Publications section provided editorial services for these products, and graphic design for their packaging.

Geoscience editorial services were also provided to support the thirty-three geological maps, cross sections, well correlations, and geophysical images released during the year (Appendix, p. 118).

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, and resulted in more than fifty media articles covering GSWA work in 2000–01.

Publication of Fieldnotes (the GSWA quarterly newsletter first published in January 1996) continued during 2000–01 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:

- Conference of Australian Science Teachers' Association (Perth, July)
- Fifteenth Australian Geoscience Convention (Sydney, July)
- Yandal Belt Symposium (Perth, July)
- Diggers and Dealers Conference (Kalgoorlie, July)
- International Geoscience Convention (Brazil, August)
- Mining 2000 Convention (Melbourne, September)
- American Association of Petroleum Geologists International Conference (Bali, October)
- Western Australian Land Information System (WALIS) Resource Data Management Conference (Perth, November)
- Australian Mineral Foundation Hydrothermal Iron-oxide Copper–Gold Deposits Conference (Perth, December)
- Gem and Jewellery Exchange (Tucson, February)
- Gem and Jewellery Fair (Bangkok, February)
- Prospectors and Developers Association of Canada Conference (Toronto, March)
- MINEX 2001 (Perth, March)
- Australian Petroleum Production and Exploration Association (APPEA) Conference (Hobart, April)
- Twentieth International Geochemical Exploration Conference (Chile, May)
- American Association of Petroleum Geologists Conference (Denver, June).

In addition to the above, the MPR/GSWA held four 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 AGSO)
- Launch of the GSWA Urban and Development Areas Regolith–landform mapping packages (Margaret River, November)
- GSWA 2001 — New geological data for WA Explorers (Perth, March).

Of these events, GSWA 2001 was a highlight, with the release of the Hallberg 1:25 000 geology dataset, and the launch of the GeoVIEW.WA web application attracting considerable interest. Industry feedback supports the continuation of this event as a regular item on the GSWA promotional calendar.

The promotion of Western Australia's prospectivity overseas continued to increase in 2000–01. GSWA was present with display material at the International Geoscience Convention (IGC) in Brazil, PDAC 2001 in Toronto, the International Geochemical Exploration Symposium (IGES) in Chile, and at AAPG conferences in Denver and Bali.

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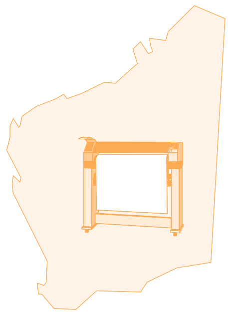
Geoscientific data management

Objectives: *To meet the needs for a spatial geoscientific database, ensuring access to and advancing the application of this database for users. In support of this mission we will:*

- *ensure the production and availability of geoscientific information in the form of high-quality maps*
- *ensure the production and availability of geoscientific information in the form of high–quality digital spatial geoscientific database products and services*
- *provide the infrastructure for the management of spatial geoscientific data*
- *develop and coordinate spatial geoscientific database policies and standards.*



2000–01 publications and products

Multicoloured map printing

The Geoscientific data management group continued to produce high-quality lithographically printed and plotter-generated geological and geophysical maps. In 2000–01, the group published thirty-three maps and images at various scales, including two plates in digital format only (Appendix, p. 118):

- Two 1:50 000 regolith–landform maps
- Nine 1:100 000 geological series maps
- One 1:250 000 geological series map
- Two 1:250 000 regolith materials series maps
- Ten project maps at various scales
- Five total magnetic intensity images
- Two radiometric images
- Two gravity images.

Geoscientific digital data packages

The following geoscientific digital data packages were released in 2000–01:

- Two Eastern Yilgarn Geoscience Database packages
- The Hallberg Murchison data package (Record 2000/20)
- Two regolith–landform data packages
- Three regolith geochemistry data packages
- One mineral resources data package
- One annual update for the Pilbara iron ore resources package
- A State geology compilation (1:500 000) released on the web
- Tectonic units of Western Australia (1:2 500 000) released on the web
- One schedule of petroleum wells (Statewide)
- Three airborne geophysics datasets
- Two petroleum initiatives project maps on CD as pdf files.

