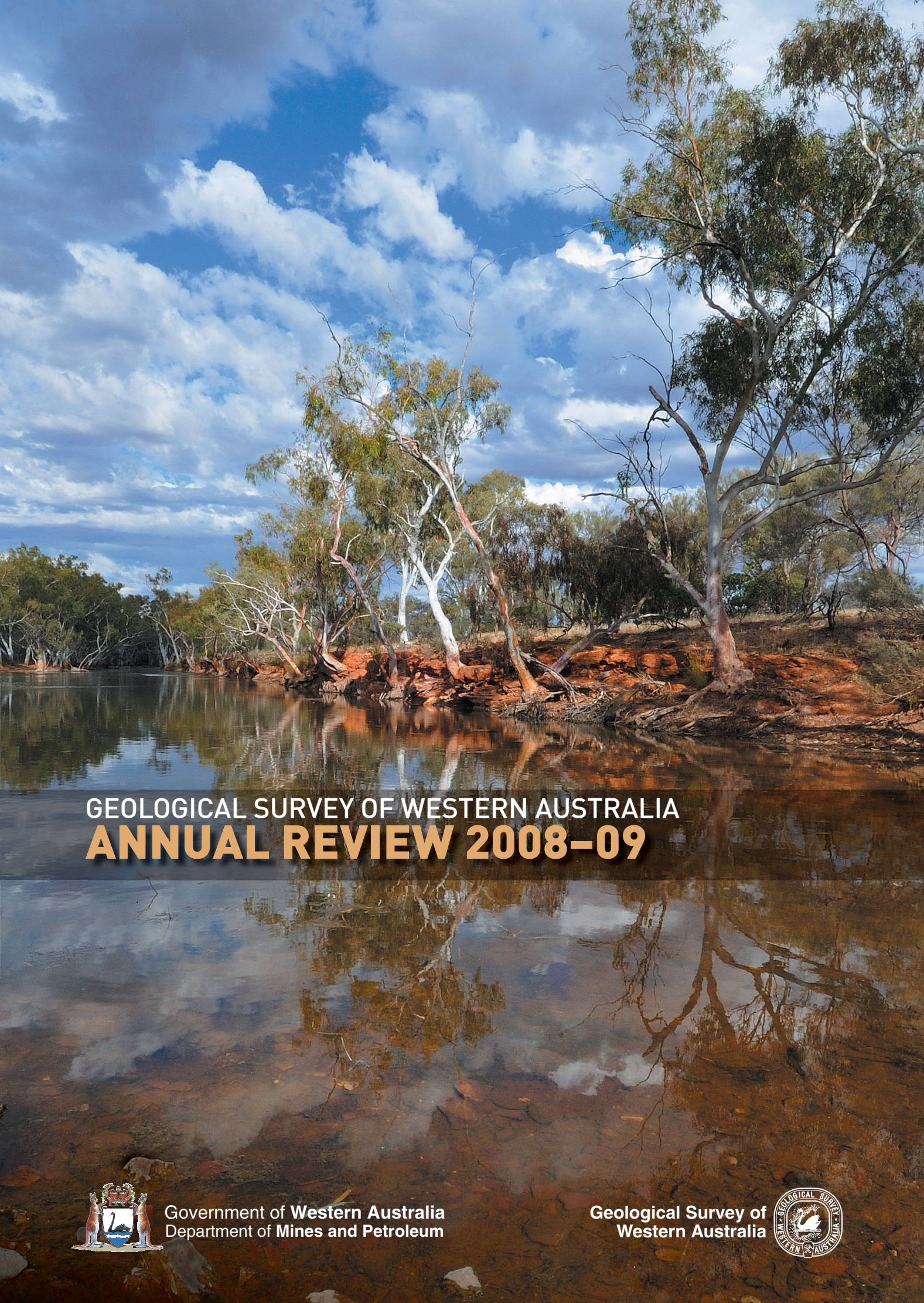
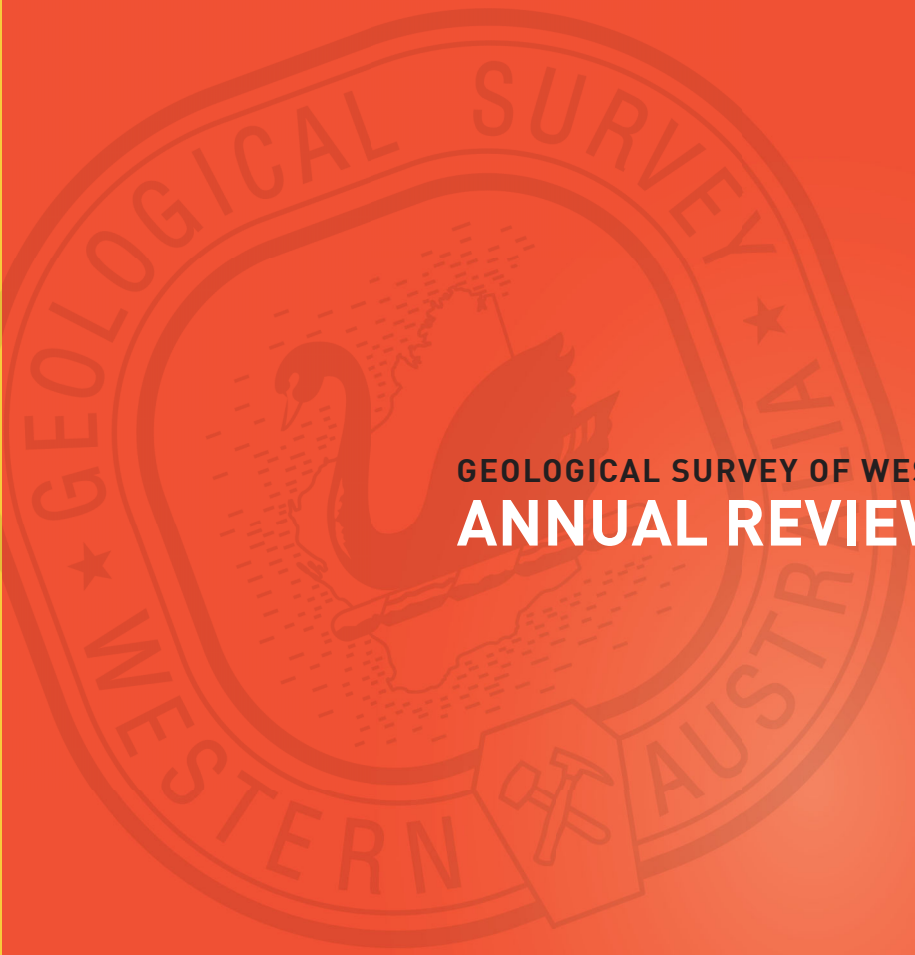


GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 2008–09

Government of **Western Australia**
Department of **Mines and Petroleum**

Geological Survey of Western Australia



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 2008–09

MINISTER FOR MINES AND PETROLEUM
Hon. Norman Moore MLC

DIRECTOR GENERAL, DEPARTMENT OF MINES AND PETROLEUM
Richard Sellers

EXECUTIVE DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
Tim Griffin

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Cover
Yandilgunna Pool on Turner Creek, Calyie
Photograph courtesy AM Thorne

Frontispiece
Large glacial erratic of rippled sandstone in the Walsh Tillite, Mount House Station, South Kimberley
Photograph courtesy Peter Haines

Contents

GSWA mission statement

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

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

Our role is to elucidate the geological framework of Western Australia and 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. These products are based on the acquisition and analysis of field data, including submitted statutory exploration reports. As well, the GSWA evaluates mineral and petroleum resources as a basis for decision making by Government, and assists and advises on a variety of community needs, including urban planning and land use matters.

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

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

As a result of the application of these skills for over 100 years, and of its role as the repository of mineral and exploration reports, the GSWA is the custodian of an immense volume of information on the geology of the State and is the premier organization providing geoscientific expertise in Western Australia.

2008–09

Year in review


Tim Griffin

Much changed in the mineral and energy sector in Western Australia during 2008–09. The global financial crisis, low commodity prices, and the tightening of equity and credit markets had a severe effect on exploration expenditure. As I write this review, however, the outlook for 2009–10 is brighter. Most commodity prices are rising, and there is optimism in the resources sector that the economic downturn caused by the financial crisis is over, at least in Australia, particularly because of the strength of China's economy.

A major change for the Geological Survey of Western Australia (GSWA) was the breakup of the former Department of Industry and Resources following the change of Government in September 2008. The promotion and regulation of the resources industry in Western Australia was transferred into the Department of Mines and Petroleum, emphasizing the policy of the new Government to encourage exploration and mining of all minerals in Western Australia. I was privileged to be the Acting Director General during the establishment of the new Department from December 2008 to June 2009, and during that time Rick Rogerson acted as Executive Director of GSWA, which included the additional responsibility for the successful introduction of the Government's Exploration Incentive Scheme.

The Exploration Incentive Scheme (EIS), the most significant event for GSWA during 2008–09, started in April 2009 when the Western Australian Government provided funding from their Royalties for Regions program to GSWA for this new five-year $80 million initiative. EIS is managed by GSWA, and the work program over the period 2008–09 to 2012–13 is dominated by pre-competitive geoscience programs including coverage of the State by airborne magnetic and radiometric surveys at 400-metre (or less) line spacing, a series of deep seismic lines, a drilling subsidy to assist mineral and energy explorers in undeveloped parts of the State who are using innovative targeting methodologies, and stratigraphic drilling by GSWA. A significant part of the new funding will be used to develop cutting-edge regional geoscience products using the new geophysical data integrated with traditional 2D geoscience studies. The aim is to produce a real 3D understanding of crustal architecture and, with improved geochronological, geochemical, and isotopic data coverage, the 4D geodynamic history as a guide to regional-scale exploration models and resources targeting. About $24 million of the funding will be of direct benefit to petroleum and energy exploration with the remainder focused on mineral exploration. EIS is discussed in more detail in the article by Margaret Ellis that follows this review. Margaret has been appointed as the Coordinator of the scheme.

ROYALTIES FOR REGIONS
EXPLORATION INCENTIVE SCHEME

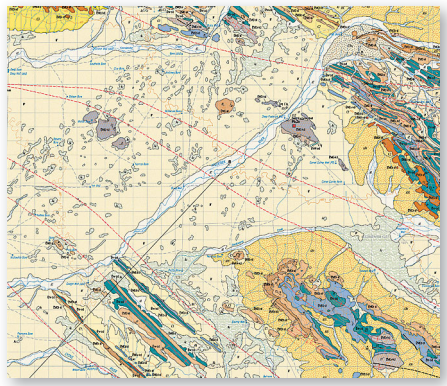
A Review of GSWA, carried out in 2007 under the previous Government, was released during 2008–09. Its recommendations are largely met by EIS.

GSWA publications

During 2008–09 GSWA published:

- 31 geoscience maps including 14 geological series maps at 1:100 000 scale
- 26 records, reports, and other publications
- 19 digital information packages.

Staff turnover, which affected the delivery of planned products in 2007–08, stabilized in the changed economic climate of 2008–09. This allowed production to return to normal levels, and regain some of the ground lost.

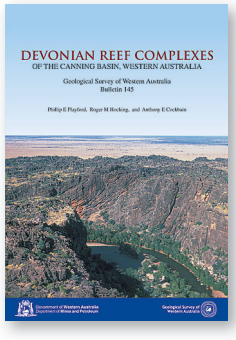


Part of Mount Augustus 1:100 000 map sheet

Our flagship 1:100 000 geological series included the release of three maps that cover parts of the Murchison Domain, a first for this underexplored portion of the Yilgarn Craton. Geological Series maps are now routinely produced by combining digital compilations of Interpreted Bedrock Geology and Regolith layers. Both of these digital layers are now standard in the Geological Information Series packages containing all the digital information available for areas covered by recently released 1:100 000-scale geological maps.

Of the 19 digital information packages released, four represented updates of Geological Information Series packages for the Central Yilgarn, East Yilgarn, Pilbara, and the west Musgrave.

The release of 26 records, reports, and other publications did not meet our planned target of 35 new releases; however, the shortfall was offset by the increased number of external publications authored by GSWA staff. This reflected a strong commitment by GSWA to maintain the high professional skills of staff through supporting involvement in national and international geoscience meetings, including the Australian Earth Sciences Convention held at the Perth Convention Centre in July 2008 and the inaugural Global Geotourism Conference held in Fremantle in August 2008. As well as having a significant presence at both conferences, highlighting work by GSWA geoscientists and their collaborators, GSWA also sponsored and published field guides and provided leadership for associated field excursions.



Perhaps the most significant publication of 2008–09 was Bulletin 145 *Devonian reef complexes of the Canning Basin, Western Australia* authored by a former Director of GSWA, Phil Playford, together with GSWA's Chief Geoscientist Roger Hocking, and former Assistant Director Tony Cockbain. The Devonian reef complexes of the Canning Basin form a spectacular belt of rugged limestone ranges that extend for some 350 km along the northern margin of the basin. They have become known as the 'Devonian Barrier Reef' and constitute what is regarded as one of the world's best preserved ancient barrier reef systems. For Phil Playford

the bulletin represents the culmination of more than 50 years of his studies of the reef complexes. Systematic research began in 1956, with West Australian Petroleum Pty Ltd, with GSWA carrying out mapping and field studies in 1962–63, published as GSWA Bulletin 118 in 1966. More field work was undertaken in the area in the 1970s and 80s, with a major effort following Phil's retirement as GSWA Director in the 1990s. Many staff and students from Australian and overseas universities have worked with GSWA on the region. The Devonian reef complexes are highly prospective for zinc and lead, and several deposits have been mined, including Pillara, Goongewa, and Cadjebut. Where the reefs extend into the subsurface they are also prospective for petroleum, with a small oilfield discovered at Blina. They are regarded as a model for similar reefs that host prolific oilfields and zinc–lead deposits elsewhere in the world. The Bulletin will be therefore essential reading for both mineral and petroleum explorers and has already received very positive reviews from around the world.

Geological mapping programs

During 2008–09 our mapping programs continued in the Archean rocks of the Yilgarn Craton. In the Murchison new mapping in the Reedy and Meekatharra areas, along with newly acquired geochronology, has helped in the recognition of a new stratigraphic framework. Mapping commenced on the Windimurra and Narndee layered mafic–ultramafic intrusions and their surrounding country rocks. In the Eastern Goldfields, mapping of the easternmost part of the Eastern Goldfields Superterrane was completed, with new geochronology suggesting that the 'Burtville Terrane' may consist of two distinct crustal elements. A new field program commenced in the Bullfinch–Forrestania and Lake Johnston greenstone belts, which will provide a link between existing 1:100 000 maps in the Eastern Goldfields and the northern Southern Cross and the Murchison Domains of the Youanmi Terrane.

GSWA is funding a component of an ongoing research project on the thermo-barometric evolution of the crust of the Yilgarn Craton by Dr Ben Goscombe, a Visiting Research Associate at Adelaide University. This project is the follow-on from the highly regarded metamorphic study of the Eastern Goldfields Superterrane undertaken by Ben in collaboration with the Predictive Mineral Discovery Cooperative Research Centre (pmd*CRC). As well as constraining models of crustal processes and tectonic settings, an understanding of the metamorphic history of the Yilgarn Craton will aid the generation of mineral exploration models for this world-class mineral province.

Examining a fault surface

Mapping in the Gascoyne Province was concentrated in the southeast and confirmed that the Ti Tree Syncline is a major structure separating zones with different structural styles and metamorphic histories. Other highlights were the discovery of mafic volcanic rocks in the Morrissey Metamorphics, the construction of a robust stratigraphy for the Mount James Formation, and the confirmation of widespread late Archean to early Paleoproterozoic granitic gneisses as basement to the Gascoyne Province north and south of the Chalba Shear Zone.

In the Edmund and Collier Basins sedimentary facies variations within the Kiangi Creek Formation point to a major, fault-bound sediment-source area to the east of the Abra polymetallic deposit. Mapping has also revealed the presence of a lenticular body of proximal felsic volcaniclastic breccia and sandstone within the

Ullawarra Formation in the upper Edmund Group. This is at a similar stratigraphic level to felsic volcanic rock that has recently yielded an age of 1460 Ma, within error of the 1465 Ma age for the Narimbunna Dolerite that intrudes the Edmund Group.

Mineral systems studies continued in the Gascoyne Province including the Minnie Creek molybdenum deposit and the Gifford Creek alkaline complex, which contains uranium-bearing carbonatites. Work also commenced on the giant Magellan lead deposit in the Yerrida Basin and continued on the Abra polymetallic deposit in the Edmund Basin.

A multi-disciplinary approach is being applied to the eastern Albany–Fraser Orogen and adjacent southeastern Yilgarn Craton to compile an Interpreted Bedrock Geology map combining new geophysical data and targeted field work, and with a specialist team also using the latest geochronology, isotopic analyses, and geochemistry. The area covers a region that stretches from the Tropicana gold deposit in the north to the southwestern end of the Fraser 'Complex'. The aim is to establish the main lithotectonic units and the timing of magmatic and metamorphic events.

In the Musgrave Province, GSWA's mapping in the 1960s and early 1970s identified two huge caldera structures — interpreted to have been formed when volcanoes collapsed into underlying magma chambers during massive eruptions more than 1070 m.y. ago. The Scamp Caldera and the Palgrave Caldera are both larger than the one associated with the Yellowstone Supervolcano in the northwestern USA. GSWA's Musgrave mapping team has begun detailed remapping in the Palgrave area to refine the model and has identified spectacular volcaniclastic units made up of thick pyroclastic flow deposits, including ignimbrite, pumice-rich beds, thick beds of obsidian, and thick and laterally extensive lahar deposits. Angular blocks of dacite up to 5 m across suspended in an ash matrix attest to the force of the eruptions. The deposits point to a series of gigantic eruptions, with the potential for the occurrence of large-scale hydrothermal mineral systems commonly associated with such large volcanoes.

Geophysical surveys

During 2008–09, 398 468 line km of airborne geophysical data were released, including surveys in the South Kimberley, Byro, and Dumbleyung areas flown in 2007–08, as well as from the 2008–09 survey in the Esperance–Balladonia area. These were the final surveys to use the pre-competitive geoscience mapping initiative funding that commenced in 2004–05. This initiative increased the 400 m line-spacing (or better) airborne and radiometric coverage of WA from 30% to in excess of 75%. Completion of coverage of Western Australia will now take place under EIS and mobilization for several surveys was underway in the latter part of 2008–09.

A gravity survey of the Musgrave region collected on a 2.5-km grid was released, together with the collection and release of the Windimurra survey in the Murchison, also on a 2.5 km grid. A gravity survey was collected in the Cunderdin area under EIS, which included the Kauring Airborne Gravity Test Range within it.

Year in review

Geochemistry

Sampling for the National Geochemical Survey of Australia continued in 2008–09 and to date 276 samples have been collected from a total of 447 sites in WA. Progress was slowed dramatically by the need to negotiate access onto Aboriginal lands and areas covered by determined Native Title or by Native Title claims, predominantly in the central and northern parts of the State. These negotiations are ongoing.

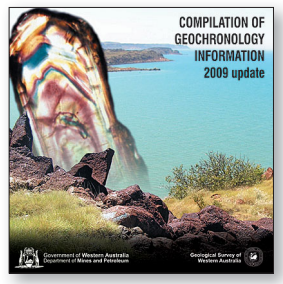
Under EIS, GSWA purchased the entire TerraSearch surface and downhole geochemistry database for WA. The exploration geochemistry data were captured from open-file company reports, and validated in terms of sample location and data quality. The dataset covers large areas of the State and includes more than 1.1 million data points, most of which are multi-element geochemistry from drillholes.

GSWA has acquired a field-portable XRF spectrometer, which can analyse for some 32 elements. One of the main applications is screening samples for geochronology use by measuring the Zr abundance in a rock to get an indication of the presence of either zircon or baddeleyite. The second major application of the instrument is identification of parent lithology from a weathered rock, which can be critical when working in the deeply weathered terrains common in the Archean of the Yilgarn Craton.

Hand-held XRF spectrometer

Geochronology

In 2008–09, 117 samples were dated, and 74 geochronology records were completed. Records are now routinely uploaded (after peer review and editing) to GeoVIEW on the DMP website as they are completed, rather than waiting for an annual release on DVD. Geochronology records can be downloaded from the Data and Software Centre <//www.dmp.wa.gov.au>, along with an extract from Geoscience Australia's OZCHRON database. The annual *Compilation of Geochronology* update on DVD will still be available to customers.



Curtin University of Technology, GSWA, and The University of Western Australia were successful in obtaining an Australian Research Council (ARC) Linkage Grant to develop a tectonothermal and mineralization history for the Gascoyne Province and the Bangemall Supergroup. The project, to be led by Professor Birger Rasmussen, will integrate his team's state-of-the-art SHRIMP phosphate geochronology using monazite and xenotime with GSWA's on-the-ground experience in the Capricorn Orogen. GSWA geochronologists will gain from the transfer of knowledge concerning this dating technique.

Land use geoscience

Many demands are placed on land for use by our modern society. Conflicting demands can be resolved when land use planning is applied sensibly to ensure the most efficient use is made of the land and its resources. The South West of WA, from Geraldton to Albany, is experiencing an unprecedented demand

for urban, rural residential, and industrial land and the public infrastructure to support it. Development along the coastal plain between Geraldton and Dunsborough is accelerating, with the potential to sterilize important deposits of raw materials.

GSWA has begun to upgrade its geological mapping along the coastal plain, initially concentrating on the area between Perth and Dunsborough, and will produce a set of maps depicting particular aspects of the geology, and showing themes of particular interest such as minerals and construction material resources, geohazards, and groundwater vulnerability to contamination. This information is being passed on to planners and developers in a way that is easily understood by non-geologists so that its proper use can be incorporated into local and regional planning policies and frameworks.

Petroleum geology

The focus of activities during 2008–09 was the Canning and Amadeus Basins. Detailed studies of the Canning Basin continued, with a number of new discoveries. Studies included the re-interpretation of the Carribuddy Group, where the Worral Formation is shown to conformably overlie the Carribuddy Group. Work on the Grant Group revealed the difficulties in correlating individual members and it may be best regarded as an undifferentiated unit. An analysis of oil obtained from mineral drilling in the Admiral Bay Fault Zone suggested it was sourced from the Goldwyer Formation, whereas previously the Bongabinni Formation was regarded as the main source. Studies of the Acacia Sandstone suggested its provenance was from adjacent Neoproterozoic basins rather than the North Australian Craton.

During the year, 3103 documents (representing 175 GB of information) were loaded into WAPIMS. The total number of publicly available documents is now 16 626 (650 GB). Worldwide, there were 3900 registered users of WAPIMS (in March 2009).

MINEDEX and WAMEX

The new MINEDEX database was continually enhanced during the year with added functionality, and has proved particularly useful for uranium explorers in WA following the policy change to allow uranium mining.

Following a smooth transition to the upgraded version of WAMEX to manage mineral exploration reporting, a new version of WAMEX Online with a spatial front-end was launched in February 2009. WAMEX now contains over 48 000 reports on open file in digital format. During 2008–09, 3894 digital reports were received, whereas 1507 were released to open file, including 1207 Sunset Clause reports. Another 2704 reports previously available on microfiche were scanned and made available.

Promotional events

GSWA continued to target major national and international mineral and petroleum exploration events as part of its role to promote the prospectivity of Western Australia and attract exploration investment to the State.

Year in review

In 2008–09 GSWA participated with Team Australia at the Prospectors and Developers Association of Canada (PDAC) and at China Mining, and had a presence at other international promotional events including NAPE (North America Prospect Expo) in Houston. A promotional visit to India was included during the year in recognition of the increasing importance of this market to WA.

Within Australia, besides the annual GSWA Seminar and Poster Display and Petroleum Open Day presented by the Department, GSWA was present at Mining 2008 in Brisbane, Diggers and Dealers in Kalgoorlie, the RIU Explorers Conference, and at the AMEC National Congress held in Perth.

GSWA Seminar and Poster Display

The future

The Exploration Incentive Scheme has put GSWA in an unrivalled position to collect, interpret, and distribute up-to-date, relevant, high-quality pre-competitive geoscience information for the resources exploration industry in Western Australia. It will allow us to apply new technologies to meet many of our objectives at a much faster rate than previously expected, and also introduce new geoscience concepts for regions of known mineralization as well as the underexplored regions of the State.

In managing a doubling of GSWA's budget over the next four years under EIS, a challenge will be to ensure there is no detrimental impact on our ongoing projects and programs. GSWA remains firmly focused on encouraging mineral and energy exploration in underexplored areas of the State with the aim of maintaining Western Australia as the preferred destination for explorers. GSWA's other role of providing expert advice to better inform land use decision-making will also be enhanced by the vast amount of new geoscience information being collected and analyzed.

One focus of GSWA activities is the completion of the airborne magnetic and radiometric coverage of WA at 400 m, or better, line-spacing. This is long overdue, and equivalent data are generally already available for other jurisdictions in Australia. There will be an expansion of other datasets including field mapping to improve geological coverage at 1:100 000 scale. In addition, gravity surveys, deep-crustal seismic traverses, magnetotelluric surveys, soil-geochemistry surveys, regolith mapping, geochronology, and isotopic studies using the latest equipment and concepts will enhance our capability to generate robust 3D geological models of the upper crust, with the potential to identify favourable zones for hosting mineralization beneath regolith cover or under thin sedimentary basins.

We are planning to modernize, expand, and integrate our systems to allow our geoscience databases to be accessed and interrogated online, and for our customers to be able to create their own customized geoscience reports and maps. Upgrading of the WAPIMS and WAMEX databases will streamline the release of information in a more usable form for the exploration industry. Of particular importance will be access to mineral drillhole information and related geochemistry.

There will be an expansion of cooperative projects between GSWA and other government geoscience organizations, including Geoscience Australia and CSIRO, and with university earth science departments.

These projects will focus on the provision of strategically important information, particularly for exploration targeting in underexplored regions, and in emerging areas such as tight gas, geothermal energy, and carbon dioxide geosequestration, where skills are in short supply.

GSWA is already playing a key role in providing expert advice and assisting with the coordination of WA projects to develop knowledge in the areas of carbon dioxide capture and storage. We are involved in how to identify the best places to sequester carbon dioxide — both for coal-fired power plants and the LNG industry.

Drill rig

Our aim is to develop an integrated approach for the delivery of new and expanded datasets and information, along with interpretations of the crustal architecture that will be usable and relevant to a range of users across the minerals and energy sector, and the broader community in general. By doing this we can provide a long-term economic base for WA that, not only relies on the export of minerals and energy commodities, but also can export its expertise and services to the resources sector worldwide.

Tim Griffin
Executive Director

Year in review

Table 1. Components and projects making up the Exploration Incentive Scheme — budgets and employees

Component	Planned Cash Flow ($ millions) 2008–09	2009–10	2010–11	2011–12	2012–13	Total	Public Servants
Exploration and environmental coordination (Total: $1.5 million)	*0.36*	*0.44*	*0.50*	*0.10*	*0.10*	*1.50*	–
Innovative drilling (Total: $26.9 million)	*0.20*	*4.18*	*6.51*	*8.28*	*7.73*	*26.90*	–
Government – industry co-funded exploration drilling	0.06	3.19	5.35	5.95	5.95	20.50	1
Targeted international exploration promotion	0.04	0.09	0.09	0.09	0.09	0.40	–
Stratigraphic drilling	0.10	0.90	1.07	2.24	1.69	6.00	–
Geophysical and geochemical surveys (Total: $33.33 million)	*0.65*	*7.395*	*9.085*	*9.615*	*6.585*	*33.33*	–
Completion of State-wide coverage by airborne magnetic and radiometric surveys	–	4.845	5.80	6.40	4.00	21.045	–
Deep-crustal seismic lines	–	0.65	1.385	2.315	1.935	6.285	–
Regional gravity surveys	0.25	1.50	1.50	0.50	0.25	4.00	–
Geochemistry of the Yilgarn Craton and its margins	0.40	0.40	0.40	0.40	0.40	2.00	–
3D geological mapping (Total: $13.8 million)	*0.69*	*2.86*	*4.63*	*4.12*	*1.50*	*13.80*	–
WA geology online — information delivery	0.10	0.50	0.50	–	0.10	1.20	1
Modernize petroleum information delivery system	0.36	0.44	–	–	–	0.80	–
3D geoscience	–	0.20	0.40	0.45	0.15	1.20	2
Open file geochemistry information delivery	–	–	0.60	0.20	–	0.80	–
Mineral drillhole database	0.15	0.50	0.45	0.45	0.45	2.00	1
Geological mapping and interpretation	0.05	0.75	0.75	0.75	0.40	2.70	1
Enhanced geochronology		0.20	0.20	0.20	0.20	0.80	–
Unconventional energy studies	0.03	0.27	1.73	2.07	0.20	4.30	1
Promoting strategic research with industry (Total: $2.3 million)	–	*0.65*	*0.65*	*0.65*	*0.35*	*2.30*	–
WA Regional Researcher Initiative	–	0.30	0.30	0.30	–	0.90	–
Supporting MERIWA	–	0.35	0.35	0.35	0.35	1.40	–
Sustainable working relations with Indigenous communities (Total: $2.17 million)		*0.555*	*0.565*	*0.535*	*0.515*	*2.17*	–
Developing Indigenous Land Use Agreements	–	0.050	0.120	0.120	0.120	0.41	–
Access-ready land for exploration	–	0.250	0.250	0.250	0.250	1.00	1
Heritage clearance for geothermal licences	–	0.160	0.040	0.010	0.010	0.22	–
Community awareness — mineral exploration	–	0.075	0.060	0.060	0.060	0.255	–
Regional heritage agreements for mineral exploration	–	0.02	0.095	0.095	0.075	0.285	–
TOTAL:	**1.9**	**16.08**	**21.44**	**23.30**	**16.78**	**80.0**	**8.0**

NOTE: See GSWA Record 2009/1 for further details of EIS and GSWA's recurrent work program

Encouraging exploration

Exploration Incentive Scheme

by Margaret Ellis

In early April 2009, in fulfilment of an election commitment, the Western Australian government announced funding of a five-year, $80 million Exploration Incentive Scheme (EIS) to encourage exploration in Western Australia for the long-term sustainability of the State's resources sector. Most of the six broad programs (Tables 1 and 2) under EIS are focused in under-explored greenfields regions.

Implementation of EIS, involving additional expenditure of between $16 and $20 million per annum over the period from 2009–10 to 2012–13 effectively means more than a doubling of the Geological Survey of Western Australia's (GSWA) budget over the period. However, with only eight contract Public Service positions approved as part of the scheme, fee-for-service arrangements, contracting-out of services, and collaborative programs with university and government research groups and centres will be required to undertake the massive work program.

Approval of EIS came after the 2007 Review of the Geological Survey of Western Australia conducted by Resource Advisors Pty Ltd, an independent consulting group. The review (Cramsie and Deegan, 2007) recommended a five-year funding increase of $59.5 million for GSWA with the option of an additional $5 million per annum for a 'collaborative drilling program'.

Although the recommendations of the review differ in detail from the six broad programs of EIS, the amount of funding for the two is remarkably similar. EIS will have an enormous impact on GSWA over the next four years and will result in a step-wise increase in the amount of pre-competitive geoscience information available for the State.

Outline of EIS

The Exploration Incentive Scheme objective is to encourage exploration in Western Australia, particularly in under-explored minerals greenfields areas and frontier petroleum basins, and maintain it at the levels needed for the long-term sustainability of the State's resources sector. In the absence of any viable alternative, Western Australia's economy and its citizens' lifestyle will continue to depend in the medium- to long-term on development of the State's resources. The scheme addresses this longer term need as well as providing some shorter term stimulus for the exploration industry during the exploration downturn caused by the global financial crisis. Importantly, the funding of a large exploration incentive package at this time signals that the State Government is serious about fostering investment in the State's resources sector and is concerned about the sustainability of resource production if discovery rates are not increased.

ROYALTIES FOR REGIONS
EXPLORATION INCENTIVE SCHEME

Two major components of the Scheme are the completion of the State's coverage by airborne magnetic surveys at 400 m (or less) line spacing and a major expansion of the area covered by gravity surveys with stations spaced less than 2.5 km apart.

Table 1 sets out the budgets for the six programs. Projects are described in more detail later. Analysis of planned expenditures under the scheme suggests that individual activities totalling $24 million out of the $80 million will directly benefit the petroleum, unconventional gas, and geothermal industries.

Table 2. Exploration Incentive Scheme

Exploration Incentive Scheme activity		*Funding ($ million)*
Exploration and Environmental Coordination in DMP		*1.5*
Drilling		
Industry–Government co-funded	*$20.9*	
Stratigraphic	*$6.0*	*26.9*
Geophysical and geochemical surveys		
Airborne geophysics	*$21.0*	
Ground geophysics and geochemistry	*$12.3*	*33.3*
3D geological mapping		*13.8*
Promoting strategic research with industry		
MERIWA	*$1.4*	
Embedding researchers in industry	*$0.9*	*2.3*
Sustainable working relations with Indigenous communities		
Petroleum	*$1.2*	
Minerals	*$1.0*	*2.2*
		80.0

EIS programs

Exploration and environmental coordination

In keeping with the objective of EIS to encourage exploration in Western Australia it is essential to support the exploration industry with a robust tenement application and management system. Enhancements are required to the web-based title systems, to facilitate online tenement application and management, and provide comprehensive approvals-tracking.

These enhancements will integrate the environmental application and approval process into the minerals and petroleum tenement management systems and provide comprehensive tracking of tenement applications through the various approval stages, with online access to the status of tenement applications available to external stakeholders via a secure sign-on.

In addition to the online lodgement and processing of tenement applications, associated reporting obligations will also be facilitated online.

Innovative drilling

The Co-funded Government – Industry Drilling Program is designed to stimulate geoscience exploration and contribute to the economic development of greenfields regional areas of Western Australia. It will preferentially fund high-quality, technically and economically sound projects that promote new exploration concepts and new exploration technologies.

Following the completion of all drilling in 2009–10, the overall results, outcomes, and successes from the incentive program will be assessed, which will contribute to the establishment of a revised strategy for the program in 2010–11 and through to 2013**.** Consultation with industry is facilitated by representatives of industry bodies in Western Australia acting through the Drilling Advisory Committee. The Committee has a mandate to provide recommendations on the broad policy framework of the co-funded drilling program as well as annually reviewing the operations of the program and recommending amendments to the programs guidelines.

Core collected by companies that gain co-funding will be available in the relevant core library (Perth or Kalgoorlie) after a 6-month confidentiality period. Reports of the drilling programs will also be released online after a similar confidentiality period.

Stratigraphic drilling will be undertaken by the Geological Survey of Western Australia (GSWA) to validate seismic interpretation and provide additional pre-competitive geoscience information for use by both petroleum and mineral explorers.

The program will complement other mineral and petroleum drilling, and will fund coring of holes in the Canning, Eucla, and southern Perth Basins. Drilling in the Eucla Basin will be aimed at identifying the nature of its crystalline basement.

The data provided will aid interpretation of formations where there is little current information, as well as help to identify potential for hydrocarbons and geothermal energy.

Drilling in the southern Perth Basin will test sedimentary units that could be used for carbon geosequestration.

Geophysical and geochemical surveys

Prior to implementing EIS, only 70% of the State was covered by medium-resolution airborne magnetic and radiometric surveys, with about 30% of the area of Western Australia having only low-resolution (1600 m) airborne magnetic and radiometric coverage. These data were acquired around 40 years ago and have little current exploration value. This project will largely complete the medium-resolution airborne magnetics and radiometrics (400 m) coverage of the State (Fig. 1).

A network of deep seismic traverses to image WA's crustal structure at depth will be generated, as shown on Figure 2. Integrated geophysical and geological transects are planned across the West Australian Craton and its margins, and adjacent Proterozoic orogens and Phanerozoic basins, to provide a key to the geological evolution of the Western Australian lithosphere. Such traverses will aid our understanding of the localization of mineral systems within the upper crust.

The lines extend and integrate pre-existing deep seismic lines, and follow existing roads wherever possible to minimize costs.

A program of regional gravity surveys will be undertaken. The objective of this program is to provide 3D geological information to complement GSWA's geological mapping in selected greenfields exploration areas.

Additionally, regional geochemical surveys will provide multi-element geochemical coverage of under-explored parts of the Yilgarn Craton to

Encouraging exploration

stimulate mineral exploration there. Data collected from the surveys will then be incorporated into GSWA's web-based geochemical database.

3D geological mapping

A series of activities falling under the 3D geological mapping program will focus on the capture of geoscientific information at depth and its seamless delivery.

The WA Geology Online project will improve geoscience information services to DMP clients by developing an integrated system that allows all geoscience databases to be accessed seamlessly online. In addition to better integrating GSWA's online information, the WA Geology Online project will develop and facilitate new databases and services linked to current and future map layers. Through this activity, GSWA clients will be able to generate customized reports and maps.

The upgrade of DMP's Western Australian Petroleum Information Management System (WAPIMS) will be completed. This will help to provide a more streamlined information submission and release system for the petroleum industry, and will ensure that the WAPIMS system is interoperable with other departmental computer systems.

Another project will build and maintain interactive 3D geological models — from prospect to crustal scale — for selected greenfields exploration areas. 3D geological models can be used to test various structural models and interpretations, and to visualize the Earth at depth. They can be used as predictive models to characterize areas of known mineralization, as well as identify similar patterns to generate new exploration targets. Once developed, the 3D models will be available to view and download from the DMP website.

The existing GSWA geochemistry database will be upgraded so that it can accept the uploading of digital geochemistry data submitted by companies, as well as existing GSWA geochemistry data. This newly designed web-based facility will allow the query and extraction of both open-file company and GSWA geochemistry. Similarly, the drillhole information database project will improve online information services to DMP customers with an integrated system that allows all drillhole data, and related geochemistry, to be queried and integrated with other GSWA online data. These improvements will enable open-file company

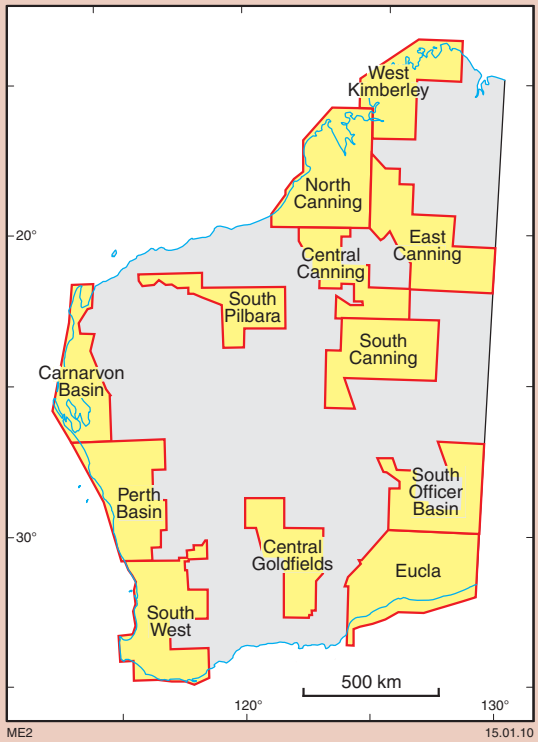


Figure 1. Planned magnetic and radiometric surveys

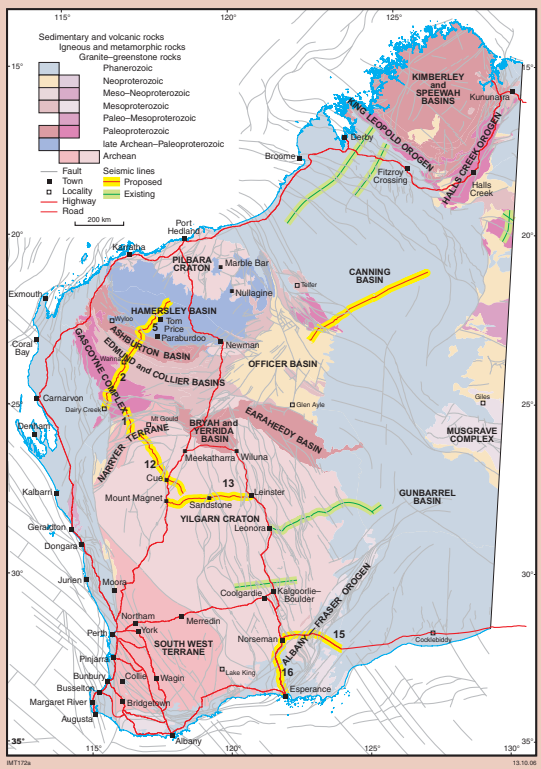


Figure 2. Planned deep-crustal seismic traverses

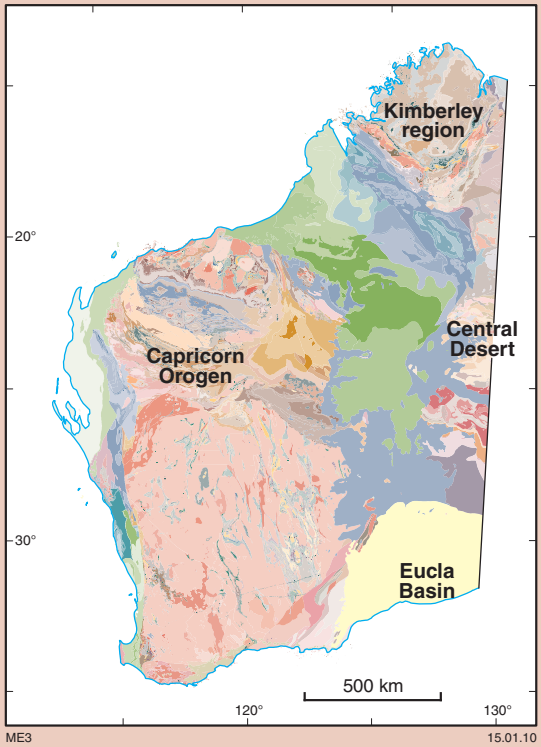


Figure 3. Remote greenfields areas will be the focus of geological mapping and interpretation.

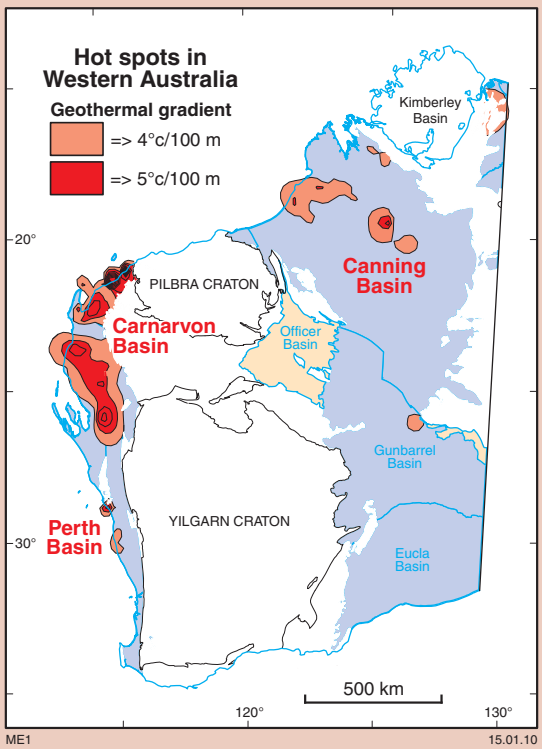


Figure 4. Hot spots in Western Australia

mineral exploration drillhole locations and down-hole geochemistry to be accessible via the DMP website.

Another project will involve undertaking regional geoscience mapping and the interpretation, from geophysical data, of bedrock under thin soil and sedimentary basin cover. The focus will be on remote greenfields areas including the basement to the Eucla Basin, the Central Desert area, the Kimberley region and the Capricorn Orogen (Fig. 3). Such a project will be built on an expanded program of isotopic dating providing information on the timing of rock units and specific geological events.

Alternative energy sources include geothermal, tight gas, and enhanced petroleum recovery from depleted reservoirs (Fig. 4). The national commitment to 'clean' energy also provides a requirement to look at coal technologies to reduce the State's carbon dioxide footprint. New geoscience information relating to the use of geosequestration to store carbon dioxide emissions is another key aspect of this project. The geothermal project will review current data for geothermal energy, conduct desktop studies on prospective basins, and provide new field data in areas with little coverage.

Promoting strategic research with industry

One of the key objectives of EIS will be helping to promote strategic research with industry. As part of achieving this goal, $900 000 will be used to develop the Western Australian Regional Researcher Initiative.

The new initiative is aimed at the rapid transfer of new geoscience concepts, skills, and technologies into the Western Australian minerals exploration industry. It will involve the placement of three embedded researchers into company exploration teams focused on greenfields areas. The researchers will be employed by CSIRO. Funding to support these employees will be split evenly between EIS and the participating exploration company sponsors. Overall, the Western Australian Regional Researcher Initiative will help promote the flow of information between research teams and industry sponsors and create a two-way training process for industry professionals and researchers.

Increased funding of $1.4 million will also be provided to the Minerals and Energy Research Institute of Western Australia to support the minerals and petroleum-related research the

Encouraging exploration

organization funds throughout the State in association with industry.

Sustainable working relations with Indigenous communities

The State Government will dedicate funding from EIS to providing initiatives designed to assist Indigenous and environmental approvals for prospecting, geoscience mapping, and mining and petroleum exploration and production. The strategy and work program will target under-explored onshore areas of the State that have access corridors to major interior basins. In addition, a model Indigenous land use agreement will be developed, which can be utilized where Native Title has been determined, and where it remains as a claim. Key objectives of this program are to address Indigenous heritage, the Future Act process under the *Native Title Act 1993*, and access to the land where exclusive Native Title exists.

Reference

Cramsie, J and Deegan, G 2007, Review of the Geological Survey of Western Australia: Resource Advisors Pty Ltd for the Department of Industry and Resources (now Department of Mines and Petroleum) <www.dmp.wa.gov.au/GSWApublications>.

Overview of mineral exploration in Western Australia for 2008–09

by PB Abeysinghe and DJ Flint

Abstract

Globally, the 2008–09 year was perhaps a once-in-a-generation event, which had monumental impacts on Western Australia. Although the financial year started with 'boom' conditions in the mining industry, the residential housing sub-prime mortgage debt problems in the USA expanded into a global financial crisis by late 2008, and numerous major economies slipped into recession by the end of 2008 and early 2009. One of the main drivers of the world economy, China, slowed its growth rate and the world-wide demand for metals also plunged. Commodity prices plunged too, and many mining companies struggled under conditions of reduced cash flow (or being cash negative) at a time of excessive debt. Numerous mines closed, reducing mine supply, but the world-wide demand for metals was even weaker. Capital for exploration and mine development was exceedingly difficult to obtain. Even 'letters of credit' for shipments of iron ore were difficult to obtain at one stage. In addition, unemployment and part-time employment in the mining sector increased.

In Western Australia, numerous operating mines closed or officially went into 'care and maintenance' mode. The nickel sector was hit particularly hard as prices had retreated by around 45% over the previous year. Despite these conditions, the value of mineral production in the State increased by 24% to a new record of $50.3 billion (excluding petroleum) in 2008–09. This was largely due to the dominance of the iron ore sector in Western Australia's minerals industry, and to contract prices for iron ore that had been set in the previous year. The value of iron ore production in Western Australia rose 53% for the year! Despite one-year fixed contracts, shipments of iron ore from Western Australia were still occasionally 'deferred' during the year or prices renegotiated (against a backdrop of markedly lower spot prices).

As expected, attempts to preserve cash and capital meant that exploration, especially for new deposits, largely stalled. Across Australia, mineral exploration expenditure declined by 12% for the year, with drilling (metres drilled) at existing deposits falling by 11% but drilling for new deposits plunging by 30% (comparable WA-specific data for metres drilled are not available).

In Western Australia, the trend was similar but the magnitude of the falls was less — as mineral exploration expenditure in Western Australia declined during 2008–09 by only 4% (in 2008–09 dollar terms). However, the area held under granted Exploration Licences in Western Australia fell by 22% by the end of 2008–09, but the area under granted Mining Leases actually increased marginally.

By mid-2009, the global markets were more stable, showing signs that the worst of the global crisis was over. Many companies were raising capital through sale of shares and sovereign wealth funds (particularly from China) emerged strongly as providers of new capital.

KEYWORDS: mineral exploration, exploration expenditure, mineral production, gold, iron, nickel, base metals, copper, lead, zinc, silver, diamond, heavy mineral sands, uranium, molybdenum, rare earth elements, vanadium, lithium, coal, antimony, tungsten, manganese, exploration drilling, Exploration Incentive Scheme (EIS), tenements, Western Australia

Overview

Significant observations for the Western Australian mineral industry during 2008–09 include:

- Mineral exploration expenditure in Western Australia decreased by 4% from $1298 million in 2007–08 to $1247 million* in 2008–09 (Fig. 1, in 2008–09 dollar terms).
- Australian mineral exploration expenditure decreased by 12% from $2536 million in 2007–08 to $2223 million in 2008–09 (in 2008–09 dollar terms).
- Western Australia's share of national exploration expenditure for minerals (excluding petroleum) increased from 51% in 2007–08 to 56% in 2008–09, and is returning towards the level of around 60% experienced during the late 1990s and early 2000s (Fig. 1).
- Quarterly mineral exploration data indicate that the rate of decline in exploration expenditure in Western Australia was slowing in the June 2009 quarter (Fig. 2).

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

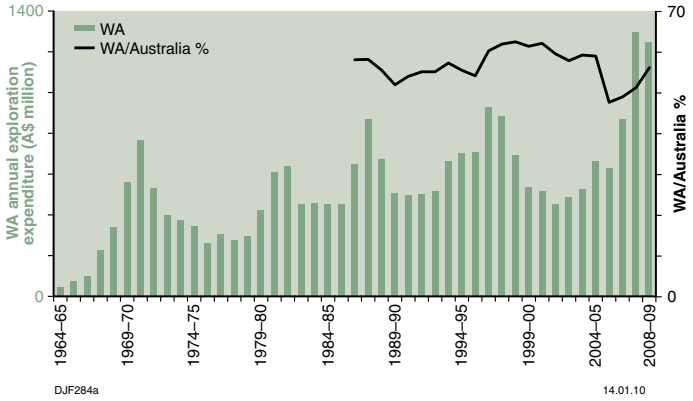


Figure 1. Mineral exploration expenditure in Western Australia, by year (2008–09 dollars)

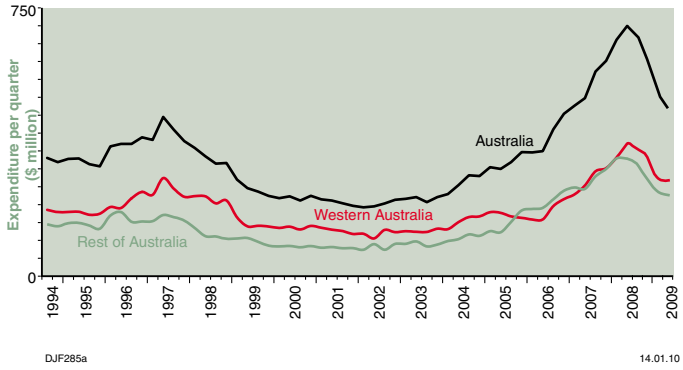


Figure 2. Mineral exploration expenditure for Australia, Western Australia, and the rest of Australia (seasonally adjusted, June 2008-9 dollars)

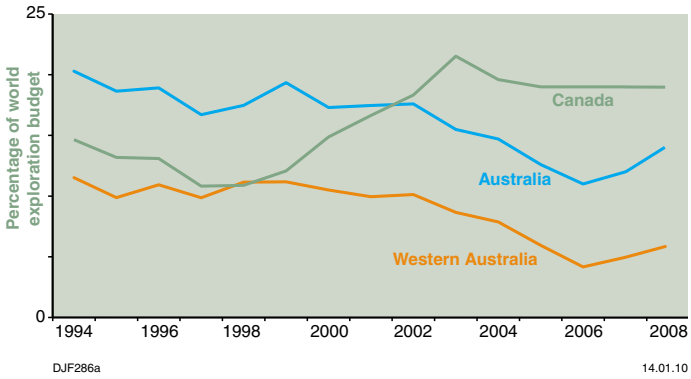


Figure 3. Non-ferrous mineral exploration expenditure — comparative market share of Canada and Western Australia since 1994 (source: Metals Economics Group (Canada), Australian Bureau of Statistics, and Department of Mines and Petroleum)

- Iron ore continued to be the key commodity for 2008–09. The value of Western Australian iron ore production increased by a remarkable 53% to $30.6 billion and iron ore exploration expenditure increased by 29% to $559 million.
- The world gold price reached a 25-year high (in US$ terms), but the gold industry in Western Australia remained fairly subdued in 2008–09. The good news was the first production of gold–copper concentrate from Newmont Mining Corporation's Boddington mine in mid-2009, and the beginning of a feasibility study of the 5 M oz Tropicana project, where commissioning is expected in 2013.
- Although the production of nickel increased by 3.5% the value of production decreased by 42%, reflecting the dramatic drop in nickel prices in late 2008 and early 2009. The fall in nickel prices has also resulted in the suspension of production from more than 10 nickel mines in Western Australia.
- The pro-uranium policy of the State Government continues to have a positive impact on the uranium sector, with numerous projects advancing, and with some being considered for mine development in the medium term. These include Yeelirrie (BHP Billiton Ltd), Lake Maitland (Mega Uranium Ltd, Itochu Corp. and Japan Australia Uranium Resources Development Co. Ltd), Lake Way (Toro Energy Ltd), Kintyre (Cameco Corp. and Mitsubishi Corp.) and Mulga Rock (Energy and Minerals Australia Ltd).
- Despite much bad news during the year, there were quite a few discoveries announced. This was to be expected, with so much spent on exploration during recent years finally coming to fruition. Discoveries include the high-profile DeGrussa massive sulfide discovery in the Proterozoic Bryah Basin, as well as Archean volcanogenic massive sulfide prospects at Bentley, Austin, and Evelyn. Gold discoveries include Musket (Higginsville), whereas iron ore discoveries include Feather Boa (Robertson Range) and Woggaginna and Jigalong (east of Newman). In addition, there were many maiden resource estimates at iron ore deposits and some also for uranium deposits.

During the last decade, the proportion of the world's non-ferrous mineral exploration expenditure in Australia has decreased from 18% to 14% (Fig. 3, based on data compiled by the

Overview

Metals Economics Group of Halifax, Canada, <www.metalseconomics.com>), of which, Western Australia's share has decreased from 11% to 6%. The sharp decline from 2002 levels in both Western Australia and Australia appeared to have bottomed in 2006 at 4% and 11% respectively, with a marginal rise in 2008 to 6% and 14%. Western Australia is actively working towards improving its competitiveness to attract investment by positive programs such as the Exploration Incentive Scheme (EIS).

The Exploration Incentive Scheme (EIS) is a State Government initiative to encourage exploration in Western Australia for the long-term sustainability of the State's resources sector. EIS will enhance the image of Western Australia as an attractive destination for mineral and energy exploration investment. This $80 million initiative, funded by Royalties for Regions over five years, will stimulate increased private sector resource exploration and ultimately lead to new mineral and energy discoveries. Further details of EIS are provided in the accompanying article (Exploration Incentive Scheme, by Margaret Ellis).

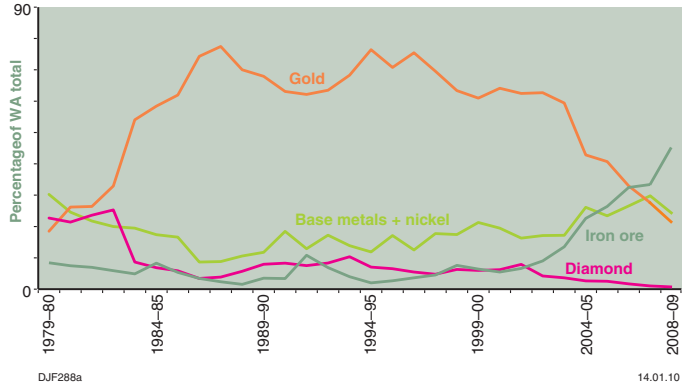


Figure 4. Exploration expenditure in Western Australia since 1979–80 (% of total, by commodity)

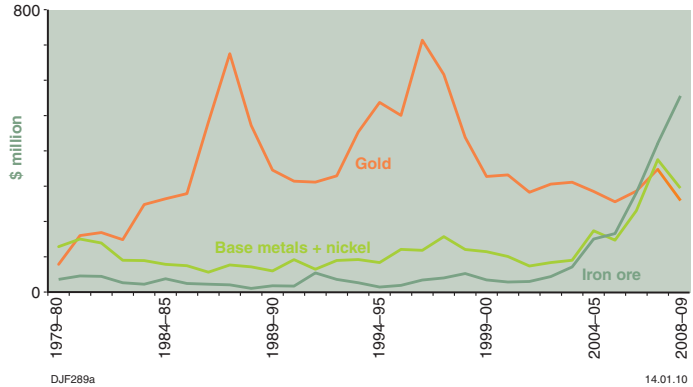


Figure 5. Gold, base metals + nickel, and iron ore exploration expenditure in Western Australia since 1979–80 (2008–09 dollars)

Developments and mineral exploration highlights by commodity

During 2008–09, exploration expenditure for iron ore continued its record-breaking run, but exploration for the other major commodities of gold, nickel, and base metals decreased (Figs 4 and 5).

Gold

Trends in the gold industry in Western Australia during 2008–09 include:

- The international gold price, in A$ terms, rose 28% — from an average of $918/oz in 2007–08 to an average of $1171/oz in 2008–09. In US$ terms, the increase during the same period was 6.2% from US$823/oz to US$874.
- Gold production fell by 4% to 135 610 kg, but the value increased by 25% to $5.2 billion. The top ten gold producing mines during 2008–09 were the Golden Mile Super Pit, Telfer, Kambalda – St Ives, Sunrise Dam, Jundee, Kanowna Belle, Agnew, Marvel Loch, Plutonic, and Higginsville.
- Despite the increase in gold prices, expenditure on gold exploration in Western Australia in 2008–09 decreased by 27% to $263 million, reversing the positive trend of the previous two years (Fig. 6).