Other activities

GeoBASE.WA

The Geoscientific Database of Western Australia (GeoBASE.WA) has been implemented in a production environment. GeoBASE.WA is the framework that integrates GSWA's spatial and aspatial data so that its customers have access to a single source for all corporate geoscientific data. GeoBASE.WA takes advantage of new technologies and contemporary information-management practices to provide management of, and access to, geoscientific data in a relational database environment. It achieves this through an easy-to-use web interface (GeoVIEW.WA) that provides interactive querying and analysis in a responsive manner.

GeoVIEW.WA

A critical component of the GeoBASE.WA framework implementation is GeoVIEW.WA, an ArcIMS application that provides customers with timely access to geoscientific data online via the web. GeoVIEW.WA provides the user with the ability to view and query a number of integrated geoscientific and related datasets via most web browser clients. The geoscience datasets include geology at 1:2 500 000, 1:500 000, 1:250 000, and 1:100 000 scales, geochronology, mineral resources, open-file geophysics, petroleum titles, an index to 2D and 3D seismic-line data, boundaries of departmental administrative regions, and mining tenements that are updated at the beginning of each month.

Databases

Web access for internal users has now been completed for a number of key geoscientific databases, including databases in support of field observations (WAROX), the mineralization program (WAMIN), and the management of the location of core (COREStore). It is planned to integrate these databases within the GeoBASE.WA environment.

GDA conversion

GSWA successfully completed the conversion of all map and digital datasets to the adopted Geodetic Datum of Australia (GDA).

Awards

GSWA received two prestigious awards for products delivered in 2000–01. RoxMAP.WA received a High Commendation at the WA Premier's Awards in November 2000, and the Mineral occurrences and exploration potential of the East Kimberley digital data package and map received a Silver Award for Excellence in Mapping Sciences at the Mapping Science Institute Australia National Conference in December 2000.

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Subprogram 3106 GEOSCIENTIFIC AND EXPLORATION INFORMATION

Geoscience information library

Objective: *To provide an effective and efficient information service that meets the needs of the Department, the minerals and petroleum industry, educational institutions, and the general public.*

Highlights and activities for 2000–01

The Library established a Library accession list recording all publications received by the Library each week. The list is emailed to staff and includes a list of all journals, books, serials, maps, and other publications received during the preceding week. It includes hotlinks to websites that provide staff with desktop access to sites with abstracts and full-text journal articles.

Over 3700 unpublished GSWA reports were indexed into the Library database. These publications provide short reports on specific areas of investigation undertaken within GSWA over many years.

A review of the publications gifts and exchange program was undertaken with a view to ensuring the program continues to meet customer needs and to ensure GSWA publications are widely distributed throughout the world. GSWA publications are distributed to 169 locations worldwide.

The Library completed the reorganization of the GSWA thin-section collection of 3.5" slides. This is the first time that over 70 000 thin sections have been placed in sequential order and stored in appropriate cabinets. Thin sections described in GSWA reports can now be readily accessed by Departmental and external customers.

Library usage

During 2000–01, 5712 users visited the Library, an increase of 5.25% on the previous year. This figure included 921 users of the microfiche facilities to access open-file exploration data. Library staff dealt with 4800 enquiries, an increase of 0.8% compared with the previous year. These figures represent the first increase in Library usage since 1997–98, reflecting our increased exposure to the public resulting from our relocation from Level 5 to Level 1 of Mineral House.

Library collections and services

Continuing efforts were made to provide access to additional datasets for users, with all records indexed on the Library OLIB database. These included:

- Indexing of 3762 GSWA internal unpublished reports held by the Library, including Geophysics (64), Geochemistry (6), Mineral resources (154), Petrology (1566), Engineering geology (592), Hydrogeology (1342), and Environmental geology (38) reports
- Commencement of the progressive capture of approximately 2500 serial titles held in the Carlisle storage facility. This includes all material received via our gifts and exchange agreements, and contains significant backruns of material that have been collected over 100 years. Cataloguing this material to the OLIB database will make this vast store of information readily available to MPR staff and external customers for the first time. Over 380 titles have been captured, including all holdings from Great Britain, Scotland, Ireland, Germany, Italy, Netherlands, United States Geological Survey, United States Bureau of Mines, Geological Survey of Canada, and South Africa

- Consolidation and filing of over 70 000 geological thin-section slides and accompanying data sheets providing original descriptions of GSWA field samples.