Although gold exploration has been the backbone of the mineral exploration industry in Western Australia since the early 1980s (and reached levels of around 75% of the total mineral exploration expenditure in the mid-1990s), its proportion of total exploration expenditure during 2008–09 declined to 21% (Fig. 4). As a result, exploration expenditure for gold is now less than that for iron (Fig. 5), and is also below the combined exploration expenditure for nickel and base metals. An inadequate level of greenfields mineral exploration is of ongoing concern for the future of gold mining in the State.

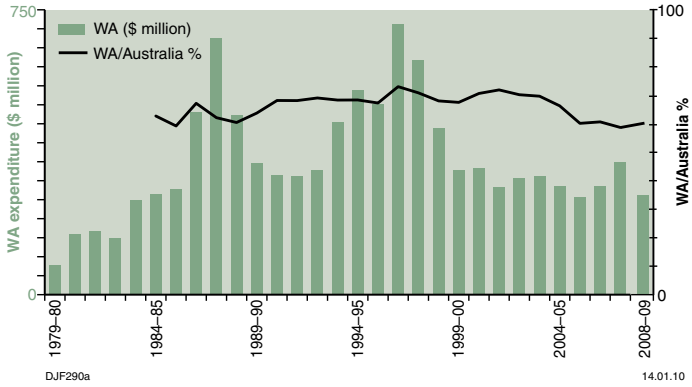


Figure 6. Gold exploration expenditure in Western Australia since 1979–80 (2008–09 dollars)

The most significant of the new mine developments for 2008–09 was the production of gold–copper concentrate from Newmont Mining's Boddington project (100 km southeast of Perth) in mid-2009. The annual gold production from this operation in the first five years is expected to average around 1 million ounces (Moz) of gold. The deposit has estimated proven and probable reserves containing 20.1 Moz of gold, with an estimated mine life in excess of 24 years (Newmont Mining Corporation, 2009).

In mid-2009, the AngloGold Ashanti Ltd / Independence Group NL joint venture announced that it would begin a feasibility study into bringing the 5 Moz Tropicana project (340 km northeast of Kalgoorlie) into production. Construction of the remote mine and infrastructure could take around two years, with commissioning in 2013. Production is expected to be 330 000–410 000 oz of gold per annum, with a mine life of approximately 15 years (Haycock, 2009; Jacoby, 2009a).

Avoca Resources Ltd established Trident at Higginsville, about 53 km north of Norseman — the State's third largest underground gold mine. Other planned underground mines include Chalice and Two Boys / Fairplay. New openpits include Fairplay, Mitchell, Musket, and Wills. The Higginsville plant is operating at 1.2 Mtpa. In 2008–09, the Trident mine produced 131 000 oz of contained gold, and Avoca is targeting production of more than 1 Moz contained gold over about 8 years (Avoca Resources Ltd, 2009).

Ramelius Resources Ltd expects its underground Wattle Dam mine, 25 southwest of Kambalda, to produce gold from June 2009, at an expected rate of 70 000 oz of gold up to third-quarter 2010 at an estimated operating cost of $385 per ounce. In addition, a diamond drillhole at Wattle Dam gold mine had an intersection of 5.5 m at 148 g/t of Au including 0.2 m at 1846 g/t Au and 0.6 m at 738 g/t Au. The results confirmed the down-plunge continuation of the high-grade zone at Wattle Dam (Ramelius Resources Ltd, 2009).

In other developments:

- Focus Minerals Ltd is mining at Coolgardie, with plans to produce 50 000 oz of gold in 2009. During the three months to December 2008, Focus increased its reserves at the Perseverance deposit of the project to 100 000 oz, giving the mine a two-year life (Focus Minerals Ltd, 2009).
- Silver Lake Resources Ltd poured its first tonne of pure gold from the Daisy Milano operation, 50 km southeast of Kalgoorlie, and processed it through its Lakewood gold processing facility, 5 km southeast of Kalgoorlie (Silver Lake Resources Ltd, 2009).
- Catalpa Resources Ltd is developing the Edna May gold project at Westonia. Edna May has reserves of 19.1 Mt at 1.2 g/t Au for 738 000 oz of contained gold (Miningnews.net, 2009).
- Integra Mining Ltd has confirmed a two-phase development of its Randalls project, 35 km east-northeast of Kambalda, with planned production totalling about 630 000 ounces of gold over 10 years (Integra Mining Ltd, 2009a).
- In late 2008, St Barbara Ltd began gold production from the Leonora operation (previously operated by Sons of Gwalia), with the first gold pour of around 1000 ounces. The deposit has more than 1.7 Moz of gold reserves grading 9 g/t Au, with an estimated mine life of more than nine years. The operation is forecast to produce 115 000 – 125 000 oz of gold in 2009 at a forecast operating cost of $540–570 per ounce (Miningnews.net, 2008).

In the gold exploration sector, a number of companies had impressive gold intersections at various projects throughout Western Australia. These include:

- 24.1 m at 36.4 g/t Au and 17.7 m at 14.3 g/t Au at Athena lode of the Trident mine. At the Western Zone lode in the same mine there was an intersection of 48.3 m at 7.1 g/t Au and 33.4 m at 12.2 g/t Au (Avoca Resources Ltd, 2009).

Overview

- 50 m at 5.75 g/t Au, 67 m at 2.75 g/t Au, and 49 m at 2.99 g/t Au at the Brilliant prospect of the Kurnalpi project (Carrick Gold Ltd, 2008, 2009).
- 27 m at 36.1 g/t Au (including 3 m at 114.8 g/t Au, 2 m at 121.8 g/t Au) at Barlee gold project, 140 km east of Paynes Find (Beacon Minerals Ltd, 2008).
- 42 m at 2.72 g/t Au from 32 m downhole at Blair North prospect at the East Kalgoorlie (Northern Mining Ltd, 2009).
- Drilling at Salt Creek, 35 km east-northeast of Kambalda, continued to produce good intersections including 56.45 m at 5.63 g/t Au, 40.5 m at 6.48 g/t Au, 1 m at 94.11 g/t Au, 0.6 m at 167.26 g/t Au, and 19.26 m at 10.48 g/t Au (Integra Mining Ltd, 2009b).
- Intersections of 5 m at 6.4 g/t Au from 3 m, including 1 m at 23.4 g/t Au and 15 m at 3.2 g/t Au from 34 m along strike of the Hawkeye deposit of the Hermes project in the Gascoyne Province (Alchemy Resources Ltd, 2009).
- 12 m at 6.86 g/t Au (including 4 m at 16.9 g/t Au) from 32 m, 5 m at 2.24 g/t Au from 36 m, and 3 m at 2.94 g/t Au from 34 m at Tregurtha prospect and 49 m at 1.17 g/t from 31 m, including 4 m at 4.78 g/t at Hughes prospect of the Lignum Dam gold project, 55 km north of Kalgoorlie (Pioneer Nickel Ltd, 2009a,b).
- 6.8 m at 15.73 g/t Au from 215 m, 3.4 m at 30.36 g/t Au from 216 m and 25.9 m at 16.56 g/t Au from 240 m at Two Mile Hill prospect near Sandstone (Troy Resources NL, 2009).
- 4 m at 31.2 g/t Au, 3 m at 23 g/t Au, and 1 m at 69.4 g/t Au at Paulsens mine, 105 km south of Pannawonica (Intrepid Mines Ltd, 2009).
- 8 m at 6.98 g/t Au from 12 m within a broader zone of 48 m at 1.62 g/t Au at Brierly prospect of the Turner River gold project (De Grey Mining Ltd, 2008).

Iron

Highlights in Western Australia during 2008–09 include:

- Another year of record production quantity, production value, and exploration expenditure.
- The value of Western Australian iron ore production increased by a remarkable 53% to $33.6 billion, although tonnage increased by only 8.5% to 316 Mt of iron ore.
- Western Australian expenditure on iron ore exploration has continued its 7-year stellar rise, climbing by 29% (to $559 million) in 2008–09 compared to 2007–08, and more than 1133% over the last seven years (Fig. 7).
- Iron ore exploration in Western Australia now attracts the highest expenditure, and from last year surpassed gold exploration expenditure (Figs 4 and 5), accounting for 45% of the total exploration dollars spent in Western Australia. At present, over 130 companies are exploring for iron ore in Western Australia.
- Numerous mines, targeting zones of supergene enrichment, were either being developed or were at an advanced feasibility stage. The State has also moved significantly closer to developing its first iron ore mine producing a magnetite concentrate.
- Following several years of intense capital investment in expansion projects in the Pilbara, Western Australia's iron ore production is set to increase significantly over the next 5–10 years.
- Overseas companies (predominantly Chinese) continued to greatly increase their direct ownership or involvement (e.g. through

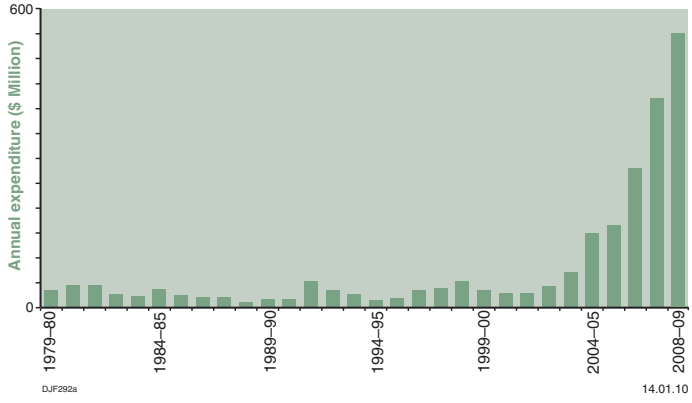


Figure 7. Western Australian iron ore exploration expenditure (2008–09 dollars)

long-term off-take agreements) in the Western Australian iron ore industry, all seeking to secure long-term supplies.

The unprecedented iron ore boom of the past three years continued, driven by extremely strong customer demand for iron ore, particularly from China, concomitant with a world-wide shortage of supply. The major producers in the Pilbara are responding rapidly by expanding their operations at existing projects and planning new ones. Also, the high iron ore prices have greatly assisted the capital-raising capabilities of junior companies. Consequently, a number of significant producers have emerged, for example Fortescue Metals Group Ltd (FMG), Atlas Iron Ltd, and foreign companies such as CITIC Pacific Ltd (potential producer), thus diminishing the historical duopoly of Rio Tinto Ltd and BHP Billiton Ltd (BHPB) in the Pilbara.

The most conspicuous corporate activity during 2008–09 involved Rio Tinto Ltd, which needed to reduce debt in the wake of the global financial crisis. Initially, BHPB launched a $66 billion takeover bid for Rio Tinto, but this was scrapped in November 2008. Rio Tinto then sought a strategic alliance with Aluminium Corporation of China (Chinalco) in February 2009, which would have included direct investment by Chinalco in Rio Tinto, but this too was scrapped in June 2009. At that time, Rio Tinto signed a non-binding agreement with BHPB to establish a production joint venture of the two companies' Pilbara iron ore operations. The proposed 50:50 joint venture would cover all current and future production operations, but not marketing of the Pilbara product.

BHPB announced in November 2008 the approval of Rapid Growth Project 5 (RPG5), which will increase installed capacity across its Pilbara iron ore operations to 205 Mtpa by the second half of 2011. Production growth will mainly come from the Yandi and Mining Area C operations (Jacoby, 2008).

Another significant development in Western Australia's iron ore industry is the entry of Atlas Iron as an iron ore producer. In March 2009, about 150 000 wet tonnes of iron ore from the company's Bobby deposit of the Pardoo iron ore project was shipped to China, using the port facilities owned by Fortescue Metals Group in Port Hedland. The miner plans to increase capacity at Pardoo to 3 Mtpa after the Utah Point port facility is commissioned and is targeting exports of 6 Mtpa by 2010 and 12 Mtpa by 2012. Atlas Iron also plans to develop its $10 million Wodgina (100 km south of Port Hedland) direct shipping ore project, and expects to begin production in early 2010 at an initial rate of 2 Mtpa (Atlas Iron Ltd, 2009a,b).

On the negative side, Rio Tinto slashed its 2008 Pilbara iron ore shipment estimates by around 10% as a result of falling demand from Chinese customers. The miner has downgraded its previous 2008 estimate of 190 Mt to a revised estimate of 170 to 175 Mt (Dudley, 2008). However, iron ore production for calendar 2009 remains at around 200 Mt, with the company expecting a recovery in Chinese steel demand in the latter half of this year. Also, Rio Tinto has put the HIsmelt pig iron plant at Kwinana on care and maintenance for 12 months until April 2010 due to depressed global pig iron prices and poor market outlook (Batten, 2009a,b).

In the magnetite sector, Gindalbie Metals Ltd is finalizing environmental approvals from the Western Australian Environment Minister for its Karara magnetite project in the Mid West region. Gindalbie and its Chinese joint venture partner, Anshan Iron & Steel Group, plan for construction and development of the large-scale project to begin in the latter part of 2009 (Svircas, 2009). Meanwhile, Grange Resources Ltd has increased its measured, indicated, and inferred resources at the Southdown deposit near Albany to 654.4 Mt at 36.5% magnetite (Batten, 2009c).

Companies exploring for iron ore in Western Australia continue to target numerous mineralization styles including channel iron deposits (CID); supergene-enriched hematite over Archean (Marra Mamba) to Paleoproterozoic (Brockman) banded iron-formations (BIF); primary magnetite in BIF (taconite ores) of the Pilbara and Yilgarn Cratons; titanomagnetite in cumulate-layered mafic–ultramafic intrusive rocks in the Pilbara Craton at Balla Balla, magnetite in BIF within the Mesoproterozoic gneiss terrane of the Albany–Fraser Orogen; clastic hematite in Paleoproterozoic–Mesoproterozoic sedimentary rocks of the Kimberley Basin (Cockatoo Island, Koolan Island); hematite iron ore mineralization in the Mid West region, and granular iron-formation deposits in the Paleoproterozoic Earaheedy and Yerrida Basins. There was ongoing interest by numerous companies in primary magnetite mineralization within BIF horizons throughout the Yilgarn Craton.

A number of junior companies in Western Australia have either announced maiden resource

estimates or upgraded existing resources. Some of these include:

- A maiden resource estimate of 11.7 Mt at 57.6% Fe for the Jimblebar Range iron ore project, 50 km east of Newman, where the mineralization is supergene hematite–goethite type overlying banded iron-formation (Warwick Resources Ltd, 2008).
- Wodgina, 100 km south of Port Hedland, now has an inferred resource of 42.73 Mt at 56.3% Fe of direct-shipping (DSO; does not require beneficiation) hematitic ore (Atlas Iron Ltd, 2009c).
- Mount Cauden deposit, 20 km south-southeast of Marvel Loch, has a maiden inferred resource of 19 Mt, comprising 15.5 Mt of banded iron-formation grading 57.5% Fe as well as 3.5 Mt of canga and detrital ore grading 51.5% Fe (Cazaly Resources Ltd, 2008).
- Jack Hills, 155 km west-northwest of Meekatharra, has a measured, indicated, and inferred direct shipping ore (DSO) mineral resource of 96 Mt at 58.7% Fe and a beneficiation feed resource of 991 Mt at 34.1% Fe (Murchison Metals Ltd, 2009).
- Resources at the Western Creek project, 20 km west-southwest of Newman, increased by a further 28% to a total inferred mineral resource of 52.4 Mt at 56.7% Fe (Giralia Resources NL, 2009).
- A maiden inferred resource of 72.4 Mt at 34.02% Fe is estimated for the Mount Oscar iron project, 20 km south-southeast of Roebourne (Fox Resources Ltd, 2009).
- A maiden inferred resource of 476 Mt at 55.4% Fe is estimated for Flinders Mines Ltd's Hamersley project, 80 km north-northwest of Tom Price (Flinders Mines Ltd, 2009).
- The mineral resource of the Balmoral South project, 60 km north-northwest of Pannawonica, has increased by 44% to 1.6 Bt at 22.6% magnetic iron (MagFe), whereas the probable ore reserve has increased by 26% to 859 Mt at 22.6% MagFe (Australasian Resources Ltd, 2009).
- BC Iron Ltd has increased the DSO resource at its Nullagine iron ore project (25 km southwest of Nullagine) in the Pilbara, to 50.7 Mt at 57% Fe (BC Iron Ltd, 2009).
- A maiden inferred resource of 127 Mt at 28.15% Fe at Emergent Resources Ltd's Beyondie project, 125 km northeast of Peak Hill (Emergent Resources Ltd, 2009).
- Grange Resources Ltd has increased the measured, indicated, and inferred resources at its Southdown deposit, 80 km northeast of Albany, to 654.4 Mt at 36.5% magnetite (Batten, 2009c).

Some iron ore exploration successes include:

- A new high-grade iron ore (banded iron-formation) discovery at Woggaginna, 55 km southeast of Newman (Warwick Resources Ltd, 2009).
- High-grade hematite mineralization was intersected in drilling at Jigalong, 110 km east of Newman (Hannans Reward Ltd, 2008).
- Discovery of the Feather Boa prospect, 95 km east-southeast of Newman, part of the Robertson Range iron ore project (FerrAus Ltd, 2008).
- Thick intersections of high-grade bedded iron mineralization (e.g. 117 m at 63% Fe) from 61 m at the Railway deposit, 80 km south-southeast of Wittenoom (United Minerals Corporation NL, 2008).
- A hematite-enriched zone (e.g. 70 m at 58.4% Fe) from the surface to a depth of about 80 m, at Mount Webber, 60 km southwest of Marble Bar (Haoma Mining NL, 2009).

Nickel

Broad trends for the nickel industry in Western Australia during 2008–09 include:

- The international nickel price in 2008–09 fell dramatically (by 45%) from an average of $31 908 per tonne in 2007–08 to an average of $17 626 in 2008–09.
- The decrease in the nickel price led to a dramatic fall (by 42%) in the value of nickel production in 2008–09 to $3 billion, although the production quantity increased by 3.5% to 178 kt of contained nickel.
- Nickel exploration expenditure in Western Australia decreased by 14.5% to $247 million (Fig. 8).
- The dramatic fall of nickel prices led to the closure of a number of nickel laterite as well as nickel sulfide mining operations.

Key points in the nickel laterite sector include:

- BHPB's Ravensthorpe operation that began production in late 2007 was put on care and maintenance in January 2009.
- Norilsk's Cawse nickel laterite operation, 50 km northwest of Kalgoorlie, that began production in 1998, was also put on care and maintenance in June 2008.
- Vale Inco has decided not to proceed with the full feasibility study for the Kalgoorlie Nickel Project of Heron Resources. Heron will seek a new partner for the development of the project when the optimization study is completed (Heron Resources Ltd, 2009a).
- Heron entered into an agreement with the Chinese company, Ningbo Shanshan, for the Yerilla nickel–cobalt project (which includes the Jump-Up Dam deposit) with Shanshan able to earn a 70% interest in the project. The project will process around a million tonnes of laterite ore per annum, producing a concentrate for further processing in China (Heron Resources Ltd, 2009b).

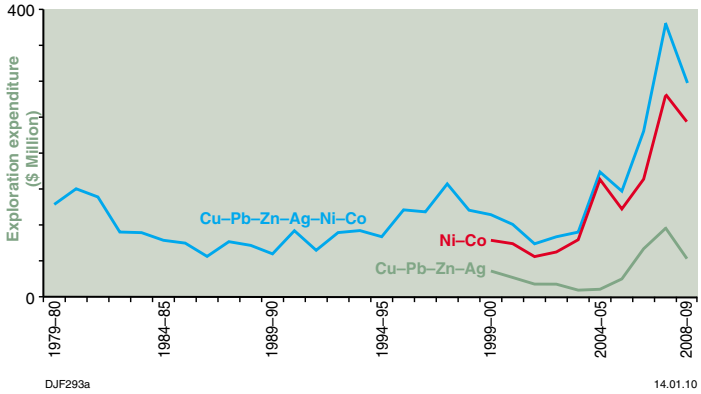


Figure 8. Western Australian nickel, cobalt, and base metal exploration expenditure (2007–08 dollars)

- GME Resources Ltd has suspended work on the feasibility study for its NiWest nickel project in the Leonora region, to be reviewed once world nickel markets have stabilized (GME Resources Ltd, 2008).

Key points in the nickel sulfide sector include:

- A significant number of operations were put on care and maintenance. These include Palmary Enterprises Ltd's Beta Hunt, Mincor Resources NL's Wannaway and Miitel, and Australian Mines NL's Blair operation, all near Kambalda; Norilsk's Black Swan operation near Kalgoorlie, Waterloo operation near Leinster, and Lake Johnston operation (Maggie Hays and Emily Ann mines); BHPB's Rocky Reward operation near Leinster; Xstrata Plc's Sinclair operation in the Leinster region; Panoramic Resources Ltd's Copernicus operation north of Halls Creek; and Fox Resources Ltd's Radio Hill operation south of Karratha.
- Permits are being finalized for Western Areas NL's Spotted Quoll openpit mine at Forrestania. First production from Spotted Quoll should overlap production from the high-grade Lewinsky Lode at the top of the Flying Fox T5 orebody, starting in early 2010. As well, a feasibility study has commenced for an underground mine at Spotted Quoll (Western Areas NL, 2009a).
- Western Areas' Cosmic Boy nickel concentrate plant at Forrestania was officially opened and processed its first ore in early 2009. The company plans to double the capacity of the concentrator from the current 300 000 tpa ore to a nominal 550 000 tpa (Western Areas NL, 2009b).
- Work is also progressing well at Western Areas' Diggers Rocks South underground mine at Forrestania, where production is expected to commence in the latter half of 2009 (Western Areas NL, 2008).
- Western Areas announced that the company has executed an agreement with Jinchuan Group Ltd for a contract to sell up to 25 000 t of nickel in concentrate over a two-year period from the Forrestania nickel project (Western Areas NL, 2009a).
- Drilling at the Lounge Lizard deposit at Forrestania continued to produce impressive nickel intersections and (as at February 2009), the deposit was estimated to contain indicated and inferred resources of 1.149 Mt at 4.62% Ni. An agreement between Western Areas and Kagara Ltd will enable an early start to nickel production from the Lounge Lizard, by accessing it from the Flying Fox decline. The initial production rate is expected to be 50 000 tpa ore (Western Areas NL 2009c; Kagara Ltd, 2009).
- BHPB has approved the development of the US$152 million (A$177 million) Talc Redesign

project at its Mount Keith nickel mine. The project, which is expected to begin in 2011, will allow the concentrator to enhance the processing of talc-bearing ore types at the Mount Keith operations (Jacoby, 2009b).

- Poseidon Nickel Ltd announced a maiden resource for its newly discovered Cerberus nickel sulfide deposit, near Laverton. The inferred resources are estimated at 1.03 Mt at 2.45% Ni for 25 269 t of contained nickel (Poseidon Nickel Ltd, 2009).
- Extensional diamond drilling by Independence Group at the new Moran nickel deposit near Kambalda, located in the Long South lava channel, continued to intercept high-grade nickel sulfide leading to an estimated indicated resource of 401 000 t at 6.9% Ni and an inferred resource of 55 000 t at 8.3% Ni for the deposit. Independence Group is well advanced in planning the development and mining of this deposit, with first ore production expected to be in mid-2010 (Independence Group NL, 2009).
- Mincor Resources upgraded the potential of its operating Carnilya Hill mine, northeast of Kambalda, announcing high-grade nickel sulfide intersections some 320 m beyond the end of the current mineral resource (Mincor Resources NL, 2009).
- South Boulder Mines Ltd announced significant drilling results from The Bulge C2 nickel sulfide prospect at its Duketon project, near Laverton. Intersections include 17.82 m at 1.11% Ni (0.05% Cu, 0.08g/t Pt + Pd) from 287.18 m (South Boulder Mines Ltd, 2009).
- Drilling at the Grey Dam prospect (Kurnalpi project), 90 km east-northeast of Kalgoorlie, returned significant intersections including 43 m at 1.09% Ni and 0.055% Co and 20 m at 1.4% Ni and 0.12% Co (Condor Nickel Ltd, 2008).
- Panoramic Resources announced impressive drilling results from the resource definition drilling at the Deacon deposit, 38 km south-southeast of Kambalda. The intersections include 24.57 m at 2.87% Ni and 0.24% Cu; 14.48 m at 2.89% Ni and 0.20% Cu; 25.79 m at 3.27% Ni and 0.33% Cu, and 23.10 m at 2.73% Ni and 0.23% Cu (Panoramic Resources Ltd, 2008).

Base metals (copper–lead–zinc–silver)

Broad trends in the base metal sector in Western Australia during 2008–09 include:

- Copper–lead–zinc–silver exploration expenditure in the State fell by a dramatic 46% — from $98 million in 2007–08 to $53 million in 2008–09 (Fig. 8, 2008–09 dollars).
- There was a significant fall in base metal prices in 2008–09 compared to 2007–08 with copper, lead, and zinc falling by 26% (to $6434/t), 40% (to $1932/t), and 36% (to $1863/t), respectively.
- Although copper production in the State in 2008–09 increased by 11% (from 124 529 t in 2007–08 to 137 841 t in 2008–09), the value decreased by 18% to $889 million. The increased copper production was largely due to the steady output from the Nifty mine in the Paterson Orogen and increased production from the Telfer and Golden Grove operations.
- Lead production in the State continued to decrease (36%), from 25 706 t in 2007–08 to 16 415 t in 2008–09, due to the halt in production at the Magellan lead mine in April 2007 and the closure of the Pillara mine (Teck Cominco Ltd / Xstrata joint venture; 76 km southeast of Fitzroy Crossing) in mid 2008. The only other producing lead mine was Golden Grove. The value of lead production decreased by 61% to $32 million.
- Zinc production in the State decreased by 31% (from 197 129 t in 2007–08 to 136 011 t in 2008–09) and the value decreased by 57% to $249 million. The production decrease was due to the closure of the Pillara mine.

Key points for base metal projects in Western Australia include:

- In late 2008, Kagara announced an initial resource estimate for their Admiral Bay deposit in the Canning Basin. This resource amounts to 2.3 Mt of contained zinc and 2.8 Mt of contained lead, respectively, the largest zinc and the second largest lead resources in a single deposit in Western Australia. Scoping studies have shown that the deposit has the potential to produce 300 000 t of zinc, 250 000 t of lead and 4.5 Moz of silver annually (Kagara Ltd, 2008).

- With the opening of the Boddington gold–copper operation by Newmont in August 2009, the production of copper in Western Australia is likely to increase by another 30 000 tpa (Boddington Gold Mine, 2008; Newmont Mining Corporation, 2009).
- Empire Resources Ltd announced maiden indicated and inferred resources totalling 1 070 000 t grading 1.82% Cu and 0.78 g/t Au for its Just Desserts deposit of the Yuinmery project, 120 km southeast of Mount Magnet, which was discovered in late 2007 (Empire Resources Ltd, 2009).
- The Pillara mine at Lennard Shelf, 75 km south-southeast of Fitzroy Crossing, owned by the Teck Cominco / Xstrata joint venture, was put on care and maintenance in August 2008 (Teck Cominco Ltd, 2008).
- In January 2009, the Zn-rich Scuddles mine of the Golden Grove project was placed on care and maintenance by OZ Minerals Ltd in response to the continuing decline in the world zinc price. The expected production of zinc in 2009 is now in the range of 80 000–85 000 t of zinc concentrate, compared to 139 900 t produced in calendar 2008. Although zinc production decreases, the company has plans to increase copper-in-concentrate production by approximately 14 000 t to between 35 000–40 000 t in 2009, compared to 28 461 t produced in calendar 2008. The ownership of Golden Grove has now changed to China Minmetals Non-ferrous Metals Company Ltd (Jacoby, 2009c; OZ Minerals Ltd, 2008a,b).
- Ivernia Inc. has begun the shipment of lead carbonate concentrate from the Magellan mine, 30 km west of Wiluna, through the Port of Fremantle. Ivernia placed the Magellan lead mine on care and maintenance in April 2007, due to environmental problems associated with transportation of lead ore through the Port of Esperance (Miningnews.Net, 2007; Jacoby, 2009d).
- In January 2009, Aditya Birla Minerals Ltd announced that its Oxide operations at Nifty were suspended due to changed market conditions and reducing yield from the remaining copper inventory in the heaps. However, production from its underground mine is continuing (Aditya Birla Minerals Ltd, 2009).
- The underground mining operations at Radio Hill nickel–copper mine, 25 km south of Karratha, were completed and the mine was placed in temporary suspension in late September 2008 (Fox Resources Ltd, 2008).
- The Whim Creek mine, 90 km east of Roebourne, which commenced production of copper in June 2005, finished mining in March 2009 (Straits Resources Ltd, 2009).
- Jabiru Metals Ltd reached an agreement with OZ Minerals to market Jabiru's concentrate (Jabiru Metals Ltd, 2009).

A significant exploration success is the discovery of volcanogenic massive sulfides at the DeGrussa prospect of the Doolgunna project (60 km east of Peak Hill) located at the boundary zone between the Archean Marymia Inlier and the Proterozoic Bryah Basin. Drilling by Sandfire Resources NL, in May 2009, returned significant gold–copper intersections of 23 m at 2.4% Cu and 3.1g/t Ag from 66 m. Follow-up drilling has yielded more spectacular intersections, including 50.1 m at 8.4% Cu and 2.9 g/t Au from 242.5 m, signalling a major discovery of copper–gold mineralization in Western Australia (Sandfire Resources NL, 2009a,b).

Other highlights in the exploration sector are:

- Significant copper–zinc mineralization, in a volcanogenic massive sulfide system, was discovered by Silver Swan Group Ltd at the Austin prospect, 60 km south-southwest of Meekatharra. Drill intersections include 66 m at 1.5% Cu from 106 m in hole 08ATD007 and 49.1 m at 7.2% Zn from 118 m in hole 08ATD001. This hole also intersected 33.55 m at 1.7% Cu from 120.45 m including 7 m at 4.2% Cu from 120.45 m (Silver Swan Group Ltd, 2008).
- Drilling by Anglo Australian Resources NL at the Sandiego deposit, part of the Koongie Park project (24 km southwest of Halls Creek), continued to produce significant copper, zinc, and silver intersections including 68 m at 6.8% Cu, 9.6% Zn, 98.7 g/t Ag, and 0.34 g/t Au from 100 m (Anglo Australian Resources NL, 2008).
- In late 2008, Jabiru Metals Ltd announced the discovery of a new zone of volcanogenic massive sulfide mineralization at Bentley, approximately 4.5 km south of the Jaguar mine. Intersections include 20.8 m at 1.3% Cu, 11.6% Zn, 1.2% Pb, 0.8 g/t Au, and 196 g/t Ag from 459.4 m (Jabiru Metals Ltd, 2008a,b).

Overview

- Drilling has confirmed the presence of significant massive sulfide mineralization at the Evelyn prospect of the Libertee–Indee project, 30 km south of Whim Creek. Intersections include 20 m at 5.6% Cu, including 3 m at 29.8% Cu from 16 m and 18 m at 3% Cu, 9% Zn, 0.7% Pb, 55 g/t Ag, and 1.5 g/t Au from 72 m (Venturex Resources Ltd, 2009).
- Drilling at the Erayinia project, 150 km east-southeast of Kalgoorlie, continues to produce significant zinc intersections including 5 m grading 10.5% Zn and 4 m at 11.5% Zn (ABM Resources NL, 2008).
- Drilling at Mount Angelo North, 30 km southwest of Halls Creek, returned a significant intersection of 69 m at 3.84% Cu and 0.89% Zn (3D Resources Ltd, 2008).
- Ashburton Minerals Ltd announced significant copper, gold, bismuth, and platinum group element (PGE) assays from a number of prospects in the Pokali area within 3.5 km of the Mount Webb project, about 400 km north-northeast of Warburton. Assays from a number of samples from the Pokali South prospect include 13.30% Cu (sample A0151), 19.08 g/t Au (sample A0148), and 78.05 g/t Ag, and 2.63 g/t Pd in sample A0152 (Ashburton Minerals Ltd, 2008).

Diamond

Diamond production (strictly sales production rather than mine production) in Western Australia in 2008–09 fell to 9 million carats (Mct), which is a significant fall of 67% compared to the 2007–08 production of 28 Mct. The fall in production led to a 57% fall in the value of diamond sales to $262 million.

Expenditure on diamond exploration in Western Australia for 2008–09 was $5 million, which is a disappointing fall of 62% from the estimated $13.2 million spent in 2007–08 (Fig. 9, in 2008–09 dollars). Diamond exploration expenditure is now less than 1% (Fig. 4) of the total Western Australian mineral exploration expenditure. This is the seventh year in a row that diamond expenditure in Western Australia has declined (now at its lowest level in 30 years), reflecting the general lack of exploration success and hence investor interest.

Rio Tinto owns and operates the Argyle diamond mine in Western Australia. Diamond production for 2008–09 decreased to 14.274 Mct from 16.024 Mct in 2007–08. Production from Argyle's AK1 openpit mine is expected to continue through to 2011. When production from the southern end of the pit is completed in 2009, mining is expected to move to the Northern Bowl and continue until further ore becomes available from the underground mine. In January 2009, Rio Tinto announced that the Argyle underground mining project will be slowed to critical development activities only. Full production from the openpit is now expected to start in 2013, with the underground operations enabling the life of the mine to be extended till about 2018 (Rio Tinto Ltd, 2009).

In December 2007, Gem Diamonds Ltd, a global diamond company, acquired the Australian-listed Kimberley Diamonds that owns the Ellendale mine (135 km east-southeast of Derby). The production of diamond from Ellendale in 2008–09 decreased by 45% to 266 868 carats compared to the 2007–08 production of 487 416 carats.

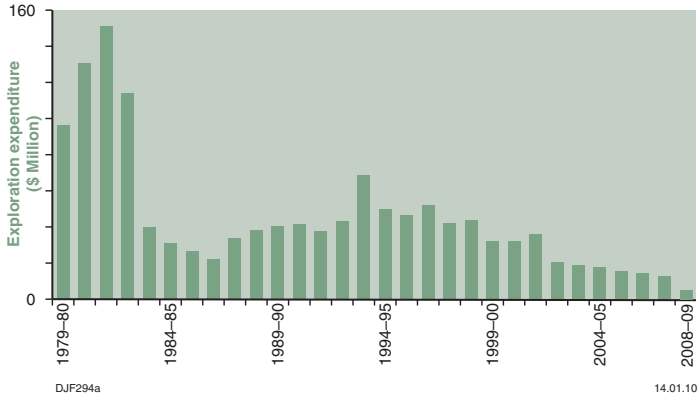


Figure 9. Western Australian diamond exploration expenditure (2008–09 dollars)

Mining operations ceased at the Ellendale 4 pipe and the mine was placed on care and maintenance. The company shifted its focus to the Ellendale 9 pipe to maximize cash flow (Gem Diamonds Ltd, 2009).

Blina Diamonds NL recommenced exploration in June 2008 at its Ellendale 9 North alluvial project at Ellendale, and by the end of 2008 a total of 37 970 t had been excavated and processed, returning 4813 stones for 2117.27 ct, with an average grade of 5.58 cpht (carats per hundred tonnes). An alluvial channel was also discovered over the eastern end of the Ellendale 9 lamproite pipe (Blina Diamonds NL, 2009).

Heavy minerals (Ti–Zr and garnet)

Production of heavy mineral sands (garnet, ilmenite, leucoxene, rutile, and zircon) in Western Australia in 2008–09 decreased by 29% to 990 496 t, with the value decreasing marginally (<1%) to $697 million.

In 2008–09, expenditure in Western Australia on heavy mineral sands exploration decreased by 14% to $13 million (Fig. 10). With the switch in exploration focus to the eastern Eucla Basin and the Murray Basin in Australia's eastern states in the mid-1990s, Western Australia's share of Australian exploration expenditure for heavy minerals fell from nearly 70% of the total in the mid-1990s to only 29% in 2002–03. It has recovered in recent years and was 43% in 2008–09, a slight increase from last year's figure of 40%.

In late 2008, Iluka Resources Ltd, the market leader in this industry in Western Australia, announced its intention to stop production indefinitely from its synthetic rutile kiln 4, located at Narngulu in the Mid West. The kiln is one of four synthetic rutile kilns in Western Australia and will be idled effective from mid-2009. During 2008, mining operations at its Cloverdale operation also ceased. In January 2009, Iluka also announced the closure of its Wagerup mine, south of Perth. Iluka also plans to complete its mining operations at Waroona in late 2009, following the exhaustion of higher value synthetic rutile feedstock ilmenite. During mid-2009, the Gingin mining and processing operations were closed as a result of exhaustion of ilmenite suitable for the higher value synthetic rutile feedstock. Eneabba remains the principal mining operation in the Mid West. Iluka hopes to secure final regulatory approvals to commence mining at Tutunup South in the South West in late 2009. In addition, the approval process for Tutunup is underway with the aim to commence mining in the second half of 2011. Iluka is continuing to explore in the Perth Basin to delineate resources for near-mine extensions in the South West (Tutunup) and Mid West (North Mine remnants) regions. Also, stratigraphic drill testing commenced west of Eneabba where Iluka completed an aeromagnetic survey that identified anomalies (Iluka Resources Ltd, 2008; 2009a,b,c).

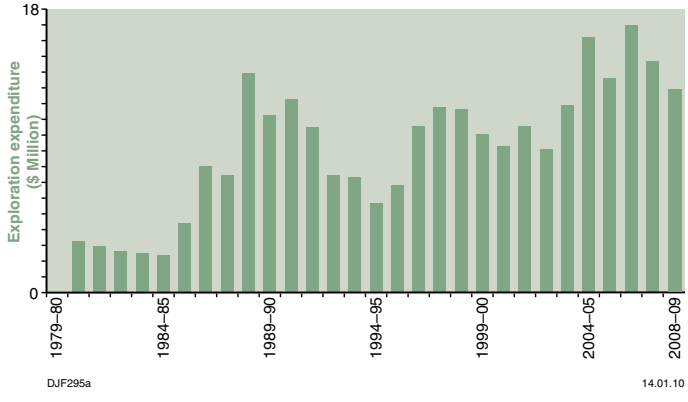


Figure 10. Western Australian heavy mineral sand (Ti–Zr) exploration expenditure (2008–09 dollars)

Other highlights in the heavy minerals sector for 2008–09 include:

- The Gwindinup mine, 15 km south of Bunbury, successfully ramped up to full production after plant commissioning in early 2008 (Bemax Resources Ltd, 2008).
- The environmental approvals process is almost complete for Matilda Zircon Ltd's Keysbrook mineral sands project, 50 km south of Perth (Matilda Zircon Ltd, 2009).
- Image Resources NL has estimated, indicated, and inferred resources totalling 261 Mt containing 6.4 Mt of heavy minerals at its deposits in the North Perth Basin, which include Helene, Hyperion, Bidaminna, and Titan. In addition the company has identified a 1.4 km-long high-grade zone at Cooljarloo averaging more than 20% heavy minerals, with mineralization up to 100 m wide and 6 m thick (Image Resources NL, 2009a,b).
- Diatreme Resources Ltd continued to explore the Western Australian portion of the Eucla Basin. The company announced a 50% increase in the resource estimate for the Cyclone deposit at Wanna Lakes, boosting the potential for a new world-class zircon province in the Western Australian portion of the Eucla Basin. The new measured, indicated, and inferred resources total 98.4 Mt at 2.88% heavy minerals, containing 2.8 Mt of heavy minerals. Exploration is continuing at Hurricane and Jubilee Lakes prospects in the Eucla region (Diatreme Resources Ltd, 2009a,b).
- Strong interest has been shown in Gunson Resources Ltd's Coburn zircon project (230 km north of Geraldton) from potential investors and end users in China, including two large companies introduced by The Balloch Group. Gunson has made a decision not to proceed with China Triumph International Engineering

(CTIEC) as the general engineering contractor for Coburn construction, instead choosing Sedgman Ltd as the preferred engineering contractor for project construction (Gunson Resources Ltd, 2009a,b,c).

Uranium

The pro-uranium policy of the State Government continues to have a positive effect on exploration expenditure for uranium in the State. Expenditure — that had been negligible in the previous decade — increased by a further 6% to $28.3 million in 2008–09 (Fig. 11).

Several companies are now planning to produce uranium in the near future:

- BHPB has flagged a 2011 construction start for its Yeelirrie uranium project (70 km south of Wiluna), which is estimated to contain an indicated resource of 35 Mt at 1.5 kg/t of U_3O_8 for 52 500 t of U_3O_8 (Jacoby, 2009e).
- Mega Uranium Ltd announced a new indicated resource of 27.6 Mt at 378 ppm U_3O_8 (23 Mlb (million pounds) of contained U_3O_8) and an inferred resource of 3.6 Mt at 274 ppm U_3O_8 (2.2 Mlb of contained U_3O_8) for their Lake Maitland deposit, 105 km southeast of Wiluna. The company plans to commence uranium production in late 2011 with an annual output of 1.65 Mlb U_3O_8 (Mega Uranium Ltd, 2009).
- Toro Energy Ltd plans to sell uranium by 2013 from its Lake Way mine near Wiluna and is in discussions over project funding. The project has estimated measured, indicated, and inferred resources totalling 20.21 Mt at 548 ppm U_3O_8 for 11 070 t of contained U_3O_8 (Toro Energy Ltd, 2009).
- Energy and Minerals Australia Ltd announced an initial inferred resource of 44.36 Mt at 550 ppm U_3O_8 for 24 520 t of contained U_3O_8 for the Mulga Rocks deposits, 225 km northeast of Kalgoorlie (Energy and Minerals Australia Ltd, 2009).
- Cameco Corporation is exploring the Kintyre uranium deposit, 72 km south-southwest of Telfer. The deposit was acquired (70%) from Rio Tinto in August 2008. The remaining 30% is owned by Mitsubishi Corporation (Cameco Corporation, 2009).

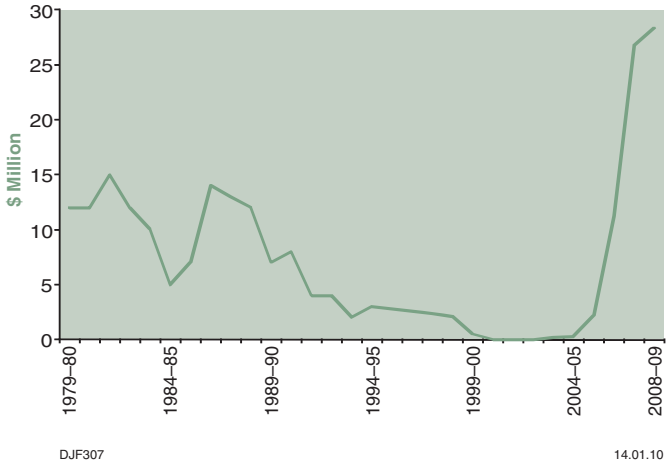


Figure 11. Uranium exploration expenditure in Western Australia since 1979–80 (2008–09 dollars)

Other commodities

Expenditure on exploration for other mineral commodities in Western Australia in 2008–09 has increased by 31% to $80 million. 'Other commodities' includes all industrial minerals, alumina, construction materials, PGE, molybdenum, tantalum, manganese, chromium, vanadium, rare earth elements (REE), and coal–lignite. Of these, exploration during 2008–09 was focused on molybdenum, vanadium, spodumene, and manganese.

In the molybdenum sector, the fall in the world price of molybdenum oxide (to approximately US$10/lb) in late 2008, forced Moly Mines Ltd to change focus at its proposed Spinifex Ridge porphyry Mo–Cu mine in the Pilbara to a smaller scale mine and plant, with a capacity in the order of 8–10 Mtpa, producing 11 to 13 Mlb molybdenum per annum (Moly Mines Ltd, 2009).

In the REE sector, Lynas Corporation Ltd announced in early 2009 the suspension of work at its Mount Weld rare earths project, 30 km south-southeast of Laverton, due to shortage of funding. Lynas had already completed the first mining campaign and had stockpiles of ore at Mount Weld. The deposit is estimated to contain measured, indicated, and inferred resources of 12.24 Mt at 9.7% REO for 1184 kt of REO (Lynas Corporation Ltd, 2009).

In the vanadium sector, developments were deeply affected by the global financial crisis:

- In early 2009, Windimurra Vanadium Ltd, owner of the Windimurra Vanadium project,

75 km east-southeast of Mount Magnet, has called in the administrators, as the company was unable to raise the funds needed to keep it afloat. The Windimurra deposit is estimated to contain measured, indicated, and inferred resources totalling 177 Mt at 0.46% V_2O_5 (Dudley, 2009; Windimurra Vanadium Ltd, 2009).

- Reed Resources Ltd has completed a definitive feasibility study aimed at establishing a vanadium mine at Barrambie, 65 km north of Sandstone. The study indicated the processing plant and associated infrastructure will target a throughput of 3.2 Mtpa of vanadium-bearing magnetite mineralization at a grade of 0.82% V_2O_5 and produce either about 11 200 t of vanadium pentoxide per annum or 7700 t of ferro-vanadium per annum, for a minimum 12-year period. The deposit is estimated to contain indicated and inferred resources totalling 65.2 Mt at 0.82% V_2O_5 (Reed Resources Ltd, 2009a,b).

- On a brighter note, Aurox Resources Ltd is still planning to develop Western Australia's largest vanadium resource at Balla Balla, 10 km northwest of Whim Creek, but predominantly as an iron ore mine instead. It is proposed to process the vanadiferous titanomagnetite to produce an iron ore concentrate with around 0.85% V_2O_5, along with about 7000 tpa of ferrovanadium ($Fe_{80}V$), and a titanium concentrate of about 43%–46% TiO_2 (Aurox Resources Ltd, 2009).

In the lithium sector, Galaxy Resources Ltd plans to develop its Mount Cattlin hard-rock spodumene project, at Ravensthorpe, as the world's second-largest hard-rock lithium operation. Galaxy Resources was successful in raising capital (about $65 million) during the worst phase of the economic downturn. Galaxy hopes the project will produce 137 000 tpa of spodumene concentrate containing 6% lithium. Plans are also underway to establish a lithium carbonate chemical facility in Jiangsu Province in China, producing 17 000 tpa of lithium carbonate. The company is targeting the rechargeable-battery sector in China and plans to produce a 100% battery-grade product, which attracts a premium price of 10–15% over technical-grade lithium (Galaxy Resources Ltd, 2009).

In the coal sector, Rey Resources Ltd announced initial measured, indicated, and inferred resources totalling 511 Mt of sub-bituminous coal for the Duchess–Paradise project, 135 km southeast of Derby, in the Canning Basin. Rey Resources is investigating the potential of the deposit to support an initial 2 Mtpa thermal coal export operation (Rey Resources Ltd, 2009a,b).

In the antimony sector, Northwest Resources Ltd announced indicated and inferred resources totalling 1.33 Mt at 8.3 g/t Au (353 000 oz) and 1.02% Sb (7300 t) at its Nullagine gold project (Northwest Resources Ltd, 2009).

In the tungsten sector, Hazelwood Resources Ltd announced measured, indicated, and inferred resources totalling 10.07 Mt at 0.18% WO_3 (cut-off grade of 0.1% WO_3) in its Big Hill deposit, 45 km northeast of Nullagine. More than 70% of the resource is in the measured and indicated categories (Hazelwood Resources Ltd, 2009).

In the manganese sector, Mesa Minerals Ltd announced its inaugural shipment of manganese lump ore (24 000 t) to China from its Ant Hill mine, 55 km east-southeast of Nullagine. The shipment was the first from trial production and the company anticipates larger scale mining of manganese at Ant Hill deposit as well as at the nearby Sunday Hill deposit (Mesa Minerals Ltd, 2009). In addition, several companies reported high-grade manganese intersections from exploration drilling:

- Aurora Minerals Ltd reported high-grade manganese up to 55.1% Mn from its Capricorn Southeast project in central Western Australia (Aurora Minerals Ltd, 2009).

- Shaw River Resources Ltd is focused on preparations for initial drilling at its Baramine project, 80 km northwest of the Woodie Woodie manganese mine, where preliminary exploration has identified wide zones of manganese mineralization, including 24 m at 38.7% Mn and 10 m at 50.3% Mn (Shaw River Resources Ltd, 2009).

- Exploration with encouraging results is continuing at the Mount Minnie project, 95 km southeast of Onslow, and at the 701 Mile project, 75 km south of Newman (Shaw River Resources Ltd, 2009).

- Exploration drilling by AusQuest Ltd at the Table Hill manganese project, 200 km east-southeast of Newman, is continuing, with encouraging intersections. Intersections include 3.9 m at 47.5% Mn from 286.8 m, and 1.3 m at 47.7% Mn from 326.1 m (AusQuest Ltd, 2008, 2009).

Overview

Drilling activity

The upward trend in exploration drilling activity throughout Australia between 2002–03 and 2007–08 reversed sharply in 2008–09 and, as expected, the sharpest falls were experienced in exploration drilling for new deposits. The fall in exploration drilling around existing deposits was not as severe. The details are as follows:

- Metres drilled during 2008–09 in Australia decreased by 19% (by 1.869 million metres) to a total of 7.887 million metres (Fig. 12).
- The estimated drilling for mineral exploration in Western Australia followed a similar trend with metres drilled during 2008–09 decreasing by 11% (0.57 million metres) to a total of 4.42 million metres (based on Western Australia's proportion of total Australian exploration expenditure for each year as the ABS does not release WA-specific data).
- Mineral exploration drilling for new deposits in Australia decreased sharply (30%), from 3.92 million metres in 2007–08 to 2.72 million metres in 2008–09.
- By contrast, mineral exploration drilling at existing deposits in Australia decreased more modestly (11%), from 5.83 million metres in 2007–08 to 5.17 million metres in 2008–09.

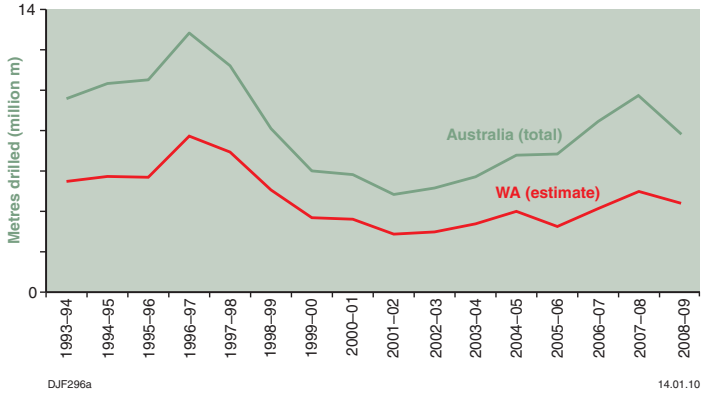


Figure 12. Mineral exploration drilling in Australia and Western Australia

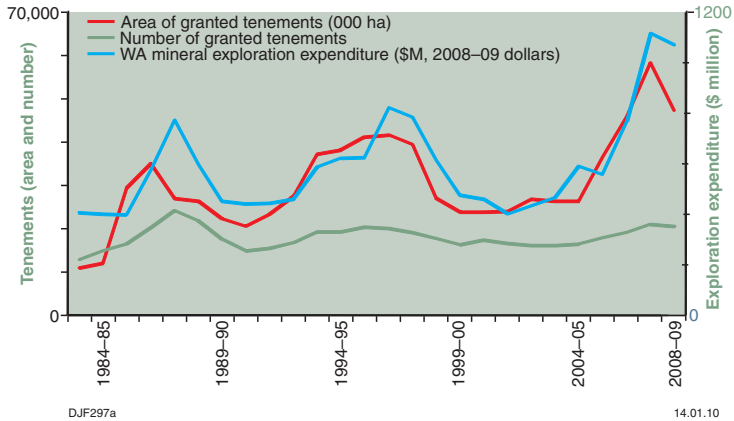
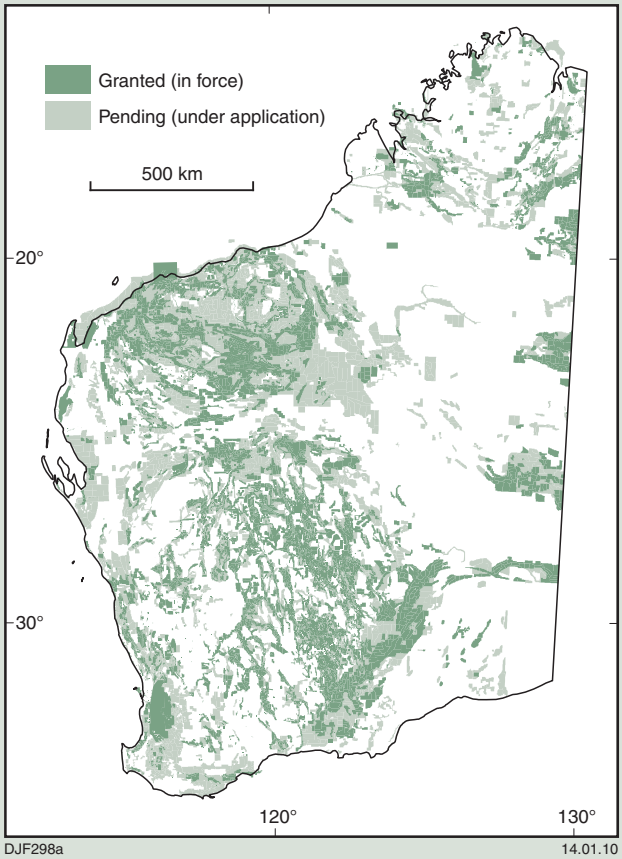


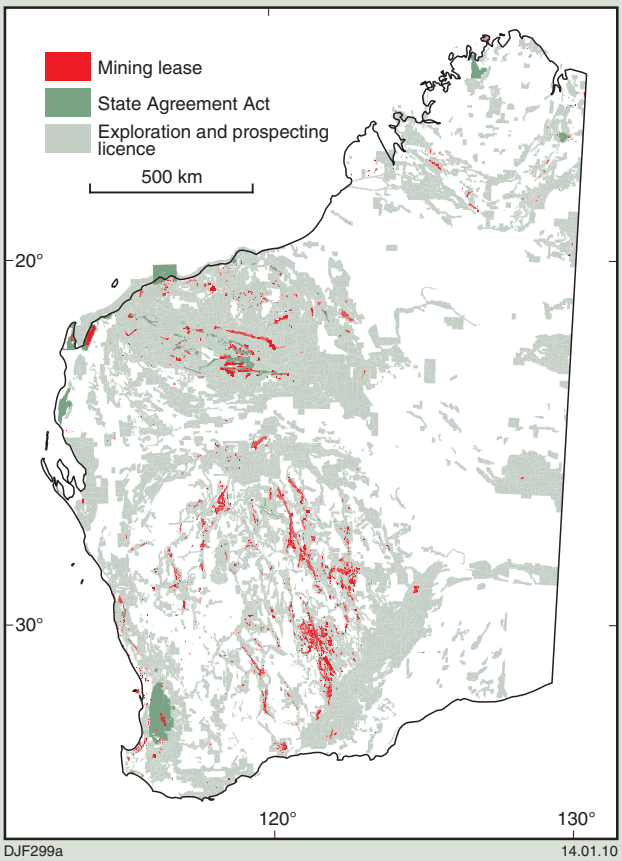
Figure 13. Trends in exploration expenditure and tenement activity (1904 and 1978 Mining Acts) since 1983–84 (source: Department of Mines and Petroleum)

Mining tenement activity

Tenement statistics also demonstrate the end of the boom phase and a rapid response to the changing global economic conditions, with an immediate and sharp drop in Exploration Licences and in new applications for tenements, but with the number of Mining Leases staying relatively constant (Fig. 13). The details are:

- The number of granted tenements (in force) in Western Australia during 2008–09 decreased by 2.5% (521), from a total of 20 910 in force at 30 June 2008 to 20 389 at 30 June 2009.
- The area under granted tenure decreased by 11.1 million hectares (Mha) or 19%, from a total of 58.2 Mha at 30 June 2008 to 47.1 Mha at 30 June 2009.
- The big reduction was in Exploration Licences (ELs), where the number of granted ELs in force at 30 June 2009 dropped by 11.8% (636) and the area under tenure of granted ELs dropped by 22% (11.3 Mha). Hence the number and area held under all *other* tenement types actually rose slightly over the year!
- Statistics for Mining Leases show an increase from 2007–08 to 2008–09, rising in number from 5 474 to 5 613 and in area under granted tenure from 2.03 to 2.06 Mha.
- As expected, the number of applications received by the Department during the year for new tenements also decreased, from 4 154 in 2007–08 to 3 882 in 2008–09.
- These statistics are despite a big improvement in the speed of processing tenement applications within the Department, where the backlog of tenement applications (for tenements of all types) dropped by 5 764, from a total of 14 703 at 30 June 2008 to 8 939 at 30 June 2009.





The distribution of tenements, both granted and under application at 30 June 2009, is shown in Figure 14. The distribution of mining leases, exploration and prospecting licences (granted and under applications) and State Agreement Act areas is shown in Figure 15.

Figure 14 (top left). Distribution of mining and exploration tenements, granted and pending, in Western Australia as at 30 June 2009

Figure 15 (bottom left). Distribution of Mining leases, Exploration and Prospecting licences (granted and pending), and State Agreement Act areas in Western Australia as at 30 June 2009

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Uranium

Uranium: a new start for Western Australia

by Ivor Roberts

Uranium is a naturally occurring radioactive element and radioactivity is a normal part of the natural environment. Uranium is a relatively common element and has the same abundance as tin with an average crustal abundance of 2–3 ppm. It is a lot more abundant than the precious metals gold, platinum, and silver.

In Australia, limited quantities of uranium ore were mined more than seventy years ago for medical purposes and as a pigment, but from the 1950s, Australia has produced significant quantities from operations in South Australia, Northern Territory, and Queensland. Uranium has never been mined in Western Australia. Currently there are only three operating uranium mines in Australia; : Ranger in the Northern Territory, and Olympic Dam and Beverley in South Australia. Honeymoon and Four Mile mines, also in South Australia, are approved but not yet in production. All of Australia's production is exported solely for the generation of electricity.