Future work

A review of the operations of the Library service following the merger of the former Departments of Minerals and Energy and Resources Development into the new Department of Mineral and Petroleum Resources will be undertaken. This will ensure that the Library service continues to meet the information needs of the Department and external customers.

Assuming that access security issues are resolved, external customers' access to the OLIB Library database via the worldwide web will be available in the latter half of 2001.

The Library's MS Access database of GSWA reports published in the past 100 years will be electronically transferred to the OLIB Library database. This will enable all staff to access these records via the Intranet and will be available to external customers when OLIB is made accessible via the worldwide web. This dataset will provide customers with access to over 3000 GSWA published reports that can be searched by author, title, series, commodity, geological time, subject keyword, and more.

Sorting and storing of large-plate thin sections and polished mounts will be undertaken.

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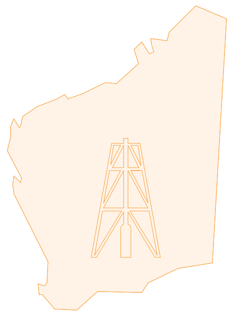
Statutory exploration information group



Objectives: *To manage the collection and storage of statutory mineral and petroleum exploration reports relating to tenements in Western Australia, and to ensure the efficient dissemination of information in these reports to industry.*

This subprogram covers all aspects of the submission, management, and release of both mineral and petroleum exploration data through WAMEX (the Western Australian mineral exploration database) and WAPIMS (the Western Australian petroleum information management system).

Highlights for 2000–01

- During 2000–01, metadata and format standards for the reporting of exploration data in digital form were finalized in consultation with industry groups. These standards were consolidated in 'Requirements for the submission of mineral exploration data in digital format' and form the core of standards accepted by the Chief Geologists Conference as the basis of national reporting requirements for the mineral exploration industry.
- The Petroleum data management pilot project was successfully undertaken and a decision was made to implement the Finder Data Management System. This process was nearing completion at the end of the year.
- The 'Schedule of petroleum wells Western Australia — 2001 update' was released.

Report submission

Mineral exploration

During the year, 1981 mineral exploration reports (2894 volumes) were received, representing industry activity on 9284 tenements. The total number of volumes held is now 73 393. 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 38% of all reports submitted during the year containing some digital data.

Reporting standards (mineral exploration)

This year has been the fifth full year of required compliance with the 'Guidelines for mineral exploration reports on mining tenements' and the first year in which companies could submit data in digital format according to the Department's requirements. The quality-control checking by Departmental staff has found that the compliance of the hardcopy reporting has been increasing, with a reduction to 18% in the number of reports not complying with the 'Guidelines for mineral exploration reports on mining tenements'. The submission of digital data is voluntary and, as the 'Requirements for the submission of mineral exploration data in digital format' were still subject to revision after industry consultation, many companies had not prepared the appropriate software or templates to submit the data according to these requirements.

The 'Requirements for the submission of mineral exploration data in digital format', which were developed in consultation with industry groups, have been adopted by the interdepartmental working group as the basis of National reporting requirements for the mineral exploration industry, and at year's end had been revised after further consultation with industry groups.

Petroleum exploration

During 2000–01, activities on the 206 active petroleum tenements in Western Australia generated 44 869 sets of data, an increase of 40% over the previous year, to make a total of 711 769 registered sets of petroleum data held or administered by the Department. The datasets include reports, seismic sections, well logs, digital data, maps, cores and cuttings, and palaeontological data.

WAMEX and WAPIMS databases development

Following a tender process undertaken in 1999–2000, Schlumberger were contracted to undertake a pilot project to test if their Finder system was capable of fulfilling the petroleum data-management requirements of the Department. This pilot project was successfully completed and, based on the findings, the Department decided to implement the Finder system. This implementation process commenced during the year, with all petroleum exploration data (as well as data in Petroleum Operations Division) being uploaded into the system. The new database is expected to be commissioned in the early months of the next reporting year.

No significant changes were made to the WAMEX database. 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 is needed. This review is scheduled to commence in the next year.

Significant progress has been made in a project that has investigated means of attaching images of scanned exploration reports to the web-based version of WAMEX. This service is currently being tested, and it is anticipated that over 4000 reports will be available for viewing over the web when this system is live early next year.

Data release

Mineral data

During the year, 3262 reports were released to open file, bringing the total number of open-file mineral reports to 29 483.

Petroleum data

During 2000–01, 322 edited reports, 344 unedited reports, 67 sets of well logs, and 29 sets of seismic sections were released. The downturn in exploration expenditure in the petroleum industry was most graphically reflected in the 55% decrease to 63 requests for loans of seismic tapes. There was an 87% decrease (to 719 requests) in the number of seismic tapes being requested. In addition, 72 requests for sample drillcore or cuttings and 16 requests for palaeontological data were satisfied.

Future work

- Refinement of the ‘Requirements for the submission of mineral exploration data in digital format’
- Final implementation of the new petroleum database system incorporating management of all petroleum exploration data
- Continuation of scanning to pdf files (rather than microfiching) of mineral exploration reports prior to release to open file
- Provision of both scanned and generated files of mineral exploration data via the web-based WAMEX interface
- Review of the current WAMEX database and core library database
- 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 hard-copy reports.

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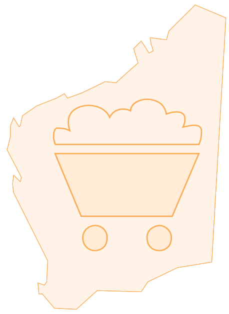
Subprogram 3107
INVENTORY OF ABANDONED MINE SITES

Inventory of abandoned mine sites



Objective: *To locate abandoned mine sites in the State and document factors relevant to their safety and the 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 2000–01

The inventory project, which commenced in 1999–2000, has the objective of locating abandoned mine sites in the State and documenting factors relevant to their safety and the environmental hazards they pose. This will provide a sound basis for providing advice on remedial action and rehabilitation of high-risk abandoned mine sites.

An innovative database for field use on a palm-top computer, linked to satellite navigation equipment capable of locating mine sites to around three metres of accuracy, was designed in 1999–2000 and has very successful in assisting fieldwork. The method has sparked the interest of equivalent Departments in the Northern Territory, South Australia, and Queensland. The rate of collection of data continues to be high, with 24 264 potential hazards added to the inventory during 2000–01. The two-year total of points in the inventory stood at 33 184 at 30 June 2001. The total also includes some potential hazards completely or partially rehabilitated by mining tenement holders, with location data supplied to the Department by companies.

Substantial quantities of historic production data were captured during 1999–2000, and office-based identification of historic production sites using tenement information was almost completed during 2000–01.

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 35% of all abandoned mine sites are in the high-priority category. At 30 June 2001, approximately 50% of known high-priority production sites had been inspected during the first two years of the program.

Fieldwork during 2000–01 was conducted at high-priority sites around Sandstone, Meekatharra, Wiluna, Leonora, Laverton, and Kalgoorlie. Fieldwork around Kalgoorlie is being directed at surveying all sites for the four 1:50 000 map sheet 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 area into 2001–02.

An innovative system for attributing aggregate risk to a site, based on the data collected, has been developed and is being tested.

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Appendices

List of acronyms and abbreviations

AAPG	American Association of Petroleum Geologists
ABS	Australian Bureau of Statistics
AESIS	Australian Earth Science Information System
AGIA	Australian Geoscience Information Association
AGSEAN	Australian Geologist Skills and Employment Advancement Network
AGSO	Geoscience Australia, formerly Australian Geological Survey Organisation
AMEC	Association of Mining and Exploration Companies (Inc.)
AMF	Australian Mineral Foundation
AMIRA	Australian Mineral Industries Research Association Limited
ANZMEC	Australian and New Zealand Minerals and Energy Council
ANU	Australian National University
APLA	Australian Prospectors and Leaseholders Association
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
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
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 and WAPEX are registered Trade Marks

Planned achievements and publications released

Major planned achievements for 2000–01

The GSWA program for 2000–01 was an ambitious project-based program of work designed to promote Western Australia's exploration potential. The programmed Planned Achievements for 2000–01 were:

- release of 26 geological maps at various scales;
- publication of 42 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of 13 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 2000–01, changing priorities resulted in the completion of a different mix of published output for the year than was originally planned. The balance shifted with more maps (33) and fewer books (38) published. Eighteen digital datasets were released (13 planned), which reflects changing technology and a greater volume of geoscience data being provided in digital form. In particular, provision of data via the internet grew during the year, with the release of the State 1:500 000-scale solid geology and the launch of GeoVIEW.WA (a web-based map viewer) via the MPR website. In overall terms, GSWA publication milestones for 2000–01 were exceeded. The total combined number of published products released was 89 and exceeded our stated target of 81.