Abstract

Uranium mineralization is widespread in Western Australia, with 28 known uranium deposits hosting at least 200 000 t of U_3O_8. Renewed granting of mining leases for uranium in Western Australia provides new opportunities for resource companies and the resulting new mine development should lead to added economic growth and higher employment, particularly in regional areas. The requirement to reduce greenhouse gas emissions from power generation will lead to higher demand for uranium as a feedstock for nuclear power generation overseas, thus providing a market opportunity for aspiring Western Australian uranium miners. Western Australia is highly prospective but under-explored and opportunities still exist for the discovery of more uranium deposits in a variety of geological settings.

KEYWORDS: Uranium deposits, uranium resources, uranium exploration, uranium policy, radioactivity, calcrete-hosted uranium, roll-front uranium, unconformity-associated uranium, carbonatite-hosted uranium

Policy reform

On the 17 November 2008, the Western Australian Government announced that new mining leases granted in the State would include the right to produce uranium. This decision overturned a policy in place since 2002 that had prohibited holders of new mining leases from developing uranium deposits. Between June 2002 and September 2008 the right to mine uranium was excluded from the 1475 mining leases issued during that period. However, during this same period exploration for uranium was not prohibited and exploration did take place, but not at a level that reflected Western Australia's high prospectivity.

Western Australia's change in policy brings it into line with South Australia, the Northern Territory, and the Australian Government, which all encourage responsible uranium exploration and mining. Community concerns about the uranium industry started in the late 1970s with the Ranger Inquiry in the Northern Territory in 1976–77. In 1984, the Australian Government adopted the 'three mine policy' that limited the industry to the three existing mines: Ranger and Nabarlek in the Northern Territory and Olympic Dam in South Australia. With the closure of the Nabarlek mine, the policy changed to become the 'no new mines policy'. The consequence of these policies, together with low uranium prices, was to discourage further exploration and to prevent the development of Western Australian uranium deposits, such as Yeelirrie by Western Mining Corporation (now BHP Billiton) and Kintyre by CRA Exploration (now Rio Tinto). It was not until April 2007 that the Australian Government changed its restrictive uranium position and encouraged the State governments of Queensland and Western Australia to remove their ban on uranium mining.

Uranium exploration and production

For 2008–09, uranium exploration expenditure in Australia dropped by 20% from the previous year (Australian Bureau of Statistics, 2009). However, in Western Australia there was a rise of 7%, attributed to potential uranium miners increasing their exploration activity to validate resources at

Table 1. Uranium exploration in Australia (A$ millions)

Year	Queensland	Western Australia	Northern Territory	South Australia	AUSTRALIA
2003–04	0.2	0.2	4.8	5.3	**10.5**
2004–05	0.4	0.3	6.9	13.1 (est)	**20.7**
2005–06	4.6	2.2	19.1	30.3	**56.1**
2006–07	9.0 (est)	11.2 (est)	30.1	63.8	**114.1**
2007–08	38.1	26.8 (est)	48.7	118.0	**231.5**
2008–09	29.5 (est)	28.6 (est)	54.5	72.6	**185.3**

NOTES: Exploration for uranium is prohibited in NSW and Victoria and exploration in Tasmania is negligible.
Reference: Australian Bureau of Statistics (2009)

Table 2. Uranium resources in Australia at December 2008

	Total resources (t U)	Percentage of Australia's total resources (%)
South Australia	1 240 593	77
Northern Territory	246 045	15
Western Australia	88 132	6
Queensland	37 947	2
New South Wales	0	-
Victoria	0	-
Tasmania	0	-
Australia: total (rounded)	**1 613 000**	**100**

Reference: Geoscience Australia (2009)

a number of deposits following the policy shift to allow uranium production (Australian Uranium Association, 2009).

In 2008–09 South Australia still dominated Australia's uranium exploration, followed by Northern Territory. Surprisingly Queensland, despite a decline in exploration activity in 2008–09, retained third place, with Western Australia fourth. Exploration for uranium is banned in NSW and Victoria (Table 1).

In terms of Australia's identified uranium resources, Western Australia has 6%, placing it after South Australia (77%) and Northern Territory (15%) but ahead of Queensland (2%). South Australia's large resource is predominantly from Olympic Dam — the largest uranium deposit in the world (Table 2). According to Geoscience Australia (2009), Australia has 38% of the world's low-cost uranium (reasonably assured resources recoverable at less than US$80/kg U), but produced only 19% of the world's uranium during 2008. Australia, including Western Australia, clearly has the potential to mine greater quantities of uranium.

Annual world uranium consumption is forecast to be about 78 000 t U_3O_8 in 2009, with annual uranium production of about 56 000 t U_3O_8 (Lampard, 2009). The shortfall is being met by production from decommissioned nuclear warheads, stockpiles, and reprocessing of spent fuel. The uranium spot price rose to over US$130/lb during the latter half of 2007; for many years it was between US$10 and US$15/lb. Currently it is about US$45 (December 2009), with long-term projections for a price of between US$70 and US$80/lb. This projected price rise takes into account both existing and planned construction of nuclear power reactors. There are 436 operational nuclear power plants, 43 under construction, 106 at an advanced stage of planning, and 266 are proposed (World Nuclear Association information as at January 2009, *in* Rio Tinto, 2009). This could lead to a shortage of uranium in the next decade.

Uranium was first discovered in Western Australia in 1910 associated with pegmatites in the Pilbara region, when the mineral's radium content was actively sought for its therapeutic properties (Carter, 1981). In the late 1940s to mid-1950s exploration was prompted by the demand for uranium for military purposes, but no significant Western Australian deposit was discovered. From the late 1960s to the 1970s uranium exploration increased due to the anticipated demand from nuclear power generation. With the introduction of airborne radiometric surveys, new deposits — particularly uraniferous calcrete drainage systems — were discovered, for instance the

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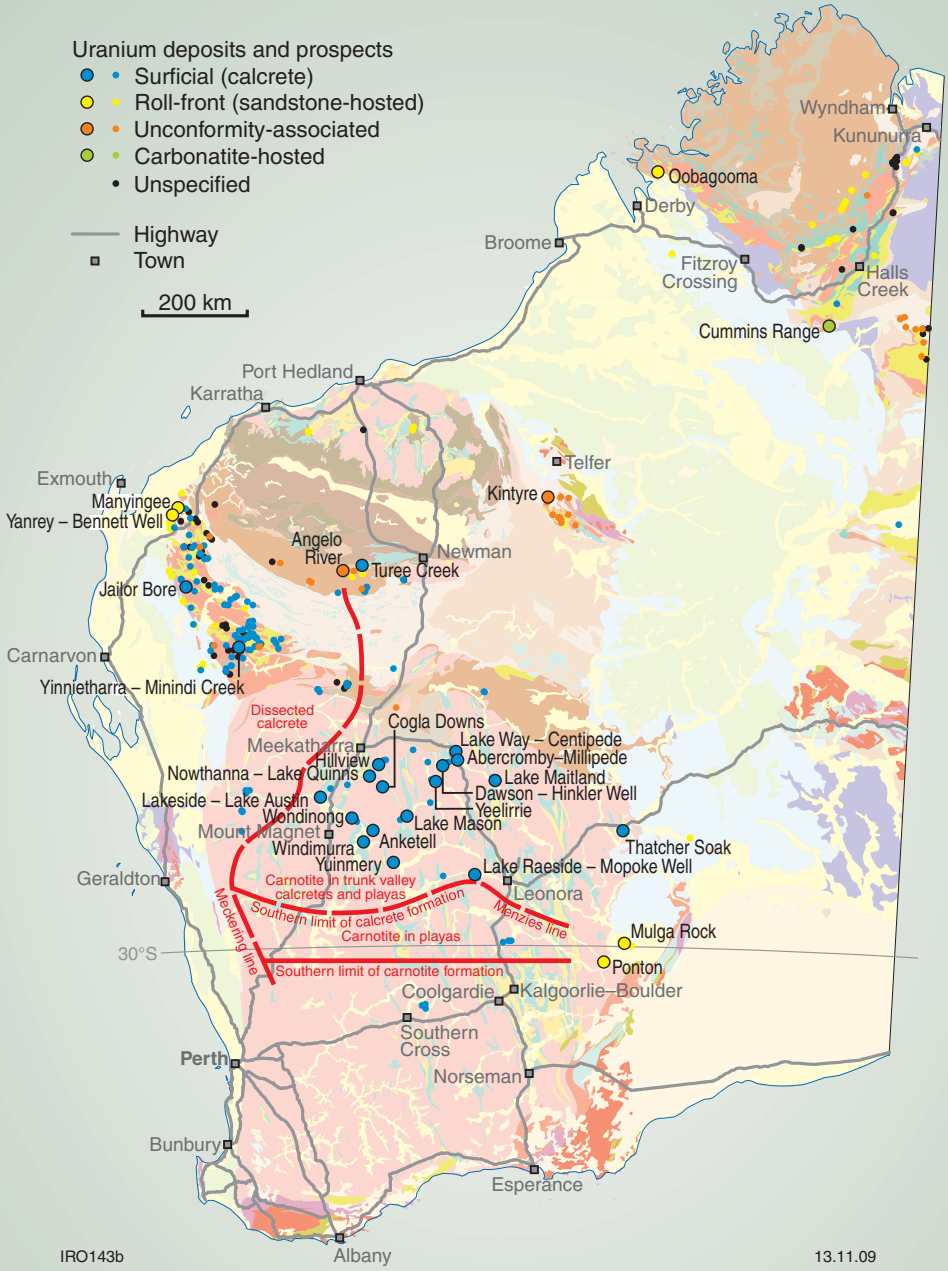

Figure 1. Uranium deposits and prospects in Western Australia

Yeelirrie deposit in the northern Yilgarn Craton. Between 1973 and 1979 and from 1984 to 2008 uranium exploration and mining developments were constrained by either Federal and State Government policies or low uranium prices.

Western Australian deposits

Uranium deposits are widespread in Western Australia: from the Proterozoic Halls Creek Orogen and Paleozoic Canning Basin in the Kimberley, to the Paleozoic Southern Carnarvon Basin and the Cainozoic paleodrainage systems overlying the northern Yilgarn Craton (Fig. 1) Western Australia is well endowed, and currently known resources are about 200 000 t U_3O_8 in 28 deposits.

The main uranium mineralization styles are: unconformity-associated (such as Kintyre), roll-front or sandstone-hosted (such as Mulga Rock, Manyingee, Oobagooma, and Ponton), and surficial or calcrete-hosted (such as Yeelirrie, Lake Maitland, Lake Way – Centipede, and Thatcher Soak). Styles of lesser importance are carbonatite-hosted (such as the Cummins Range deposit), pegmatite-hosted, and vein- and conglomerate-hosted prospects (Table 3). Australia is under-represented in several types of uranium deposits. Skirrow et al. (2009) noted that Australia has no giant uranium deposit hosted in sedimentary basins, nor, given the abundance of unusually uranium-rich igneous rocks in Australia (including Western Australia), does it have magmatic deposits directly related to magmatic processes. Skirrow et al. (2009) also highlighted the importance of understanding uranium mineral systems as a tool for targeting area selection for exploration: i.e. to understand key processes controlling where and how uranium is deposited. Using such a uranium systems-based approach, combined with empirical data, previously unrecognized uranium provinces or districts may be identified.

The A$80 million 'Exploration Incentive Scheme' (EIS) recently announced by the Western Australian Government will encourage exploration in Western Australia, particularly in under-explored ('greenfields') regions. Funded over five years beginning in 2008–09, EIS will stimulate increased private sector resource exploration and, together with the Australian Government's Onshore Energy Security Program of Geoscience Australia, will provide pre-competitive geoscientific data and new area selection concepts for the targeting of uranium mineralization.

The new Geoscience Australia radioelement map of Australia, produced from public-domain airborne radiometric surveys and adjusted to the International Atomic Energy Agency's Global Radioelement Data, provides a valuable exploration tool to identify potential uranium deposits (Wilford et al., 2009). For example, the U^2/Th ratio is clearly effective in separating the primary uranium in uranium-rich granites from secondary uranium in calcrete-hosted deposits (Wilford et al., 2009). This U^2/Th ratio is also useful for deposits of other styles, such as unconformity-associated and roll-front or sandstone-hosted, that are at or near the surface.

Unconformity-associated deposits

The Kintyre unconformity-associated uranium deposit was discovered by CRA Exploration (now Rio Tinto) in 1985, when the first drillhole into the prospect intersected 77 m of mineralization averaging 0.25% U_3O_8 (McKay and Miezitis, 2001). Kintyre is similar to the Proterozoic Ranger and Jabiluka deposits in the Northern Territory.

The Kintyre deposit is hosted by metasedimentary rocks of the Yandagooge Formation in the Rudall Complex (of the Paterson Orogen) adjacent to the unconformity with the Neoproterozoic Coolbro Sandstone (Jackson and Andrew, 1990; Hickman and Clark, 1994; Ferguson et al., 2005). The favourable lithologies for mineralization are interbedded chlorite schist and chert, with uranium present as pitchblende within a system of narrow, closely spaced veins (Jackson and Andrew, 1990). Associated with the pitchblende veins are minor amounts of bismuth, bismuthinite, chalcopyrite, bornite, galena, and gold (Jackson and Andrew, 1990). The main gangue minerals are chlorite, dolomite, ankerite, and calcite. Within the metasedimentary rocks enclosing the ore zones chlorite alteration is widespread, and cherts are red to brown in colour due to the presence of hematite (Jackson and Andrew, 1990). In section, the Kintyre deposit is a shallow-dipping lens with a maximum depth of 150 m below the surface (Jackson and Andrew, 1990).

A number of areas of the State have potential for unconformity-associated uranium deposits. They include: other areas of the Rudall Complex, although access is restricted in the Rudall River National Park; the Turee Creek area, where unconformity-associated mineralization is associated with the unconformity between the Paleoproterozoic metasedimentary rocks of the

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Wyloo Group of the Ashburton Basin and the Mesoproterozoic Bresnahan Group (McKay and Miezitis, 2001); the unconformable contact between the Edmund and Collier Basins with the underlying basement, mainly the Gascoyne Province (Cooper et al.,1998); and the unconformity between the Kimberley Group sedimentary rocks and the deformed basement of the Lamboo Complex in the Halls Creek area (Hassan, 2000; McKay and Miezitis, 2001).

Roll-front deposits

Roll-front uranium is a type of sandstone-hosted uranium deposit that is crescent-shaped in cross section, with mineralization cutting across the sedimentary layering. Typically, sandstone-hosted deposits are contained in fluvial or marginal-marine sandstones that are medium- to coarse-grained, poorly sorted, and contain pyrite and organic matter, either as disseminations or lignite seams (McKay and Miezitis, 2001).

Roll-front deposits are formed at the interface between rocks or groundwater under reduced conditions and oxidized, uranium-enriched groundwater, thus marking the oxidation interface or redox boundary (McKay and Miezitis, 2001; Hou et al., 2007). Major deposits of this type include Manyingee, Oobagooma and, possibly, Mulga Rock.

Roll-front uranium deposits are present within Permian and Cretaceous sandstone formations

Table 3. Western Australia uranium deposits

Project name	Project owner	Ore (Mt @ kg/t)	Contained U_3O_8 (kt)
Yeelirrie	BHP Billiton	35.0 @ 1.50	52.5
Kintyre	Cameco, Mitsubishi	23.3 @ 1.50	35.0
Mulga Rock	Energy and Minerals Australia	44.6 @ 0.56	24.8
Lake Maitland	Mega Uranium, Itochu Corp Japan, Australia Uranium Resources Development Co.	31.2 @ 0.36	11.4
Lake Way – Centipede	Toro Energy	20.2 @ 0.55	11.1
Manyingee	Paladin Energy	13.4 @ 0.8	10.7
Oobagooma	Paladin Energy	8.3 @ 1.2	10
Ponton	Manhattan Corporation, Deep Yellow	16.0 @ 0.31	5
Thatcher Soak (Uranex)	Uranex	17.0 @ 0.29	4.9
Hillview	Encounter Resources, Avoca Resources	27.6 @ 0.17	4.8
Dawson – Hinkler Well	U3O8	20.6 @ 0.23	4.7
Nowthanna – Lake Quinns	Impact Minerals	10.4 @ 0.45	4.7
Windimurra	Maximus Resources, Apex Minerals, Windimurra Resources	19.1 @ 0.18	3.5
Thatcher Soak (Eleckra)	Electra Mines	16.1 @ 0.17	2.8
Anketell	Energy Metals	16.3 @ 0.17	2.7
Abercromby – Millipede	Barrack, Norilsk/MPI	3.4 @ 0.66	2.3
Yanrey – Bennett Well	Cauldron Energy	7.3 @ 0.3	2.2
Lake Raeside – Mopoke Well	Energy Metals	7.0 @ 0.26	1.8
Lake Mason (Energy Metals)	Energy Metals	7.9 @ 0.17	1.3
Wondinong (Aura)	Aura Energy	6.5 @ 0.19	1.2
Lakeside – Lake Austin	Energy Metals	2.6 @ 0.32	0.8
Angelo River	Danny Smith	0.6 @ 1.24	0.8
Cummins Range	Navigator	3.6 @ 0.22	0.8
Jailor Bore	Matsa Resources, William Robert Richmond	1.4 @ 0.50	0.7
Yuinmery	Aldershot Resources	1.6 @ 0.37	0.6
Yinnietharra – Minindi Creek	U3O8	3.5 @ 0.12	0.4
Turee Creek	Aldershot Resources, Cameco	1.1 @ 0.35	0.4
Cogla Downs	Citic Nickel Australia	0.1 @ 0.78	0.1
Lake Raeside (Red Oak)	Red Oaks	0.1 @ 0.41	0.05
	TOTAL	**365.8**	**202.05**

Surficial (calcrete-hosted) Roll-front (sandstone hosted) Unconformity-associated Carbonatite-hosted

of the Southern Carnarvon Basin, particularly adjacent to the Gascoyne Province. Discovered in 1974, the largest deposit is at Manyingee. It is in the Cretaceous fluviodeltaic Birdrong Sandstone, filling a paleochannel eroded in the basement granite with the uranium accumulated at a redox boundary in the sandstone (Brunt, 1990).

Located in the Canning Basin adjacent to the King Leopold Orogen, the Oobagooma deposit was discovered in 1983 and is hosted by the Lower Carboniferous Yampi Sandstone on the Lennard Shelf. Uranium mineralization at Oobagooma is in the form of uraninite and pitchblende and, as reported by Keats (1990), contains two mineralized levels, with the upper level containing higher grade zones in classic roll-fronts.

The Mulga Rock deposit, discovered in 1978, is hosted by organic-rich clay within a buried Eocene paleochannel along the southwestern margin of the Gunbarrel Basin. The paleochannel sediments overlie the Yilgarn Craton and the Albany–Fraser Orogen (Fulwood and Barwick, 1990). The uranium mineralization is the result of the absorption of uranium-bearing complexes by fine-grained carbonaceous sediments, and is spatially controlled by redox boundaries (Keats, 1990). Further research needs to be carried out on Mulga Rock as it is an unusual deposit and is the host for a variety of elements besides uranium.

Significant potential appears to exist for the discovery of new uranium deposits in the Canning Basin along the margin of the King Leopold Orogen, in the Carnarvon Basin adjoining the Gascoyne Province, and in the Gunbarrel Basin adjacent to the Yilgarn Craton.

Surficial uranium deposits

Surficial uranium deposits are surface or near-surface uranium concentrations in sediments or soils of Eocene to Recent age (Hou et al., 2007; McKay and Miezitis, 2007).

The most important type of surficial deposit is calcrete-hosted, the dominant type of mineralization with identified uranium resources in Western Australia (Fig. 2). Carnotite is the main uranium mineral in the calcrete. The term 'calcrete' is used for limestone (calcium and magnesium carbonate) deposits associated with valley-fill sediments in ancient valleys and existing trunk-drainage systems. The calcrete is typically interbedded with sand and clay. Calcrete occurrences are concentrated in the northeast of the Yilgarn Craton, north of the so-called 'Menzies line', which is an arbitrary line of separation between groundwaters of different compositions (Fig. 1). North of the line the groundwater is typically neutral to alkaline and less saline than groundwater south of the line. The calcrete has been eroded west of the 'Meckering line' (see Fig. 1) due to rejuvenated south- and west-flowing river systems (Butt et al., 1977).

Uranium enrichment takes place at the final stage of calcrete formation by the precipitation of carnotite. Occurrences are generally restricted to areas of granitic bedrock containing high background levels of uranium ('hot' granites). Western Australia has large areas of Archean and Proterozoic granitic and associated volcanic rocks known to have high background levels of uranium, i.e. >10 ppm U — 4 times average crustal abundance (Schofield, 2009). North of about latitude 30°S, but south of the 'Menzies line', carnotite mineralization is present within playa lakes without the development of calcrete.

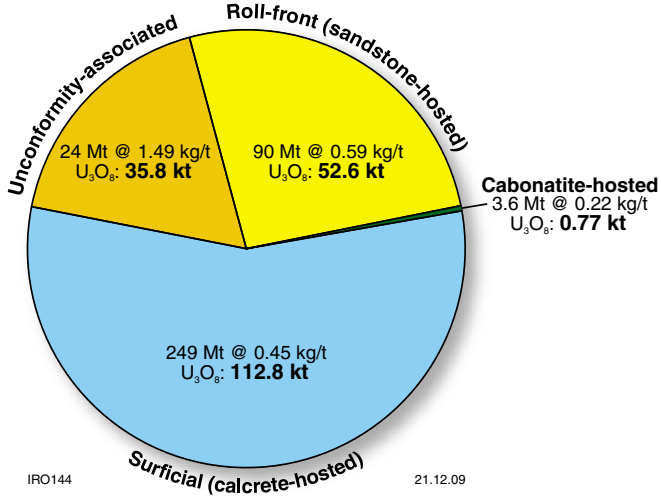

Figure 2. Resources and styles of uranium mineralization in Western Australia

Three types of calcrete-hosted mineralization have been documented by Butt et al. (1977):

a) trunk-valley calcrete, with mineralization in channels, platforms, and channel deltas;

b) playa lakes with near-surface gypsiferous and calcareous clays or carbonaceous sediments below the surface enriched in uranium; and

c) dissected calcrete containing uranium mineralization in terraces above the present watertable.

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Most of the calcrete-hosted uranium deposits were discovered in the late 1960s and early 1970s. Yeelirrie is the largest, containing an estimated 35 Mt indicated resource of uranium, with an average grade of 1.5 kg/t U_3O_8, to give a total of 52 000 t of contained U_3O_8: it is the State's largest uranium deposit. Other major calcrete-hosted uranium deposits include Lake Maitland, Lake Way – Centipede, Thatcher Soak, Hill View, Dawson – Hinkler Well, and Nowthanna – Lake Quinns.

Despite the number of calcrete-hosted deposits in the northern Yilgarn Craton, there is potential for further discoveries in this region, as well as in the Gascoyne Province and Ashburton Basin.

Carbonatite-hosted deposits

Carbonatite-hosted is another style of uranium mineralization with known resources. The Proterozoic Cummins Range carbonatite hosts rare earth oxide and phosphate mineralization with associated uranium (Andrews, 1990). The rare earth oxide mineralization was discovered in the late 1970s (Andrews, 1990). However, recent exploration has highlighted the significant uranium potential of this unusual intrusion (Navigator Resources Ltd, 2009).

Potential for other styles

Western Australia hosts a diverse and significant number of uranium deposits, but could there be other deposit types yet to be found?

Quartz-pebble conglomerate deposits make up a major proportion of the world's uranium resources. However, they are among the lowest grade deposits mined, with grades as low as 0.01% U_3O_8. Major examples are the Elliot Lake deposits in Ontario, Canada and the Witwatersrand gold–uranium deposits in South Africa where uranium is recovered as a byproduct of gold mining. The uraninite-bearing conglomerates are highly pyritic and usually crop out around the edges of Archean and Paleoproterozoic basin sequences.

Quartz-pebble conglomerates containing uranium (and gold) are known in Western Australia. In the Hamersley Basin several zones of low-grade uranium and gold mineralization are in Archean quartz-pebble conglomerate beds of the lower Fortescue Group. The Mesoarchean Lalla Rookh Sandstone of the Pilbara Craton also has exploration potential (McKay and Miezitis, 2007). In the Halls Creek Orogen low-grade uranium and gold mineralization is in quartz-pebble conglomerate of the Saunders Creek Formation. Another example is low-grade uranium mineralization intersected during exploration in quartz-pebble conglomerates in the Yerrida Basin. Thus, the Hamersley Basin, Halls Creek Orogen, and the Yerrida Basin all appear to be prospective areas to find quartz-pebble conglomerate uranium deposits.

Pegmatites in the Gascoyne Province host a multitude of uranium occurrences. Resources have not been estimated. For example, the Mortimer Hills uraninite-bearing pegmatite has been compared to the Rossing uranium deposit in Namibia, south west Africa, and the suggestion made that the region could be classed as a uranium province (Carter, 1984).

Resource development

Currently, four uranium projects are significantly advanced, with the proponents aiming to commence mining between 2012 and 2014.

Mega Uranium Ltd was granted a mining lease over the Lake Maitland deposit in October 2009 and is progressing definitive feasibility studies. Application for environmental assessment has been submitted to Commonwealth and State Governments with production planned to commence in 2012 (Mega Uranium Ltd, 2009).

Toro Energy Ltd (2009) has indicated that it has completed an optimization study for the Lake Way – Centipede project and that a risk review will be completed prior to a bankable feasibility study. Applications for environmental assessment have been submitted to Commonwealth and State Governments, and first production is planned for 2012–13.

An openpit scoping study for mining the Ambassador orebody of the Mulga Rock project is in progress and environmental and heritage surveys are underway. Uranium production from Ambassador is targeted for 2013 (Energy and Minerals Australia Ltd, 2009).

Production from the Yeelirrie deposit is expected in 2014 and will be under the *Uranium (Yeelirrie) Agreement Act 1978*. This State Agreement is between the State and BHP Billiton (originally Western Mining Corporation) and permits BHPB to mine and treat uranium ore, and transport and ship uranium oxide concentrate (yellowcake)

through a port or ports in Western Australia. However, the Government has stated that it will not permit the transport of uranium oxide concentrate through any residential area. As all ports with container facilities in Western Australia have adjacent residential developments, it is anticipated that the export of uranium oxide concentrate will be through either South Australia or the Northern Territory. BHPB is currently at the pre-feasibility stage and has recommenced drilling to confirm the resource. Community consultations are in progress, and investigations for the Environmental Impact Statement and options to export uranium oxide concentrate via established and approved routes from South Australia or the Northern Territory have commenced (BHP Billiton, 2009).

It is expected that other major deposits, such as Kintyre, Manyingee, and Oobagooma, will not be developed until after 2015.

Legislation

Uranium mining and export requires approval under both Commonwealth and State legislation. Besides the usual State mining requirements under the *Mining Act 1978*, *Mines Safety and Inspection Act 1994,* and the *Radiation Safety Act 1975*, approvals are required under Australia's *Environmental Protection and Biodiversity Conservation Act 1999*, the *Nuclear Non-Proliferation (Safeguards) Act 1987*, and the *Radiation Protection and Nuclear Safety Act 1998*. Under the Customs (Prohibited Exports) Regulations of the *Customs Act 1901*, an export licence is necessary for the export of radioactive material and the transport of uranium must be conducted in accordance with the Commonwealth Radiation Protection and Control (Transport of Radioactive Substances) Regulations.

The requirements for approval need to address actual risks, while taking into account community concerns, and cover exploration and mining, the transportation of uranium concentrate or yellowcake, the management of waste material from the mining operation, and export controls. Australia's uranium resources are strategic commodities that are treated differently from other minerals due to the risk of nuclear proliferation. The Customs (Prohibited Exports) Regulations 1958 require export approval by the Commonwealth Minister for Industry, Tourism and Resources. Exporting uranium can only take place if the uranium is solely used for peaceful, non-explosive purposes, it is exported only to countries that are party to the Non-Proliferation Treaty and have a bilateral safeguards agreement with Australia, and the countries are responsible for the management of waste produced from the use of Australian uranium.

Using best practice developed in other Australian jurisdictions, the Western Australian Department of Mines and Petroleum will ensure that all State and Federal approvals are integrated.

The approach being followed by the State Government is based on principles outlined by the Uranium Industry Framework Steering Group (Uranium Industry Framework, 2006).

Conclusion

Western Australia is entering a new era where a projected increase in demand for the State's widespread uranium resources coincides with encouragement of uranium mining by the State and Commonwealth governments. Currently, there are a number of projects at an advanced stage of planning and moving through the stringent approvals process to have uranium mining approved.

Despite the significant potential for new discoveries, exploration activity in the past has not reflected Western Australia's level of uranium prospectivity.

The release of new pre-competitive information over the coming years by both the Geological Survey of Western Australia and Geoscience Australia will assist in identifying areas of potential, particularly unconformity-associated and roll-front or sandstone-hosted deposit styles that are important producers elsewhere in Australia and overseas. With uranium mining now encouraged by the State Government, there is a new start for explorers and miners in Western Australia.