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 will (in 2001–02) allow the delivery to customers of digital reports and data via the worldwide web.

Products released in 2000–01 allowed the Geological Survey again (for the sixth successive year) to exceed its target productivity improvement of 5%. A real productivity gain of 5.84% was achieved in 2000–01.

Maps, books, and datasets released in 2000–01

Geological series maps

1:50 000 Regolith–landform resources maps

COWARAMUP by G. J. Hall, J. R. Marnham, and R. L. Langford
HOWATHARRA by R. L. Langford

1:100 000 Geological Series

BARLEE by A. Riganti
BUNGALBIN by S. F. Chen and S. Wyche
GLENBURGH by S. A. Occhipinti and S. Sheppard
MOUNT BELCHES by M. G. M. Painter and P. B. Groenewald

PRESTON by C. A. Strong, A. H. Hickman, and C. J. Kojan
SATIRIST by R. H. Smithies and T. R. Farrell
WALLARINGA by R. H. Smithies, D. C. Champion, and R. S. Blewett

1:100 000 Geological Series preliminary release

MAROONAH by D. McB. Martin, A. M. Thorne, and I. A. Copp
MANGAROON by D. McB. Martin and A. M. Thorne

1:250 000 Geological Series

DAMPIER – BARROW ISLAND by A. H. Hickman and C. A. Strong

1:250 000 Regolith Materials Series

BYRO by P. A. Morris
WINNING POOL – MINILYA by A. J. Sanders

1:500 000 maps

Western Australian State geology (www release)
Iron ore deposits of the Pilbara region

Geological maps at other scales

Tectonic units map of Western Australia, by I. M. Tyler (1:2 500 000)

Western Australia mineral deposits and petroleum fields 2001 (1:2 500 000)

Western Australia atlas of mineral deposits and petroleum fields 2001

Geology and mineral resources of the Mid West Region, by F. Vanderhor (Record 2000/14 , Plate 1)

North–south well log correlation Edel 1 – South Turtle Dove 1B, by A. Crostella (Report 75, Plate 1) *in pdf format*

Key seismic horizon maps, Lennis area, Officer Basin, by S. N. Apak and H. T. Moors (Report 77, Plate 1)

Seismic isochron maps, Lennis area, Officer Basin, by S. N. Apak and H. T. Moors (Report 77, Plate 2)

Geophysical profiles across the Woodleigh impact structure, by R. P. Iasky, A. J. Mory, and K. A. Blundell (Report 79, Plate 1) *in pdf format*

Geophysical images

MOUNT PHILLIPS total magnetic intensity image (1:250 000)
MOUNT PHILLIPS ternary radiometric image (1:250 000)
SANDSTONE total magnetic intensity image (1:250 000)
SANDSTONE ternary radiometric image (1:250 000)
Bangemall–Gascoyne region total magnetic intensity image (1:500 000)
Yandal greenstone belt and adjacent areas total magnetic intensity image (1:500 000)
Earaheedy Basin total magnetic intensity image (1:500 000)
Gravity anomaly map of Western Australia (1:2 500 000)
BYRO Bouguer gravity image (1:250 000)

Bulletins

144 **Geology of the Fortescue Group, Pilbara Craton, Western Australia,** by A. M. Thorne and A. F. Trendall

Reports

73 **Petroleum geology of the Peedamullah Shelf and Onslow Terrace, Northern Carnarvon Basin, Western Australia,** by A . Crostella, R. P. Iasky, K. A. Blundell, A. R. Yasin, and K. A. R. Ghori

75 **Geology and petroleum potential of the Abrolhos Sub-basin, Western Australia,** by A. Crostella

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

78 **East Yilgarn Geoscience Database, 1:100 000 geology Menzies to Norseman — an explanatory note,** by P. B. Groenewald, M. G. M. Painter, F. I. Roberts, M. McCabe, and A. Fox

79 **The geophysical interpretation of the Woodleigh impact structure, Southern Carnarvon Basin, Western Australia,** by R. P. Iasky, A. J. Mory, and K. A. Blundell

83 **East Yilgarn Geoscience Database, 1:100 000 geology of the north Eastern Goldfields Province — an explanatory note,** by P. B. Groenewald, M. G. M. Painter, and M. McCabe

Records

2000/1 **Program 2 — Industry support: Geological Survey plan for 2000–01 and subsequent three years**

2000/10 **Geology of the Southern Carnarvon Basin, Western Australia — a field guide,** by R. M. Hocking

2000/14 **Geology and mineral resources of the Mid West Region,** by D. J. Flint, P. B. Abeysinghe, Gao Mai, J. Pagel, D. B. Townsend, F. Vanderhor, and F. Jockel

2000/16 **Revised lithostratigraphy for Proterozoic rocks in the Earaheedy Basin and nearby areas,** by R. M. Hocking, J. A. Jones, F. Pirajno, and K. Grey

2000/18 **Regolith–landform resources of the Cowaramup–Mentelle 1:50 000 sheet,** by J. R. Marnham, G. J. Hall, and R. L. Langford

2000/19 **Gravity data — Kingston and Stanley 1:250 000 sheets, Western Australia,** by S. I. Shevchenko

2000/20 **Notes to accompany the Hallberg Murchison 1:25 000 geology dataset, 1989–1994,** by J. A. Hallberg *(digital publication)*

2001/3 **Gravity data — Winning Pool – Minilya 1:250 000 sheets, Western Australia,** by S. I. Shevchenko

2001/4 **A classification system for regolith in Western Australia,** by R. M. Hocking, R. L. Langford, A. M. Thorne, A. J. Sanders, P. A. Morris, C. A. Strong, and J. R. Gozzard

2001/5 **GSWA 2001 extended abstracts: new geological data for WA explorers**

2001/7 **Regolith–landform resources of the Howatharra 1:50 000 sheet,** by R. L. Langford

Explanatory Notes

1:100 000 Geological Series

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

Geology of the Earaheedy 1:100 000 sheet, by R. M. Hocking, N. G. Adamides, F. Pirajno, and J. A. Jones

Geology of the Fairbairn 1:100 000 sheet, by N. G. Adamides, F. Pirajno, and R. M. Hocking

Geology of the Glenburgh 1:100 000 sheet, by S. A. Occhipinti and S. Sheppard

Geology of the Johnston Range 1:100 000 sheet, by S. Wyche, S. F. Chen, J. E. Greenfield, and A. Riganti

Geology of the Lake Giles 1:100 000 sheet, by J. E. Greenfield

Geology of the Paterson 1:100 000 sheet, by L. Bagas

Geology of the Satirist 1:100 000 sheet, by R. H. Smithies and T. R. Farrell

Geology of the Warrawagine 1:100 000 sheet, by I. R. Williams

1:250 000 Geological Series

Duketon 1:250 000 sheet, Western Australia, by T. R. Farrell

Laverton 1:250 000 sheet, Western Australia, by A. J. Stewart

Wiluna 1:250 000 sheet, Western Australia, by T. R. Farrell

1:250 000 Regolith Geochemistry Series

Geochemical mapping of the Byro 1:250 000 sheet, by P. A. Morris and A. L. Verren

Geochemical mapping of the Winning Pool – Minilya 1:250 000 sheets, by A. J. Sanders and S. A. McGuinness

Miscellaneous

GSWA Annual Review 1999–2000

Mineral exploration and development in Western Australia in 1999 and 2000, by D. J. Flint and P. B. Abeysinghe

Fieldnotes v.17

Fieldnotes v.18

Fieldnotes v.19

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

Digital products

East Yilgarn Geoscience Database, Eastern Goldfields, Menzies to Norseman 1:100 000 digital geological data package (Report 78)

East Yilgarn Geoscience Database, north Eastern Goldfields Province, Cunyu to Cosmo Newbery 1:100 000 digital geological data package (Report 83)

Hallberg Murchison 1:25 000 geology dataset, 1989–1994 (Record 2000/20)

Regolith–landform resources of the Cowaramup 1:50 000 sheet (Record 2000/18)