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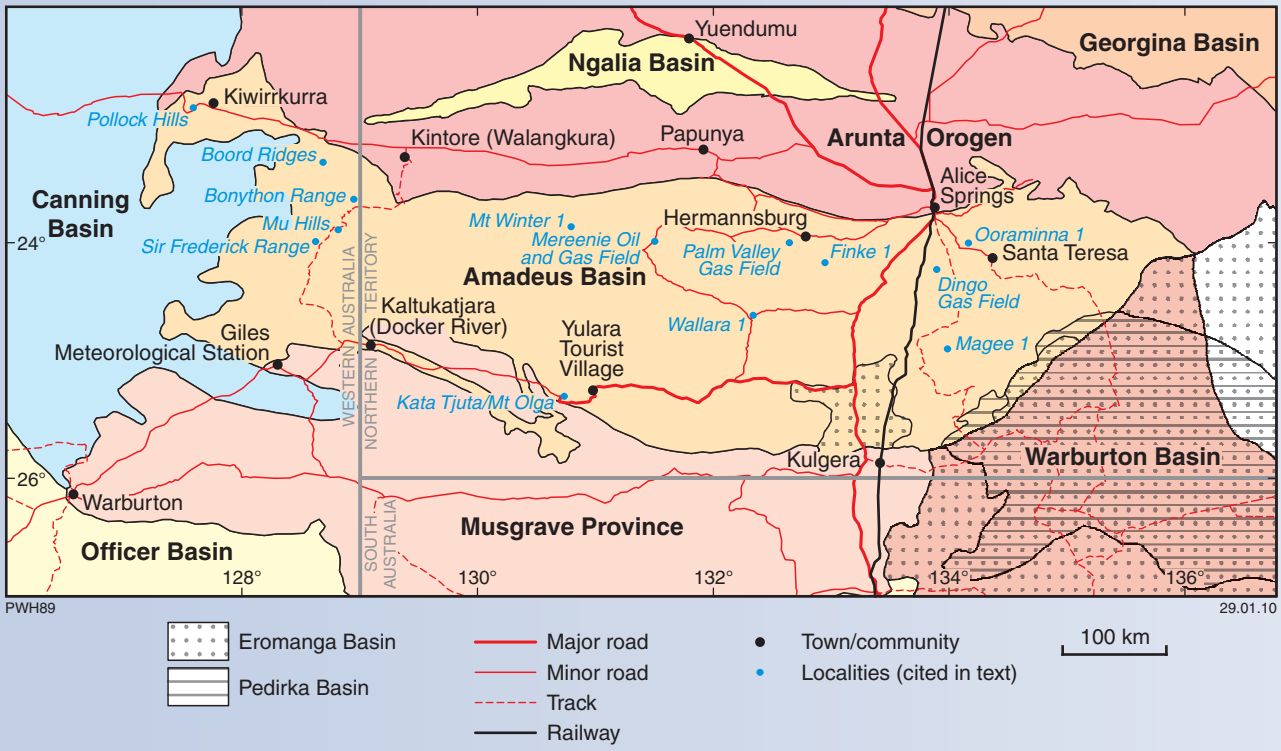

Figure 1. Locality map showing Amadeus Basin and adjacent tectonic units, and localities referred to in the text.

The Amadeus Basin in Western Australia: a forgotten corner of the Centralian Superbasin

by PW Haines, HJ Allen, and K Grey

Abstract

Recent fieldwork by the Geological Survey of Western Australia indicates the need for substantial revision of the stratigraphy of the Amadeus Basin in Western Australia. This is because a more complete Neoproterozoic succession, with closer similarities to the established stratigraphy within the Northern Territory than previously realised, appears to be present. The thick Boord Formation, previously interpreted as a correlative of only the glacigene Areyonga Formation of the Northern Territory Amadeus Basin, actually contains two discrete glacial successions, and greater thicknesses of non-glacial strata. This succession contains several disconformities and closely resembles the entire interval between the Bitter Springs Formation and the Arumbera Sandstone of the northeastern Amadeus Basin. The lithostratigraphic similarities are strongly supported by stromatolite biostratigraphy, which can also be used to subdivide the underlying Bitter Springs Formation into correlatives of existing members in the Northern Territory. There is no compelling evidence of the previously postulated interdigitation of the entire Boord and Carnegie Formations. Instead, the thick siliciclastic package comprising the Carnegie Formation, Sir Frederick Conglomerate, Ellis Sandstone, and Maurice Formation are probably synorogenic (Petermann Orogeny) and thus are likely correlatives of the Neoproterozoic to Early Cambrian Arumbera Sandstone – Mount Currie Conglomerate package of the eastern Amadeus Basin. The recognition in Western Australia of the same stratigraphic intervals that have demonstrated or possible source potential in the Northern Territory, increases the petroleum prospectivity of the Amadeus Basin in Western Australia.

KEYWORDS: Amadeus Basin, Centralian Superbasin, Neoproterozoic, lithostratigraphy, stromatolite biostratigraphy, petroleum

The Amadeus Basin (Wells et al., 1970; Korsch and Kennard, 1991) is a thick package of Neoproterozoic to Paleozoic sedimentary rocks exposed over about 170 000 km^2 in central Australia (Fig. 1), mainly within the Northern Territory (NT), although a significant portion extends across the border into Western Australia (WA). The present Amadeus Basin is interpreted as a relic of the former Centralian Superbasin (Walter et al., 1995), which was fragmented during the late Neoproterozoic to earliest Paleozoic Petermann Orogeny, and mid-late Paleozoic Alice Springs Orogeny (Haines et al., 2001). The northern and southern boundaries of the present Amadeus Basin are thus mainly of tectonic origin, produced by uplift and erosion of basin strata to expose Paleo–Mesoproterozoic metasedimentary and igneous rocks of the Arunta Orogen and Musgrave Province, respectively. The basin continues westward and eastward beneath younger basins, such as the Canning Basin to the west.

Basin tectonics are complex, being the result of halotectonics (Dyson and Marshall, 2007) and the superimposed effects of the two orogenies. The latter were accompanied by deposition of coarse clastic foreland deposits, thickest near tectonically controlled basin margins (Wells et al., 1970; Haines et al., 2001). The basin is extensively folded and faulted, but generally unmetamorphosed, with local exceptions associated with basin margin tectonism. Compared with the Amadeus Basin in the NT, where the Neoproterozoic succession is overlain by thick Paleozoic successions, the WA component appears to be mainly of Neoproterozoic to possibly Cambrian age, with only small local outliers of confirmed later Paleozoic rocks. Superficial Permian deposits are considered part of the overlying Canning Basin, and are not discussed further.

Previous work

In contrast to the NT portion of the Amadeus Basin, which has undergone multiple phases of study by Government organizations, universities, and exploration companies, the WA part of the basin is poorly known and has only been mapped at reconnaissance level. The main area of outcrop (MacDonald* and Rawlinson) was mapped by the Bureau of Mineral Resources (BMR, now Geoscience Australia) in 1960 (Wells et al., 1961, 1964, 1970). Peripheral areas were mapped by joint BMR and Geological Survey of Western Australia (GSWA) parties in the early 1970s. A review of the stratigraphy, based on comparisons with the stratigraphy of the eastern Amadeus Basin, was published by Grey (1990). However, most areas have not been re-visited by Government geologists since first-pass mapping, with the exception of recent and current GSWA programs, and there has been limited exploration for petroleum or mineral resources. Reasons for this lack of activity have included poor access due to remoteness and a perception of low prospectivity.

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

The western extremities of the Amadeus Basin are largely covered by surficial deposits. Consequently there is little continuity of outcrop and, coupled with the perception of significant facies changes from east to west (now seen as largely an artefact of miscorrelation), a mostly separate stratigraphic nomenclature was set up for the portion of the basin near and west of the WA state border (Fig. 2). The basin-wide Neoproterozoic stratigraphic nomenclature and correlation scheme of Wells et al. (1970) has undergone significant modification in the NT (Weste, 1989; Korsch and Kennard, 1991), particularly in the better exposed northeastern part of the basin, but correlations between far west and east have not been reassessed through field examination until now. Only the Heavitree Quartzite and its equivalent the Dean Quartzite, and the overlying Bitter Springs Formation were previously recognized in both areas.

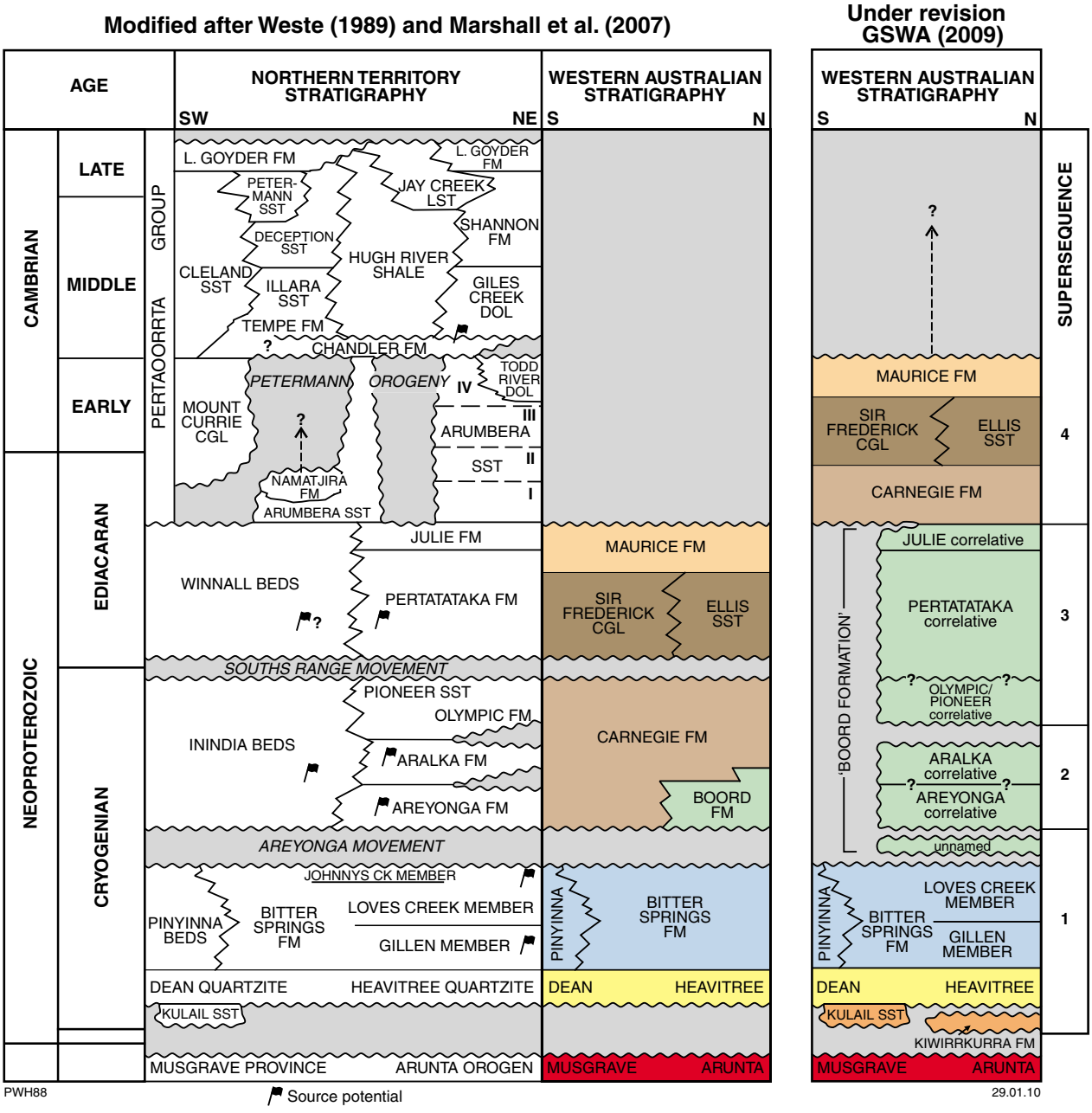

Figure 2. Stratigraphy of the Northern Territory and Western Australian Amadeus Basin, comparing the most commonly used current scheme on left with our revisions in progress at right. The supersequence scheme of Walter et al. (1995) is shown at far right.

New geoscience

Progress towards revised stratigraphy and correlations

Basal clastic units

The basal unit of the Amadeus Basin along almost the full length of the northern margin is the Heavitree Quartzite (Fig. 3a). In WA this unit is typically thinner, less heavily silicified, and its lower part more conglomeratic than in the NT. In the Pollock Hills area, the Heavitree Quartzite is underlain by a unit of coarse red-brown lithic and pebbly sandstone that was previously mapped as part of the Paleoproterozoic Pollock Hills Formation of the basement Arunta Orogen (Blake, 1977). However, this unit is separated from the main volcanic and volcaniclastic succession of the Pollock Hills Formation by a marked angular unconformity, while having similar structural attitude to the Heavitree Quartzite, although the contact is covered. Recently named the Kiwirrkurra Formation (Geological Survey of Western Australia, 2008), this unit tentatively is considered as part of the Amadeus Basin succession. The Dean Quartzite is the assumed equivalent of the Heavitree Quartzite on the southern margin of the Amadeus Basin. In the NT, the original Dean Quartzite has been recently subdivided to differentiate a local basal lithic and felspathic unit, the Kulail Sandstone (Close et al., 2003), a possible correlative of the Kiwirrkurra Formation. The Kulail Sandstone has been mapped westward to the state border, and clearly extends into WA, but has yet to be delineated further west.

Bitter Springs Formation

In the eastern Amadeus Basin the Bitter Springs Formation is a mixed carbonate, siliciclastic, and evaporite succession that has been subdivided into the Gillen, Loves Creek, and Johnnys Creek Members, in ascending order. It contains a regional disconformity at the base of the Loves Creek Member (Ambrose, 2006). The Gillen Member typically contains a halite unit in the subsurface responsible for widespread halotectonic deformation (Dyson and Marshall, 2007). In WA the Bitter Springs Formation has not been previously divided into members. Such subdivision is difficult on purely lithostratigraphic grounds because of structural complications, incomplete sections, and generally poor outcrop, but is desirable because of implications for petroleum prospectivity. Stromatolite biostratigraphy appears to be the best approach for outcrop sections, because the members have distinct stromatolite assemblages (Walter, 1972). Most stromatolite localities thus far identified in the Bitter Springs Formation in WA contain elements of the *Acaciella australica* Stromatolite Assemblage (Stevens and Grey, 1995; Fig. 3c), implying correlation with the Loves Creek Member and with similar successions in other Australian Neoproterozoic Basins. However, *Tungussia erecta* (Fig. 3b) has been found at a lower stratigraphic position, just above the top of the Heavitree Quartzite in the Pollock Hills area, confirming the presence of a correlative of the Gillen Member in WA. Complexly folded outcrops of Bitter Springs Formation, particularly in the Bonython Range (Fig. 3d) are suggestive of halotectonics and the presence of subsurface halite within the Bitter Springs Formation in WA, presumably within the Gillen Member. Dentith and Cowan (2009) interpreted salt withdrawal basins from geophysical data over the WA Amadeus Basin.

Boord Formation

Over most of the NT Amadeus Basin, the Bitter Springs Formation is overlain disconformably by the glacigenic Areyonga Formation or the partly laterally equivalent Inindia beds (Wells et al., 1970; Weste, 1989; Grey, 1990). Under the WA stratigraphic scheme of Wells et al. (1964), the Bitter Springs Formation is overlain, also with disconformity, by the mixed carbonate–siliciclastic Boord Formation or the siliciclastic Carnegie Formation. Wells et al. (1970) correlated the Boord Formation with the Areyonga Formation because both contain glacial diamictite. The lower Carnegie Formation was also correlated with the Areyonga Formation, despite there being no recognized glacigene strata, because of its perceived stratigraphic relationships, including inferred interdigitation with the entire Boord Formation. Grey (1990) preferred to correlate the Boord–Carnegie package with the younger glacigene Olympic Formation and Pioneer Sandstone of the northeast Amadeus Basin. Recent fieldwork has led to the recognition that the Boord Formation is a composite unit that contains disconformities and correlates with several northeastern Amadeus Basin formations, with considerable time spread. We also found no compelling evidence for the inferred lateral equivalence of the Boord and Carnegie Formations. While there may be some interdigitation of facies between the top of the Boord Formation and the basal Carnegie Formation, most of the latter appears to be younger. We propose eventual abandonment

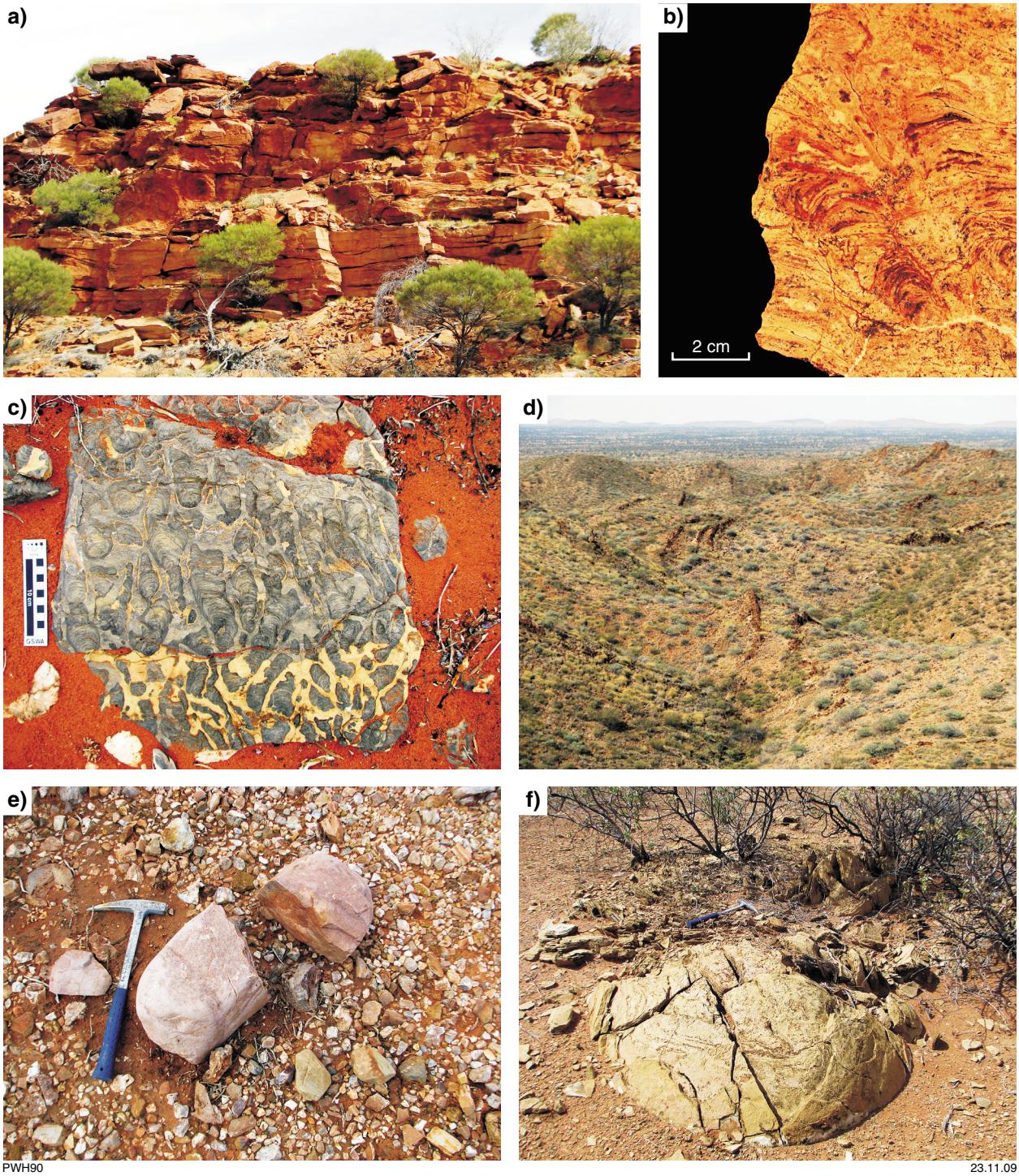

Figure 3. Field and hand specimen photographs: a) Heavitree Quartzite, Pollock Hills; b) Stromatolite **Tungussia erecta**, *Gillen Member, Pollock Hills; c) Columnar stromatolites, Loves Creek Member, Boord Ridges; d) Complexly folded outcrop of Bitter Springs Formation, Bonython Range; e) Large rounded quartzite clast, Areyonga Formation correlative, Boord Ridges; f) Large isolated domical stromatolite, Aralka Formation correlative, Boord Ridges*

of the term 'Boord Formation', but until a new stratigraphy is finalized we will use this term informally for the composite package (Fig. 2).

Lower 'Boord Formation'

At the type section in the Boord Ridges the base of the 'Boord Formation' was defined by a poorly exposed zone of chert rubble overlying the Bitter Springs Formation (Wells et al., 1964). The contact was inferred to be a disconformity because the chert was considered to have been reworked from the silicified top of the Bitter Springs Formation. We found that where it is best exposed this chert-dominated zone can be resolved into two discrete stratigraphic units, the lower comprising in situ stromatolitic and ooid chert (silicified carbonate) about 150 m thick with rare preservation of non-silicified stromatolitic carbonate. This as yet unnamed unit has a poorly preserved basal lithic (chert-bearing) sandstone suggesting a disconformity separates it from the Bitter Springs Formation. Identification of the stromatolite *Baicalia burra* also suggests that it is significantly younger than the Bitter Springs Formation, and implies correlation with the informally named 'Finke beds' intersected above the Bitter Springs Formation in petroleum exploration wells Finke 1 and Wallara 1 in the NT (Grey et al., in press), and the upper Buldya Group of the Officer Basin and the Burra Group of the Adelaide Rift Complex. The upper part contains no exposures of in situ chert, but, in rare outcrops, the angular chert clasts are shown to be embedded in a grey mudstone matrix. It appears that in this case the chert rubble at the surface represents a lag deposit over chert-bearing diamictite. The chert rubble is also associated with sparse quartzite and sandstone pebbles and cobbles (Fig. 3e) displaying facets and rare striations suggestive of a glacigene origin; glacigene influence at this level in the 'Boord Formation' was not previously recognized. We infer that this basal unit, which is estimated to be about 150 m thick and appears to have an irregular lower boundary suggestive of a disconformity, is most likely a correlative of the Areyonga Formation, rather than the previously recognized diamictite, which lies stratigraphically higher in the succession.

The probable correlative of the Areyonga Formation is overlain by a thick (approximately 450 m) — and mostly covered or very poorly exposed — interval that appears to be mainly dominated by siltstone and shale, with increasing carbonate at the top. The basal contact is not exposed. Multiple horizons of isolated domical stromatolites (Fig. 3f), often nucleated on intraclastic debris, are present in the upper part, and are very similar to undescribed stromatolites in the eastern Amadeus Basin that are probably older than the Pioneer Sandstone (Grey, 2005, p. 93). The siltstone unit is capped by a ridge-forming intraclastic, microbial, and stromatolitic limestone unit. Based on lithology, stratigraphic constraints, and stromatolites this combined interval is a likely correlative of the Aralka Formation of the northeast Amadeus Basin and the central Inindia beds to the south.

Upper 'Boord Formation'

A second and better exposed interval of glacigene diamictite lies with angular erosional contact over the Aralka Formation correlate, locally removing the upper ridge-forming limestone. This is the glacial unit noted by earlier workers (Wells et al., 1961, 1964), and contains pebble- to boulder-sized clasts of limestone, dolomite, sandstone, quartzite, and chert, and rarer granite and volcanic and metamorphic rocks. The largest clasts, several metres in size are clearly derived from the nearby underlying stratigraphy, most notably the ridge-forming limestone unit. Many of the smaller clasts, particularly well-indurated sandstone and quartzite, are rounded, faceted, and striated (Fig. 4a). The matrix, where preserved, is brown to grey, sandy mudstone. The diamictite is interbedded with lenticular sandstone and conglomerate beds, and where significantly incised into underlying stratigraphy is commonly underlain by a basal pebbly and cross-bedded sandstone unit tens of metres thick. We interpret this second glacigene interval, which averages about 100 m in thickness, as a correlative of the Olympic Formation and laterally equivalent Pioneer Sandstone of the northeastern Amadeus Basin.

The upper glacial unit is overlain by a unit about 300 m thick. Local poor exposures suggest that it is dominated by red-brown siltstone and shale, with thin interbeds of fine- to medium- and rarely coarse-grained sandstone, mainly in the upper third. The basal contact is not exposed. Lithologically, it closely resembles the Pertatataka Formation, which overlies the Olympic Formation and Pioneer Sandstone in the northeastern Amadeus Basin. This unit grades up into a succession of limestone and dolomite interbedded with recessive intervals that are either entirely covered or display poor exposure of siltstone, and weathered silty to sandy carbonate (Fig. 4b). The facies association is typical of shallowing-upward

cycles in shallow-water carbonate successions. The ridge-forming carbonates often comprise ooid and other grainstones, and stromatolites are diverse and abundant. Significantly, the presence of the stromatolite *Tungussia julia* (Fig. 4c) provides a biostratigraphic link with the Julie Formation (Walter et al., 1979), a carbonate unit overlying the Pertatataka Formation in the northeast part of the basin. The same stromatolite is present in other Australian Neoproterozoic basins at the same stratigraphic level (Grey, 2008). At the Boord Ridges, the Julie Formation correlative is estimated to be at least 550 m thick (top not exposed), whereas an isolated occurrence about 35 km to the south-southeast is estimated to be about 800 m thick.

Latest Neoproterozoic–Cambrian

The red-brown sandstone and siltstone of the Carnegie Formation, averaging about 1700 m in thickness, is lithologically very similar to the Arumbera Sandstone of the northeastern Amadeus Basin, a deltaic succession overlying the Julie Formation and coeval with the latest Neoproterozoic to Early Cambrian Petermann Orogeny. This correlation is further supported by the common presence of *Arumberia* (Glaessner and Walter, 1975; Fig. 4d), a problematic Ediacaran fossil first reported from the lower Arumbera Sandstone but known from other Ediacaran to Early Cambrian successions worldwide. The presence of the Carnegie Formation directly over probable Bitter Springs Formation in the southern part of the WA Amadeus Basin suggests that uplift during an early phase of the Petermann Orogeny led to erosion of the 'Boord Formation' in that area.

The siliciclastic Sir Fredrick Conglomerate, Ellis Sandstone, and Maurice Formation post-date the Carnegie Formation, and are also likely related to the Petermann Orogeny. The Sir Frederick Conglomerate, of uncertain maximum thickness, is composed predominantly of well-rounded quartzite cobbles and boulders, and rarer basement clasts, deposited in a high-energy fluvial environment (Fig. 4e). We suggest approximate correlation with the Mount Currie Conglomerate of the southern NT Amadeus Basin, best developed at Kata Tjuta (Mount Olga). Both units are apparently derived from the Musgrave Province and lower Amadeus Basin to the south and southwest of present outcrops, as indicated by clast composition and imbrication, but distinct differences in clast and matrix assemblages are apparently due to spatial changes in the composition of the exposed rocks. Specifically, the Dean Quartzite is thickly developed and tectonically repeated south of the exposed Sir Frederick Conglomerate, but is poorly developed in the area south of Kata Tjuta. According to Wells et al. (1964, 1970) the Sir Frederick Conglomerate and Ellis Sandstone are lateral equivalents, but this relationship remains to be reassessed. The youngest unit of the main succession of the WA Amadeus Basin is the Maurice Formation (Fig. 4f). Its estimated exposed thickness is at least 3600 m in the south of its range (top not exposed), but its age is poorly constrained, apart from presumed conformity with the underlying units. It may extend into, or be wholly Cambrian in age — if so it could be a whole or part correlative of the Cleland Sandstone in the NT.

Paleozoic or Neoproterozoic

The Angas Hills beds (informal name) comprise a unit of red-brown sandstone and conglomerate exposed within outliers of the Amadeus Basin within the Arunta Complex north of the main basin. Blake (1977) tentatively correlated the Angas Hills beds with the Devonian Pertnjara Group of the NT Amadeus Basin, implying affiliation with the mid-Paleozoic Alice Springs Orogeny. As yet, the age of the Angas Hills beds remains unknown in the absence of biostratigraphic data, but we note that paleocurrents are typically from the south to southwest, similar to those observed for clastic sediments related to the Petermann Orogeny in the WA Amadeus Basin. Clast types are consistent with derivation from older Neoproterozoic units of the Amadeus Basin.

Petroleum prospectivity

Although still under-explored for petroleum, the NT-portion of the Amadeus Basin has had a successful history of petroleum exploration since the first wells were drilled in 1963. The large Mereenie oil and gasfield and the Palm Valley gasfield, which are still producing, were discovered in 1963 and 1965, respectively. Since then, several subeconomic fields have been discovered, and other wells have encountered significant shows from throughout much of the stratigraphic section. Although the Ordovician is considered the most prospective, a number of proven and potential source intervals and play types have been identified within the Neoproterozoic succession (Marshall, 2003, 2005; Marshall et al., 2007). Marshall (2003), revised in Marshall

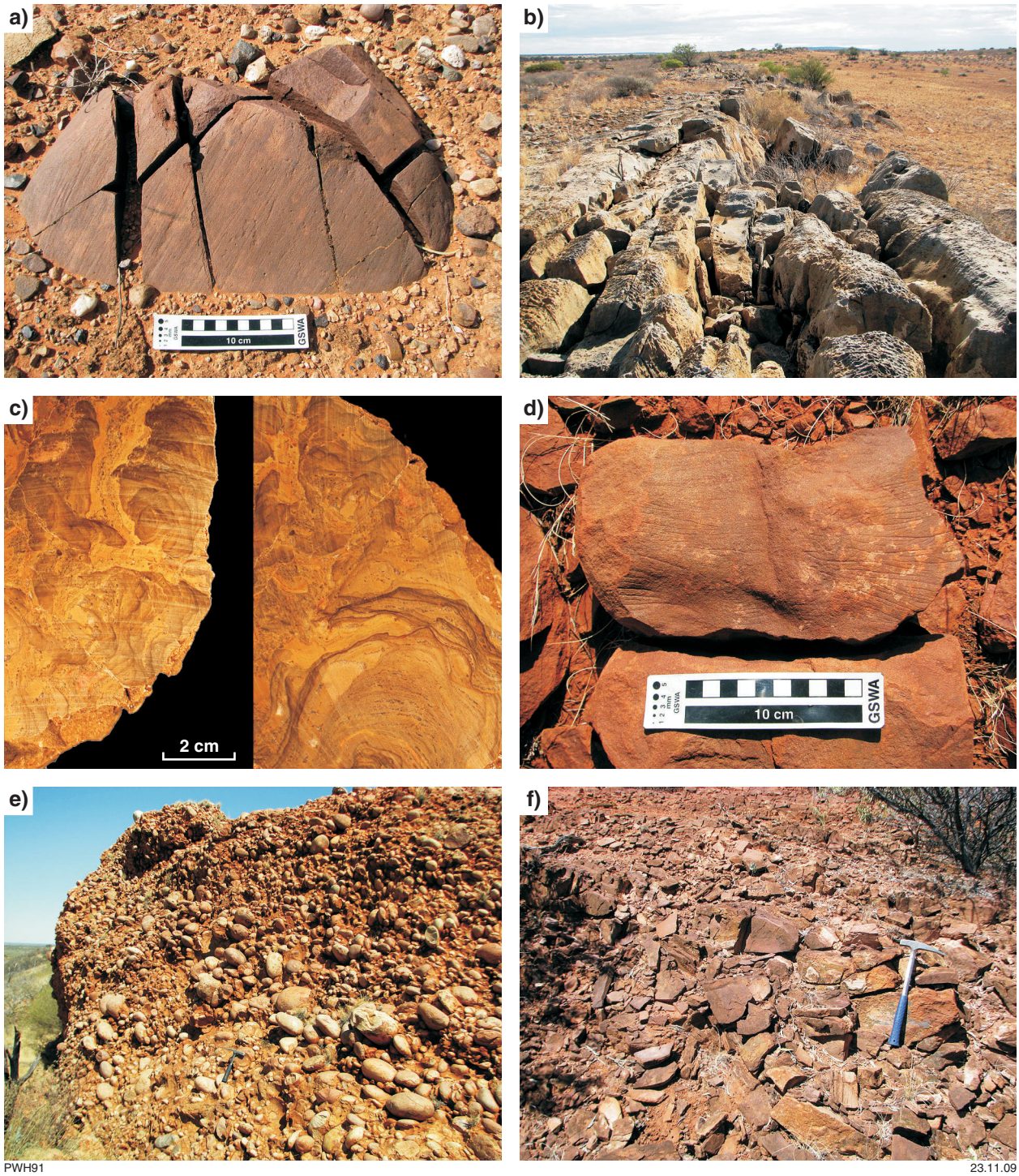

Figure 4. Field and hand specimen photographs: a) Striated quartzite clast, Olympic Formation correlative, Boord Ridges; b) Gently dipping limestone ridge, Julie Formation correlative, Boord Ridges; c) Stromatolite **Tungussia julia**, *Julie Formation correlative, Boord Ridges; d) Problematic* **Arumberia**, *Carnegie Formation, Mu Hills; e) Well-rounded quartzite cobbles in sandstone matrix, Sir Frederick Conglomerate, Mu Hills; f) Red-brown lithic and micaceous sandstone, Maurice Formation, southwest of Sir Frederick Range*

et al. (2007), recognized four Neoproterozoic to earliest Cambrian petroleum systems. The oldest, the sub-salt Gillen Member – Heavitree Quartzite play, produced a significant gas flow with high helium content in Magee 1. The second system involves potential source rocks in the upper Bitter Springs, Areyonga, and Aralka Formations and the correlative Inindia beds in the south. This system is most likely responsible for a paleo-oil column in the 'Finke beds' in Finke 1, a measured gas flow in Ooraminna 1, and oil shows in Mount Winter 1. The third system involves potential source rocks in the Pertatataka Formation and correlative Winnall beds, whereas the fourth includes the subeconomic Dingo gasfield, reservoired in the Arumbera Sandstone and probably sourced from lower systems.

In the absence of drill hole information, the source and reservoir potential, and maturity of the WA part of the Amadeus Basin remains speculative. However, recognition that the stratigraphy and facies of the WA Amadeus Basin have much more in common with the eastern succession than previously thought raises the possibility that some of the same petroleum systems and plays may be present.

Conclusions

The Neoproterozoic stratigraphy of the WA Amadeus Basin has much more in common with the NT portion of the basin than previously thought, and correlatives of most stratigraphic intervals can be recognized. Lithostratigraphic correlations are further strengthened by stromatolite biostratigraphic ties. The revised correlations lead to significant changes of inferred age for most units above the Bitter Springs Formation — the 'Boord Formation' as mapped probably spans the interval between and including the Areyonga and Julie Formations; and the Carnegie Formation, Sir Frederick Conglomerate, Ellis Sandstone, and Maurice Formation are probably latest Neoproterozoic to Cambrian synorogenic correlatives of the Arumbera Sandstone and Mount Currie Conglomerate, extending possibly to the Cleland Sandstone. The presence of Western Australian equivalents of units with proven or possible source potential in the NT increases the number of potential petroleum systems that may be present in the WA part of the basin.

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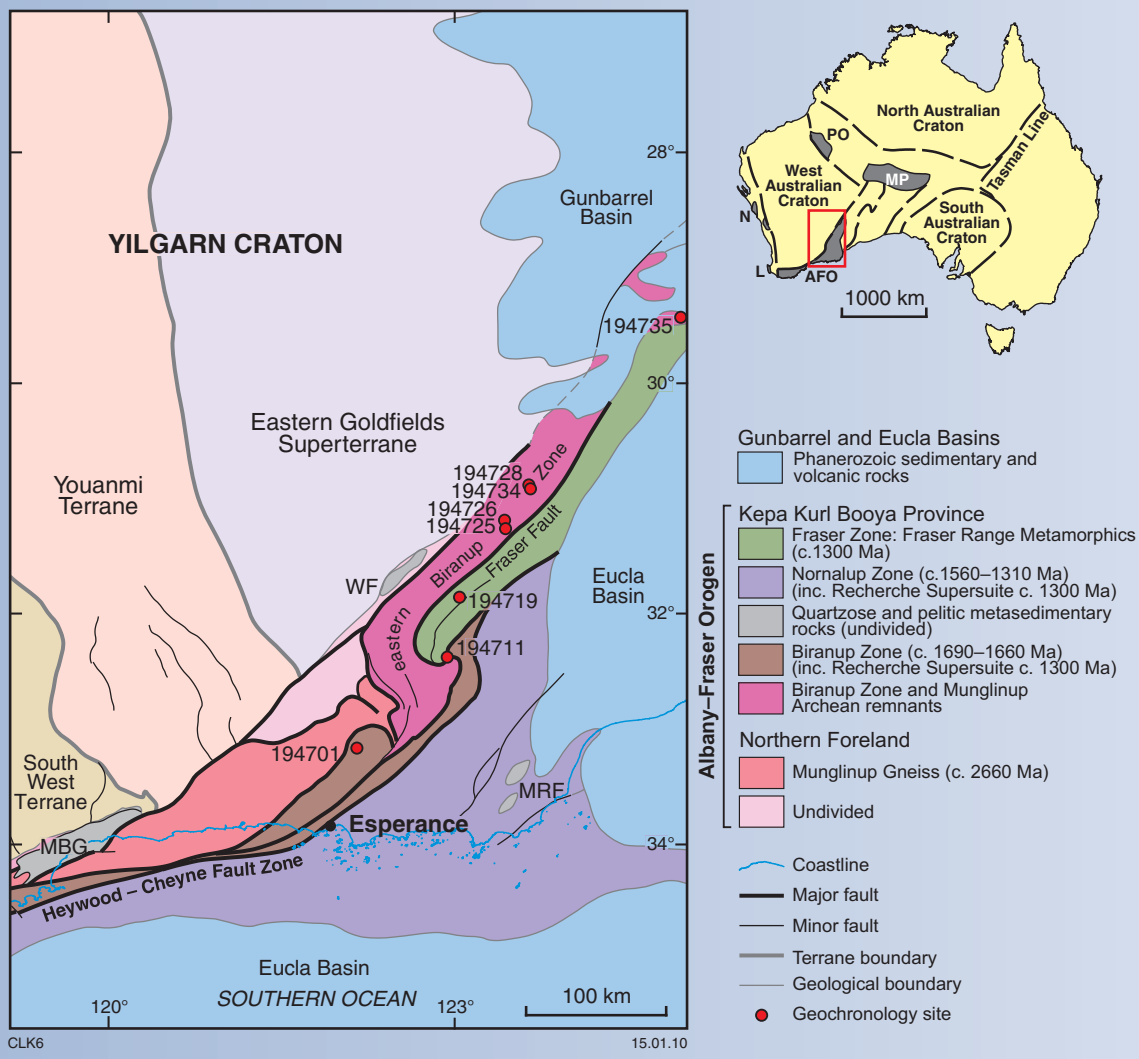

Figure 1. Preliminary geological sketch map of the eastern Albany–Fraser Orogen and east Yilgarn Craton (adapted from Spaggiari et al., 2009) showing locations of the geochronology samples.
MBG = Mount Barren Group; MRF = Mount Ragged Formation; WF = Woodline Formation. Inset map shows the location of Mesoproterozoic tectonic units of Australia; MP = Musgrave Province; PO = Paterson Orogen; N = Northampton Complex; L = Leeuwin Complex; AFO = Albany–Fraser Orogen.

New geochronology from the Albany–Fraser Orogen: implications for Mesoproterozoic magmatism and reworking

by CL Kirkland, CV Spaggiari, MTD Wingate, RH Smithies, and MJ Pawley

Abstract

The Albany–Fraser Orogen represents the Mesoproterozoic continent–continent collision of the combined North and West Australian Cratons with the combined East Antarctic and South Australian Cratons. The Kepa Kurl Booya Province is the crystalline basement of the Albany–Fraser Orogen and is divided into the Fraser, Biranup, and Nornalup Zones. Recent geochronology on the Albany–Fraser Orogen has refined our understanding of its evolution. Six samples from a transect along the eastern Biranup Zone record protolith ages of meta-igneous units between 1685 ± 8 Ma and 1657 ± 5 Ma. These ages indicate that the Biranup Zone extends from the southern Albany–Fraser Orogen to the northeast between the Yilgarn Craton and the Fraser Zone. U–Pb dating of zircons from two meta-igneous units within the Fraser Zone yields a weighted mean date of 1298 ± 4 Ma, synchronous with Stage I of the Albany–Fraser Orogeny. In contrast to the Fraser Zone, the Biranup Zone records metamorphic zircon overgrowth at 1197 ± 6 Ma, which is the first direct evidence of Stage II Albany–Fraser Orogeny activity in this part of the orogen. Dating of fracture-filling zircon, in the eastern Biranup Zone, indicates a period of crustal uplift and cooling between 1270 and 1197 Ma, consistent with separation of the Albany–Fraser Orogeny into two stages. Age similarities between the reworking of the eastern Biranup Zone and the ultra-high-temperature metamorphism of the Musgrave Province are compatible with a Mesoproterozoic extensional event in both areas at c. 1200 Ma. A temporal correlation may be made between earlier c. 1300 Ma events in the Musgrave Province and Stage I of the Albany–Fraser Orogeny, as recorded in the Fraser Zone. These early events may relate to accretion of an arc system along the Yilgarn Craton margin.

KEYWORDS: Geochronology, Albany–Fraser Orogen, Yilgarn Craton, West Australian Craton, North Australian Craton, Mawson Craton, Mesoproterozoic, U–Pb geochronology, tectonics

Convergent plate-margin processes were fundamental in assembling the various Archean–Proterozoic fragments of Australia and responsible for their reorganization into Rodinia. The Albany–Fraser Orogen (Myers, 1990) is an arcuate orogenic belt on the southern and southeastern margins of the Archean Yilgarn Craton in Western Australia (Fig. 1) that records part of this amalgamation. The predominant tectonic and metamorphic features of the belt are generally considered to have developed during the Mesoproterozoic Albany–Fraser Orogeny, which is subdivided into two stages (Clark et al., 2000): Stage I representing continental collision (c. 1345–1280 Ma), and Stage II reflecting intracratonic reactivation (c. 1215–1140 Ma). Both tectono-metamorphic stages involved oblique dextral movement and the north and northwestward transport of thrust slices (Myers, 1993; Myers, 1995). The Albany–Fraser Orogen has been divided into a foreland component (the Northern Foreland) and a basement component, defined as the pre-amalgamation, disparate, crustal fragments affected by Mesoproterozoic tectonism, named the Kepa Kurl Booya Province (Spaggiari et al., 2009).

This paper presents new zircon U–Pb geochronology and provides a geochronological framework enabling correlation with other Mesoproterozoic belts associated with the amalgamation of the combined South Australian and East Antarctic Cratons (Mawson Craton) and the combined North and West Australian Cratons.

Geological and temporal framework

The Albany–Fraser Orogen is dominated by granulite-facies paragneiss and orthogneiss intruded by late-tectonic granite plutons in the west (near Albany), and by orthogneiss and mafic granulite in the east (Fraser Zone). The Albany–Fraser Orogen is itself subdivided into a series of fault-bound tectonic units (Fig. 1). These include the Northern Foreland, pre-Stage I amalgamation basement components of the Kepa Kurl Booya Province, the Recherche and Esperance Supersuites, and various Mesoproterozoic cover rocks. The Kepa Kurl Booya Province is further divided into the Biranup Zone, the Nornalup Zone, and the Fraser Zone (Spaggiari et al., 2009).

The Biranup Zone is dominated by c. 1700–1650 Ma orthogneiss. It includes the Dalyup and Coramup Gneisses (Myers, 1995). However, both lithological units are dominated by granitic rocks with a similar crustal history and hence this distinction may not be meaningful. The origin of the Biranup Zone is unknown, but it appears to be exotic to the Yilgarn Craton. The c. 1560–1310 Ma Nornalup Zone consists of Mesoproterozoic ortho- and paragneisses (Myers, 1990; 1995). The Biranup and Nornalup Zones have been intruded by granitic rocks of the c. 1330–1280 Ma Recherche Supersuite associated with Stage I activity. Metagranitic rocks of c. 1300 to 1280 Ma age are also found in the Fraser

Range Metamorphics (De Waele and Pisarevsky, 2008) within the northeasterly trending Fraser Zone. The Fraser Range Metamorphics unit (Spaggiari et al., 2009) is a sheeted complex of gabbroic to granitic rocks with layers of variably migmatized pelitic and calcic metasedimentary rocks, all of which have been metamorphosed at high (granulite facies) temperatures close to their time of formation. Myers (1985) interpreted the mafic rocks in the Fraser Range as part of a large layered mafic intrusion, whereas Condie and Myers (1999) argued that it was the remnant of multiple magmatic arcs.

U–Pb results

U–Pb results from eight samples are presented. They are from an extensive new dataset acquired by the Geological Survey of Western Australia, which spans the entire exposed length of the eastern Albany–Fraser Orogen along the Yilgarn Craton margin (east Biranup Zone and Fraser Range Metamorphics). These results elucidate the spatial extent of Mesoproterozic tectono-metamorphic and magmatic events. The locations of the samples discussed in this paper are shown in Figure 1. Analytical methodology, U–Pb data tables, and detailed descriptions of analyses are supplied as supplementary material that is available online through the Department of Mines and Petroleum's GeoVIEW.WA integrated geoscience information system <http://www.dmp.wa.gov.au>. All geochronology results are shown on concordia diagrams (Fig. 2) and are presented in Table 1 below.

New geochronology in the context of the Fraser and eastern Biranup Zones

Two granitic samples (GSWA 194711 and 194719; Figs 1 and 2; Table 1) within the Fraser Range Metamorphics yield a weighted mean date of 1298 ± 4 Ma (MSWD = 0.045), which is interpreted as the age of magmatic crystallization, synchronous with Stage I of the Albany Fraser Orogeny. Clark et al., (1999) presented a similar age of 1293 ± 9 Ma for the crystallization of post-D1 granites. The foliation within both these samples most likely developed shortly after their emplacement; this is consistent with dates from disturbed zircon grains that suggest a radiogenic Pb-loss event soon after crystallization (Clark et al., 1999; De Waele and Pisarevsky, 2008). Within the eastern region of the Albany–Fraser Orogen syn-Stage I magmatic rocks (i.e. at c. 1300 Ma) are restricted to the Fraser Range Metamorphics (of the Fraser Zone). Outside the Fraser Zone in the eastern Biranup Zone, Stage I metamorphism and deformation resulted in the growth of homogeneous 'metamorphic' rims mantling inherited zircon seeds. The Stage I events responsible for zircon growth within the Fraser Range Metamorphics apparently did not result in a significant volume of silicate melt in the eastern Biranup Zone as no major granite bodies of this age have been found.

The southern Biranup Zone (consisting of both the Coramup and Dalyup Gneisses) comprises 1690–1660 Ma metagranitic and lesser metasedimentary rocks that have similar protolith ages to the

Table 1. Selection of new geochronology from the Fraser and Biranup Zones

Sample	*Lithology (petrology)*	*Magmatism*	*Metamorphism*	*Inheritance*
Fraser Zone				
194711	Granite (Qtz, Mc, Pl, Bt, Grt, Hbl, Ap, Zrn)	1297 ± 8 Ma		4 grains 1701–1684 Ma
194719	Granite (Qtz, Kfs, Alkf, Bt, Pl, Zrn, Ttn)	1298 ± 5 Ma		c. 1770 Ma
Biranup Zone				
194701	Orthogneiss (Pl, Qtz, Bt, Mc, Ms, Ttn, Zrn, Aln)	1685 ± 8 Ma	1203 ± 11 Ma	1749, 1766, and 1809 Ma
194725	Orthogneiss (Qtz, Pl, Kfs, Grt, Bt, Mc, Ttn, Zrn, Hbl)	1671 ± 7 Ma	1205 ± 20 Ma	
194726	Orthogneiss (Qtz, Pl, Kfs, Bt, Grt, Hbl, Ttn, Zrn)	1666 ± 11 Ma	1162 ± 39 Ma	
194734	Orthogneiss (Or, Qtz, Pl, Bt, Grt, Ap, Zrn)	1675 ± 9 Ma	1192 ± 9 Ma	c. 1780 Ma
194728	Orthogneiss (Mc, Qtz, Pl, Grt, Ttn, Bt, Zrn)	1683 ± 8 Ma	1201 ± 15 Ma	
194735	Orthogneiss (Pl, Qtz, Mc, Bt, Ep, Ttn, Ms, Ap, Zrn)	1657 ± 5 Ma	1270 ± 11 Ma & 1193 ± 26 Ma	

NOTES: Zircon U–Th–Pb ages of samples in the eastern Albany–Fraser Orogen. GSWA standard mineral name abbreviations are listed in MINEDEX. All uncertainties are at the 95% confidence level.

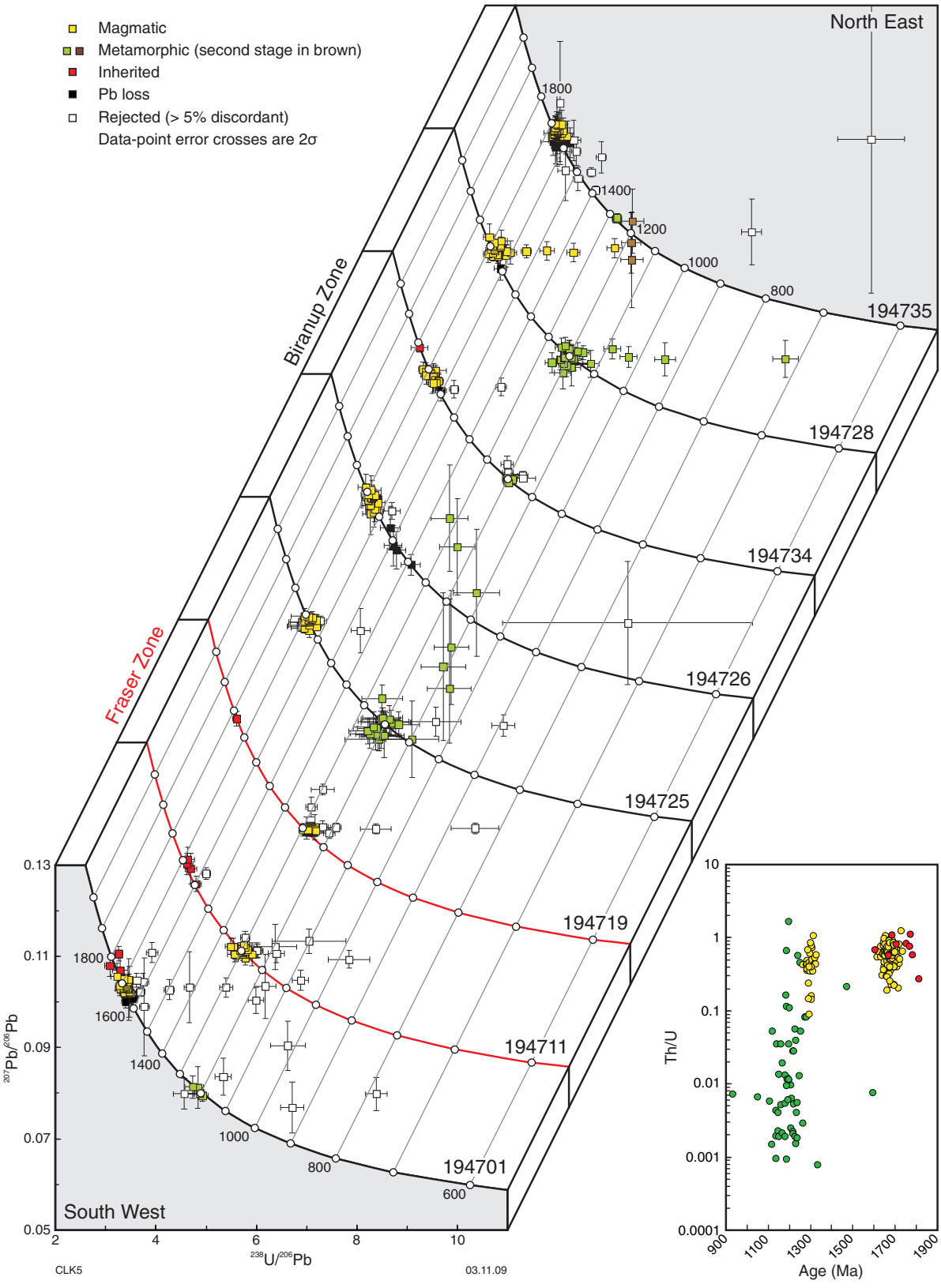

Figure 2. Stacked Tera-Wasserburg concordia diagrams for zircons analysed by ion probe

eastern Biranup Zone (Spaggiari et al., 2009). This shows that the Biranup Zone wraps around the entire southern and southeastern Yilgarn Craton margin, over a distance of at least 1200 km (Fig. 1). These gneisses lack any Archean-aged zircon inheritance, suggesting that they represent new juvenile additions to the crust, rather than pervasively reworked older crustal elements. The southern Biranup Zone rocks were metamorphosed to granulite facies conditions and intruded by the Recherche Supersuite (Nelson et al., 1995) during Stage I of the Albany–Fraser Orogeny (c. 1300 Ma), with subsequent high-temperature metamorphism during Stage II (c. 1180 Ma). No evidence of Recherche Supersuite intrusive rocks or metamorphism at this time is preserved within the eastern Biranup Zone. However, samples from this zone (GSWA 194701, 194725, 194726, 194734, 194728, and 194735; Figs 1 and 2; Table 1) do record Stage II zircon overgrowth at c. 1200 Ma. These zircon overgrowths show a range of Th/U ratios from values similar to those in magmatic crystals to dominantly lower values of around 0.001 (Fig. 2). As the Th/U compositions of the metamorphic overgrowths appear distinct from those in magmatic grains this implies a crystallization process in which the overgrowths had elemental exchange with their surrounding matrix.

Zircon overgrowths in samples from within the Biranup Zone provide a detailed picture of its Mesoproterozoic evolution. For example, zircons in GSWA 194735 record 1270 ± 11 Ma, high U, overgrowths that have developed on 1657 ± 5 Ma magmatic cores (Fig. 3). These grains were then fractured and subsequently overgrown by a later phase of homogeneous low-U rims at 1197 ± 6 Ma (weighted mean of six samples; MSWD = 1.3). These later rims most likely developed during zirconium-liberating metamorphic reactions, rather than during partial melting, as they infill fractures and retain no evidence of magmatic textures. This indicates a period of crustal uplift and cooling after the c. 1270 Ma zircon growth, prior to the development of zircon rims at c. 1200 Ma. The timing of this uplift is identical to that in the Fraser Range Metamorphics, which were exhumed to less than ~400 MPa sometime between 1288 Ma and 1260 Ma (Clark et al., 1999). It is also consistent with the interpretation of Stage I basement-derived detrital zircons within Stage II rocks in the eastern Nornalup Zone. This was interpreted to reflect extension and uplift and provided key evidence for the subdivision of the Albany–Fraser Orogeny into its two stages (Clark et al., 2000). This implies a shared uplift history between the eastern Biranup, Nornalup, and Fraser Zones, after Stage I.

Figure 3. SEM cathodoluminescence (CL) images of selected zircon grains from the dated sample GSWA 194735 (for location see Fig. 1). Ellipses indicate analysed regions labelled with the spot identification.

There is no evidence of Stage II events within the Fraser Zone, yet Stage II ages are prolific throughout the Biranup Zone. Preservation of pre-1250 Ma Rb–Sr cooling ages in the Fraser Range Metamorphics also indicates a lack of Stage II activity in that area (Fletcher et al., 1991). Inherited zircons within Stage I intrusive units of the Fraser Range Metamorphics, although limited, have ages similar to intrusive material within the Biranup Zone. This is compatible with the intrusive bodies of the Fraser Range Metamorphics passing through rocks of similar age to the Biranup Zone on their emplacement pathway. However, no evidence of a comparable Stage I thermal event in the eastern Biranup Zone is preserved. The earliest zircon-rim growth in the eastern Biranup Zone is recorded at c. 1270 Ma, but this is at least 10 Ma younger than the emplacement of granites in the Fraser Range Metamorphics and the Recherche Supersuite. Moreover, this c. 1270 Ma event appears to be recorded as metamorphic zircon overgrowths rather than as magmatic grains. Both the Fraser and Biranup Zones appear to have a comparable timing of uplift and cooling, between Stages I and II. The Fraser Fault represents a major structural boundary between the eastern Biranup and Fraser Zones. This feature may have placed the Fraser Zone at a higher structural level that was less conducive to zircon growth or regrowth. This suggests that the Fraser Fault was active during Stage II, juxtaposing the two zones.

Comparison with the Musgrave Province

The Mesoproterozoic to Neoproterozoic Musgrave Province lies at the convergence of Australia's main Proterozoic structural trends (Fig. 1), and shares certain chronological similarities with the Albany–Fraser Orogen (Wade et al., 2008).

This section highlights these similarities. Figure 4 presents a comparison of the geochronology from each region.