Regolith–landform resources of the Howatharra 1:50 000 sheet (Record 2001/7)

Geochemical mapping of the Byro 1:250 000 sheet

Geochemical mapping of the Winning Pool – Minilya 1:250 000 sheets

Geochemical mapping of the Fraser Range region

Geology and mineral resources of the Mid West Region (Record 2000/14)

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

Interpreted bedrock geology of Western Australia: 1:500 000-scale digital map *released on the www*

Tectonic units of Western Australia: 1:2 500 000-scale digital map *released on the www*

Schedule of petroleum exploration wells Western Australia — 2001 update

SANDSTONE airborne geophysics dataset

BARLEE–JACKSON airborne geophysics dataset

Bangemall airborne geophysics dataset

North–south well correlation Edel 1 – South Turtle Dove 1B (Report 75, Plate 1)

Geophysical profiles across the Woodleigh impact structure (Report 79, Plate 1)

Major planned achievements for 2001–02

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 2001–02 include:

- release of 33 geological maps at various scales;
- publication of 48 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of one GIS-based regolith geochemistry data package;
- publication of two GIS-based mineral occurrence packages;
- publication of one development areas resource dataset;
- publication of 18 seamless 1:100 000 geological maps in the Laverton–Leonora area;
- publication of several updates of previously released digital data packages;

- 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.

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.

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Note: GSWA authors are in italics

Geological Survey Liaison Committee

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.

Committee members as at 30 June 2001

Dr Jim Limerick (Chairperson)	MPR (Director General)
Dr Mark Barley	University of Western Australia
Dr Bryan Smith	AMEC
Dr Neil Williams	Geoscience Australia
Mr Peter Onley	Golder Associates
Assoc. Prof. Lindsay Collins	Curtin University of Technology
Mr Steve Mann	Chamber of Minerals and Energy
Mr Bruce Thomas	APPEA
Mr Ernie Delfos	APPEA
Mr Ralph Porter	Chamber of Minerals and Energy
Dr Pietro Guj	MPR (Investment Attraction)
Dr Mike Donaldson	MPR (GSWA)
Dr Tim Griffin	MPR (GSWA)
Dr Rick Rogerson	MPR (GSWA)

Technical Subcommittees

Regional Geoscience Mapping and Mineral Resources Technical Subcommittee

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Dr Mark Barley	University of Western Australia
Mr Peter Onley	Golder Associates
Mr Steve Mann	Chamber of Minerals and Energy
Dr Peter Cawood	Curtin University of Technology
Dr John Hronsky	WMC Resources Ltd
Dr Peter Sorjonen-Ward	CSIRO
Dr Charles Butt	CSIRO
Dr Richard Mazzucchelli	Consultant
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Mr Russell Birrell	WAMTECH Pty Ltd
Mr Leigh Bettenay	Consultant
Dr Chris Pigram	Geoscience Australia
Dr Mike Donaldson	MPR (GSWA)
Dr Rick Rogerson	MPR (GSWA)
Dr Paul Morris	MPR (GSWA)
Dr Ian Tyler	MPR (GSWA)

Petroleum Exploration Initiative Technical Subcommittee

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Dr Trevor Powell	Geoscience Australia
Mr Ernie Delfos	APPEA
Dr Clinton Foster	Geoscience Australia
Assoc. Prof. David Haig	University of Western Australia
Professor Mike Middleton	Curtin University of Technology
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Dr Rick Rogerson	MPR (GSWA)
Mr Greg Carlsen	MPR (GSWA)
Mr Jeff Haworth	MPR (GSWA)

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Mr Ian O'Donnell	Geoscience Australia
Mr Greg Steemson	Mineral Commodities Ltd
Mr Gert Landeweerd	APPEA
Mr John Scott	Black Rock Petroleum NL/P.G.A. Consultants Pty Ltd
Mr Garth Bird	Rio Tinto Exploration Pty Limited
Mr Richard Bruce	MPR (Petroleum Division)
Dr Peter Morant	Sipa Resources International NL
Dr Rick Rogerson	MPR (GSWA)
Ms Margaret Ellis	MPR (GSWA)
Mr David Howard	MPR (GSWA)
Mr Jeff Haworth	MPR (GSWA)