Intrusive rocks with protolith ages between c. 1330 and 1300 Ma form a significant component of the western part of the Musgrave Province (Howard et al., 2007; Smithies et al., 2009). The crustal

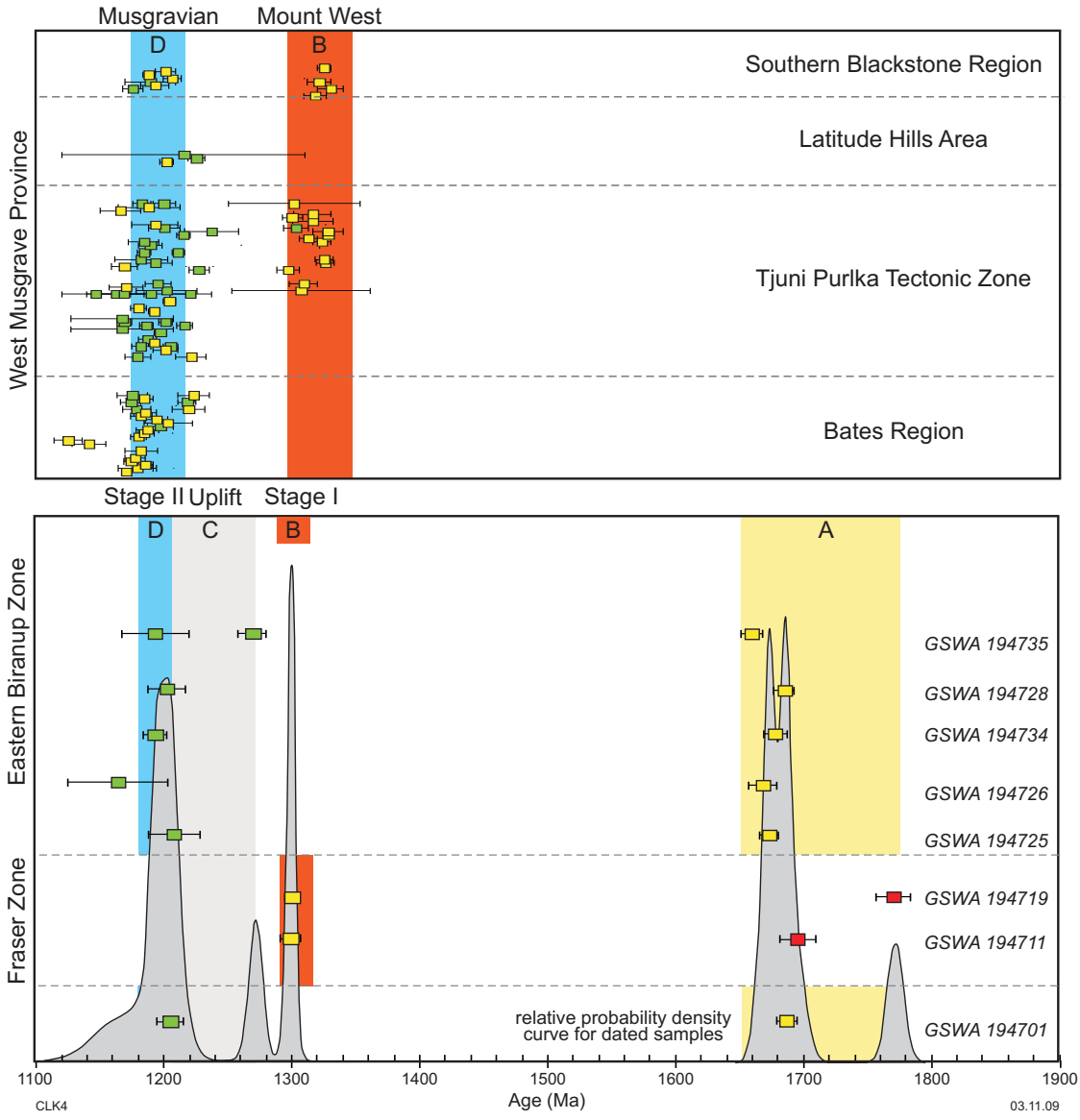

Figure 4. Space–time plot for dated samples of the Albany–Fraser Orogen compared to those from the west Musgrave Province. Each symbol represents the weighted mean age of zircon grains or parts of crystals, from a single sample, interpreted to date the following processes: metamorphism (green rectangles); inheritance (red rectangles); magmatism (yellow rectangles). Time frame (A) indicates intrusion of 1680 Ma granites and a suite of granitic to gabbroic rocks, with distinct mingling and hybridization textures, dated at c. 1665 Ma, which were emplaced into <1690 Ma psammitic to semipelitic rocks of the eastern Biranup Zone. (B) indicates c. 1300 Ma magmatism corresponding to Stage I events in the Albany–Fraser Orogen and the Mount West Orogeny in the Musgrave Province. (C) indicates brittle fracturing and uplift within the Fraser and Biranup Zones. (D) indicates metamorphic zircon growth in the Biranup Zone and ultra-high temperature events during the Musgrave Orogeny.

event that produced such melts has been termed the Mount West Orogeny. The age of this event is similar to Stage I of the Albany–Fraser Orogeny and specifically overlaps with the range of mafic to felsic components within the Fraser Range Metamorphics and the Recherche Supersuite. Several studies have suggested that the 1350 Ma and 1290 Ma events in the Albany–Fraser Orogen involved convergence and suturing of the West Australian Craton and the Mawson Craton, with the subducting oceanic slab dipping to the southeast (Clark et al., 2000). The tectonic setting of Mount West granites is unclear, but the granites retain a subduction-like geochemistry similar to Andean-style continental-arc magmas. Mount West Orogeny granites also have juvenile Nd- and Hf-isotopic compositions consistent with a continental arc setting (Smithies et al., 2009). Such a correlation leads to wider associations of the Musgrave Province and Albany–Fraser Orogen with other Mesoproterozoic (Grenvillian) orogenic belts.

The Musgrave Orogeny (1219–1155 Ma) is interpreted to reflect a period of intracratonic extension and is synchronous with Stage II tectonothermal activity in the Albany–Fraser Orogen. Stage II commenced with high-temperature metamorphism of the eastern Nornalup Zone and the Biranup Zone between 1225 and 1215 Ma (Clark et al., 2000; Bodorkos and Wingate, 2008). This was followed by emplacement of the c. 1210 Ma Gnowangerup–Fraser Dyke Suite (Wingate et al., 2000). Dawson et al. (2003) interpreted the Gnowangerup–Fraser Dyke Suite as the thermal impetus for peak metamorphism during early Stage II activity. Stage II events recorded in the Albany–Fraser Orogen are widespread in the Biranup and Nornalup Zones and include pluton emplacement as well as prolific growth of metamorphic zircons. In the southern Biranup Zone granulite facies metamorphism took place at c. 1180 Ma and re-occurred between 1170 and 1150 Ma (Spaggiari et al., 2009). In the eastern Biranup Zone metamorphic zircon growth is defined at 1197 ± 6 Ma, slightly earlier than the widespread c. 1180 Ma high-temperature metamorphism within the southern Biranup Zone. Significant extension during Stage II of the Albany–Fraser Orogeny is evident in Biranup Zone rocks at Bremer Bay where leucosomes formed in the necks of boudins at c. 1180 Ma (Spaggiari et al., 2009). The range of Stage II ages throughout the Biranup Zone would appear to reflect either protracted extension or various phases of metamorphism in an extensional to transpressional regime. Protracted extension is consistent with the tectonic scenario proposed for the West Musgrave Province, where repeated or continuous ultra-high-temperature metamorphism appears to have spanned the period, encompassing both the c. 1200 Ma and c. 1180 Ma events recognized in the Albany–Fraser Orogen.

Conclusions

The eastern Biranup Zone is composed of 1690–1650 Ma granitic to gabbroic intrusions. This indicates that the late Paleoproterozoic Biranup Zone extends from the southern Albany–Fraser Orogen to the northeast and girdles the Yilgarn Craton on its southern and eastern margins.

Two strongly foliated granitic samples within the Fraser Range Metamorphics yield a weighted mean date of 1298 ± 4 Ma (MSWD = 0.045), which is interpreted as the age of magmatic crystallization during Stage I of the Albany–Fraser Orogeny. A major foliation-forming event within the Fraser Zone must have developed after c. 1300 Ma.

The eastern Biranup Zone preserves no evidence of Stage I intrusive activity. However, evidence of Stage II metamorphic overprinting is widespread, as indicated by the development of low-uranium zircon overgrowths at 1197 ± 6 Ma. Within the eastern Biranup Zone, high-U zircon overgrowths are fractured and overgrown with a later phase of metamorphic zircon. This indicates a period of crustal uplift and cooling between 1270 and 1197 Ma. The timing of this uplift is comparable with that in the Fraser and Nornalup Zones.

The Mount West Orogeny of the Musgrave Province and Stage I of the Albany–Fraser Orogeny, at c. 1300 Ma, share a similar timing and may reflect accretion of an arc to the Yilgarn Craton. However, the general plate configuration is different in each region, which may account for some of the individual complexities in their magmatic history. The Musgrave Province is located on a junction between the North, West, and South Australian Cratons, whereas the Albany–Fraser Orogen is on a linear margin between the West Australian Craton and the Mawson Craton (the combined East Antarctic and South Australian Cratons). Similarities in both age and tectonic environment during the Stage II reworking of the Biranup Zone, and the ultra-high-temperature metamorphism of the Musgrave Province imply that a Mesoproterozoic extensional phase caused intrusive and metamorphic events in both regions during the period from 1200 to 1180 Ma.

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Program review

PETROLEUM SYSTEMS STUDIES AND PETROLEUM EXPLORATION DATA

Petroleum systems studies

Highlights and activities 2008–09

The focus of activities during 2008–09 was the Canning and Amadeus basins with other basins under a watching brief. Detailed studies of the Canning Basin continued and highlights included:

- Work on the Worral Formation shows it is conformably overlying the Carribuddy Group not unconformably as first thought. Re-interpretation of the Carribuddy Group was completed.
- Work on the Grant Group has revealed inconsistencies in resolving the correlation of the individual members of this group, and currently consideration is being made into regarding the Grant Group as an undifferentiated unit.
- An analysis of oil obtained from mineral drilling in the Admiral Bay Fault Zone, suggests the oil is sourced from the Goldwyer Formation, whereas previously the Bongabinni Formation was regarded as the main source in this area.
- Studies of the Acacia Sandstone suggest its provenance is from adjacent Neoproterozoic basins other than those of the North Australian Craton.
- Quality control of navigation for seismic surveys in the southwest Canning Basin has shown anomalies in the data, which is now being corrected.
- Identification and rescue of core from 23 mineral holes, currently stored at various sites in the Kimberley, which provides complete cored sections of the Permian, Carboniferous, Devonian and Ordovician sections not currently available in GSWA core stores.

Products 2008–09

- Geothermal Acreage Release — August 2008 (digital product)
- State Acreage Release — September 2008 (digital product)
- Record 2009/2 Extended abstract — A review of the mid-Carboniferous — Permian, Canning Basin
- Record 2009/2 Extended abstract — Geothermal studies in Western Australia

Objective: To develop consistent, basin-wide stratigraphic, structural, and petroleum systems frameworks to encourage increased onshore petroleum exploration by establishing regional context and thus help secure the State's energy future.

- Geothermal Energy Potential in Selected Areas of Western Australia (Canning Basin)
- Geothermal Acreage Release — March 2009 (digital product)
- State Acreage Release — June 2009 (digital product)
- Geothermal Acreage Release — May 2009 (digital product)
- Summary of petroleum prospectivity, Western Australia 2009: Bonaparte, Bight, Browse, Canning, Officer, Perth, Southern Carnarvon, and Northern Carnarvon Basins
- Report 105 The Carribuddy Group and Worral Formation, Canning Basin, Western Australia: stratigraphy, sedimentology and petroleum potential
- Three external papers were published

Future work

Future work will continue to focus on the Canning and Amadeus Basins and geothermal energy. Products will consist of pre-interpretive and interpretive data packages, reports, presentations, and papers.

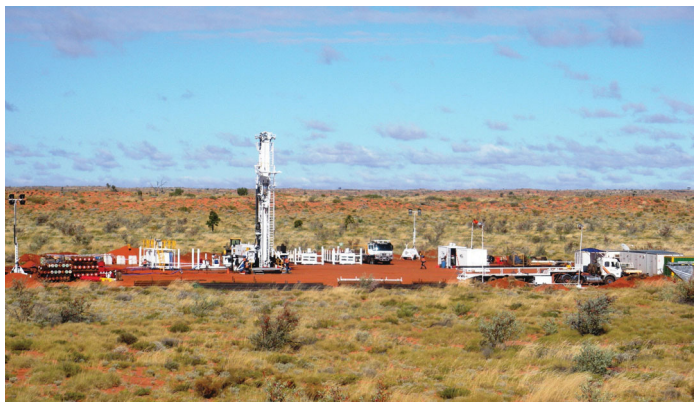

Figure 1. Sally May 2, Canning Basin (Image courtesy of Kingsway Oil Ltd)

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Petroleum exploration reports and data

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

Highlights and activities 2008–09

The program of scanning well completion reports, general well reports, and seismic reports from hard copy to PDF and TIFF formats continued with a total of 1624 reports being scanned and loaded onto the WAPIMS system for online web viewing. The scanning program also includes the scanning of hard copy seismic sections to PDF and segy (where no digital post-stack data is available).

Transcription of seismic field and processed data from the Canning and Perth basins from nine-track reels to 3590 cartridges (3433 tapes) continued to reduce the number of 'old' tapes in the archive (from 80 000 to 12 000) and move this valuable data to new and more reliable data.

WAPIMS database

Preparation for WAPIMS technical upgrade project (2009–10).

Some of the benefits expected at the completion of the project include:

- Improve integration between core WAPIMS applications
- Eliminate reliance on Paradox Forms
- Ability to easily extend the underlying data model (Seabed)
- Consolidate all data into a single entitled data repository.

Currently WAPIMS has more than 4500 external registered users, a total of 16 626 items (segy, logs, reports, and core images) and 652.5 GB of data available to the public.

WAPIMS data packages

- Comprehensive data package: the open file petroleum data from WAPIMS database is available on external hard drive, sorted by activity (seismic, wells) and basins for easy access on request from the petroleum industry.
- Geothermal data package
  - Petroleum acreage release data package
  - Navigation data package (onshore and offshore)
  - Started compiling Barrow Island data package (in collaboration with Chevron)

Data release 2008–09

During 2008–09, 392 requests were attended including well and seismic general requests and data package requests with a total of more than 10 TB of petroleum data. In addition, 153 requests for sampling or borrowing slides were processed.

Future work

Future work will continue to focus on the uploading of data into online systems, digital data remastering, processing data requests, and approvals for core sampling and lending of thin sections.

WAPIMS will undergo a technical upgrade involving:

- improvement of the data entry and data loader module
- migration of the database from Finder to Seabed database, utilising ProSource corporate
- new versions of eSearch and Decision Point.

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MINERAL RESOURCES ASSESSMENT AND MINERAL EXPLORATION DATA

Inventory of abandoned mine sites

Highlights and activities 2008–09

Although no abandoned mine sites were examined in the field during 2008–09, the inventory continued to provide baseline data on abandoned mining-related features for decision making by government, community, and industry.

- Priority for field inspection is given to abandoned mine sites within 10 km of major towns, 1 km of main roads and selected tourist routes, and within 5 km of smaller towns and communities. About 44% of all abandoned mine sites are in this high-priority category.
- Field data entry is via a hand-held computer linked to GPS equipment capable of locating mine site features such as shafts to an accuracy of around 10 m. At 30 June 2009, the program had completed the field inspection of 6006 (53%) of the abandoned mine sites, including 4956 (89%) of the high-priority sites.
- The data were first released publicly in mid-2003, along with Record 2003/9, which documents all aspects of the program. Subsequently the data have been released annually on DVD, including thumbnails of all digital photographs, and an increasing number of historical GSWA bulletins and geo-referenced historical maps. The *Inventory of abandoned mine sites: progress 1999–2007* DVD contains a total of 189 530 mine site features and 54 030 digital photographs.
- Since the redevelopment of the MINEDEX database system in mid-2008, the inventory of abandoned mine sites database (WABMINES) has been freely available for public searching, data extracts, and reports.

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

- In October 2008 the inventory of abandoned mine sites database (WABMINES) was spatially displayed in DMP's TENGRAPH online system.
- GSWA participated in the development of DMP's screening risk assessment database.

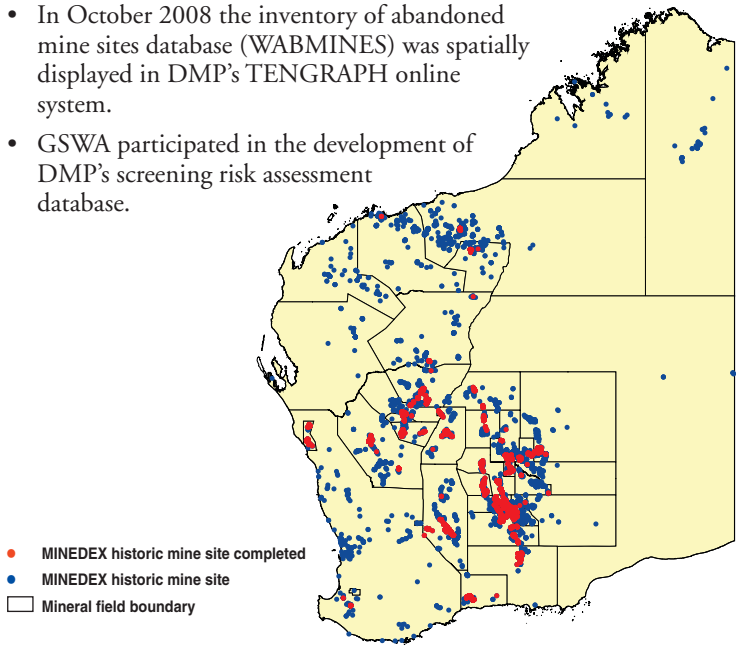

Figure 2. Status of the inventory of abandoned mine sites — MINEDEX MH sites completed as at 30 June 2009.

Future work

Continue the inventory for the high-priority abandoned sites in the Southwest region of Western Australia, and the remainder of the Yilgarn, Pilbara, and Kimberley regions.

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Figure 3. Infrastructure: First Hit mine site, Davyhurst area — collapsing remains of corrugated iron and timber buildings

Land use geoscience

Highlights and activities 2008–09

It is important to provide good geological advice to the community and government on the significance of the resource sector to the sustainable well-being of the Western Australian community and to ensure that government planning decisions do not impede resource access. The land use group provides resource assessments and thereby ensures that geological information is used in the decision-making processes of government.

Objectives: To maintain access for exploration and development of minerals, petroleum, and building materials on all lands in the State through provision of information and advice to government authorities, the resources sector, and the community. Assessments of the economic geology of areas proposed for land title and land use changes are carried out, and thereby provide advice on the impact on future exploration and resource development.

Referrals from other government departments

The group provides geological advice and comments to the Department of Planning regarding the potential impact that proposed land title and land use changes, including infrastructure expansion and development could have on future access to mineral resources. This involves resource assessments, and facilitating discussions with companies and other government agencies. In addition, comments are provided to the Western Australian Planning Commission regarding the implications of land subdivision proposals.

- During 2008–09 advice was given on 981 requests for subdivision proposals, land title or land use changes. Although this number is slightly lower than last year, it still indicates a relatively buoyant economy in Western Australia and Perth's continued urban development.

Conservation issues

- The group has been involved in policy development aimed at developing a balance between economic resource developments and managing the conservation values of resource-rich areas of Western Australia. The group continues to endeavour to develop a process whereby balanced and transparent decisions are made regarding the creation of conservation reserves, taking into account the view of all stakeholders, including those of the local communities. This is particularly important with respect to the 55 sheep and cattle stations, purchased by the Department of Environment and Conservation (DEC), whole or in part, throughout Western Australia for conversion to conservation reserves. Resource assessments of these proposed conservation reserves are continually being updated with the results of company exploration programs.
- The development of major iron ore deposits in the Yilgarn Craton has been hampered by the lack of knowledge of native flora and fauna in the mineralized areas and the intention of DEC to create Class A nature reserves. Discussions continue to take place with companies and DEC to progress exploration and proposed mining developments.

Figure 4. Drilling program at West Kalgoorlie

Community liaison

- Assistance, by way of information on geology and mineral resources, has been provided on a range of planning schemes related to Town Planning Schemes, Local Planning Strategies for local government and the Metropolitan Region Scheme.
- Conflicts between the protection of sand, limestone, clay, and titanium–zircon resources and residential development in the Perth region are typical for all expanding urban regions. Communication with town planners is important, particularly the presentation of information for the location of known deposits. The new version (second edition) of the titanium–zircon maps for the region south

of Perth, are being incorporated into planning considerations. As a consequence, the style of these titanium–zircon thematic maps will be used for maps showing the location of basic raw materials.

- In the Donnybrook area geological investigations, including mapping, are continuing to better understand the distribution of the famous Donnybrook Sandstone and to assist the local shire and the Department of Planning with appropriate land zoning to ensure sustainability of the local quarrying industry.

Planning initiatives

- With the assistance of both explorers and miners, the titanium–zircon mineral deposit mapping project in the northern part of the Swan Coastal Plain is in progress. Again these maps will be useful to planners and land owners, as well as the mining industry, as providing vectors to undiscovered mineralization.
- Limestone is an important basic raw material that has numerous applications. There is increasing demand for limestone in road construction; as a construction material, both for lime blocks and cement manufacture; mineral processing of gold ores, nickel laterite and bauxite; and as agricultural lime. However, most limestone is found in coastal areas where there is high land-use conflict, particularly due to environmental issues and residential housing development. A State lime supply strategy is progressing, with discussions between government departments continuing.
- Similar to limestone, sand is a basic raw material affected by planning issues. The shortage of sand south of Perth has resulted in the need to utilize the resources located on the Baldivis Explosive Reserve and Buffer. The group is currently working with Cemex, LandCorp and Main Roads to maximize the value to the State of this strategic sand resource and to ensure sequential use of the land for residential development. A collaborative program with Cemex is in progress to understand the geology and hydrogeology of the area and a drilling program was conducted to evaluate the quality and quantity of available sand. The air core drilling program comprised 112 holes for a total of 2050 metres and defined the structure of the unconsolidated sand deposit overlying limestone. The presence of fine gravel was identified on the eastern and western sides of the project area and possibly represents narrow north–south paleochannels or gravel beach terrace deposits.
- To determine the mineral potential of the proposed industrial land development in West Kalgoorlie and subject to the results of the drilling, to grant Ministerial clearance for Crown land to be transferred to private land an extensive rotary air blast (RAB) drilling program was managed by this group and funded by Land Corp. Seventy-seven holes were drilled for a total of 3921 metres. Results are confidential but it is likely that follow-up drilling will be required. The use of CSIRO's HyChips instrument — visible to short-wave infra-red spectrometer for scanning rock chips — assisted in the interpretation of bedrock and the regolith.
- Members of the group represent the Department on a number of intergovernmental committees dealing with basic raw materials, planning strategies, and State mineral strategies.

Geological initiatives

- Development of a management policy for the Western Australian Register of Geoheritage Sites is continuing. During the reporting period four geoheritage reserves were created for the purpose of managing ancient stromatolite fossil locations. Efforts have commenced for a similar reserve over Eranondoo Hill for the purpose of managing scientific investigations on the oldest dated zircons in the world.
- To assist in the understanding of the geology and occurrence of basic raw materials on the Swan Coastal Plain, a program is continuing to refine the geological mapping through both the merging of existing environmental geological 1:50 000 maps and fieldwork. This work will further our understanding on the impact of climate change on urban development along the coastline.

Future work

- Work on the above projects will continue as required, particularly the provision of geological information and advice, and input to regional plans, and urban, rural, and community developments.
- To assist in determining the mineral potential of areas proposed for development, drilling programs are planned in the Perth region with respect to limestone and sand occurrences.

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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 2008–09

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

Exploration performance on 1909 mineral tenements (Table 1) was reviewed during 2008–09 as part of the assessment of applications for exemption from expenditure conditions, applications for extension of term of Exploration Licences, applications for Retention Licences, applications for Special Prospecting Licences, applications for iron ore authorization under Section 111, and applications for Ministerial consent to dealings in Exploration Licences during their first year of tenure.

Since the amendments to the Mining Act were introduced in February 2006, mining lease applications received after that date can only be granted if the presence of significant mineralization has been demonstrated within the area. A mineralization report must be submitted which is then assessed by the Director of GSWA. Since the amendment, 89 mineralization reports have been assessed (42 during 2008–09). Mineralization reports that have been accepted are available for viewing on the Department's website (<www.dmp.wa.gov.au>).

Due to the strength of the world iron ore market, the number of applications under Section 111 of the Act to authorise the holder to explore for iron ore has increased substantially in recent years (654 applications in 2006–07 and 332 in 2007–08). This year, applications have remained steady at 331. There are currently 1635 tenements (up from 1133 last year) which are authorised to explore for, or mine, iron ore). Exploration expenditure for iron (from ABS figures) is close to $560 million.

There has been an ongoing interest in exploring for uranium. There are 67 active exploration projects (combined reporting groups) in the State. Expenditure on uranium exploration (from ABS figures) in 2008–09 is close to $30 million.

The number of applications for exemption from expenditure conditions received by the Department during 2008–09 has decreased to 3914 (from 4809 in the previous year). About 17% of exemption applications were refused, a similar number to last year's (18%). About 70% of applications were granted. The difference was made up by lapsed applications (tenements were surrendered before the applications could be determined).

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

Before an exemption application is finally recommended for refusal, a Departmental committee (Exemption Committee) reviews the recommendation. GSWA is represented on this committee to ensure that geoscientific issues are considered in any decision. The committee also considers whether a fine should be recommended in lieu of forfeiture where an expenditure exemption has been refused. The decision lies with the Minister and he imposed fines on 336 tenements in lieu of forfeiture during the 2008–09 period (down from 431 in 2007–08). A number of tenements (33) were forfeited.

About two years ago, the Department started to follow up breaches of Section 115A of the Act (requirement to lodge a mineral exploration report). Since then, compliance (especially in respect of a timelier lodgement of reports) has shown a marked improvement: fines for late lodgement of reports in respect to 59 tenements were imposed. Nine tenements were forfeited during the year for failure to lodge a mineral exploration report.

The number of granted exemptions seems high but most are for partial amounts. Also, the majority of exemptions are still being sought on a project basis under Section 102(2)(h). This reflects the fact that about 60% of tenements requiring reporting under Section 115A of the Act are part of projects (1055 Combined Reporting Groups in total).

Overall total expenditure on exploration and mining by industry as claimed on Form 5 Operations Reports is currently 25 times the

expenditure commitment under the Act; a 25% increase from 2007–08 to about $11 billion in 2008–09. Expenditure on mineral exploration activities (as a subset of total expenditure) increased by an impressive 65% to $1.6 billion during the same period. When looking at the figures by tenement type, increases in mineral exploration expenditure showed marked differences: expenditure on Exploration Licences increased by about 35%, whereas expenditure on mining leases nearly doubled. This shows that much of the increases in exploration expenditure were in brownfield areas.

It should be noted that due to the mode of reporting (Form 5s are generally submitted after the end of the reporting period), the expenditure figures may be up to a year behind the date expenditure was incurred.

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Figure 5. Exploration activities

Geological advice provided	Number of tenement actions					
	2003–04	2004–05	2005–06	2006–07	2007–08	2008–09
Expenditure exemption	2406	2146	1543	1310	920	1185
Extension of term of Exploration Licences	323	286	237	105	346	229
Dealings in first-year Exploration Licences	30	67	80	10	54	43
Iron ore authorization (Exploration Licences)	90	195	333	654	332	331
Iron ore drop offs (Exploration Licences)	8	15	20	36	53	66
Retention Licence applications/renewals	5	2	1	7	7	10
Special Prospecting Licence applications	6	2	1	3	10	3
Mineralization reports assessed	-	-	-	7	40	42
Total	**2868**	**2713**	**2215**	**2229**	**1762**	**1909**

Table 1. Tenement reviews

Mineral exploration reports and data

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

Highlights and activities 2008–09

- A smooth transition to the new WAMEX3 database for managing mineral exploration reporting took place in December 2008.
- A new version of WAMEX Online was introduced at the GSWA 2009 Seminar and poster display in February 2009. This new version has an increased search capacity and includes a spatial front end.
- The first annual release of Sunset Clause reports commenced in May 2009. A total of 4114 reports were available for release and of these 1611 reports have already been released. Since the commencement of report release under the Sunset Clause legislation in February 2006, approximately 17 000 reports have been released to open file.
- Scanned 1500 reports that were released to open file including 1200 reports released under the Sunset Clause.
- Scanned 2700 reports, previously only available as microfiche for release via the Web.
- During the year 3894 mineral exploration reports were received representing industry activity on 8635 tenements. The total number of reports now held in the WAMEX database stands at 68 500.

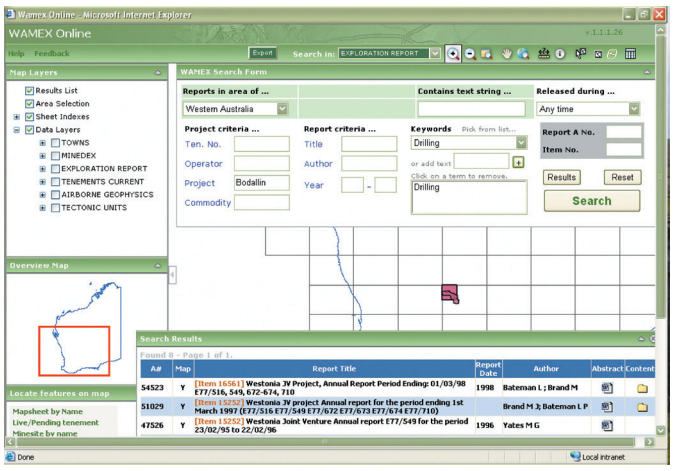

Figure 6. Screenshot from WAMEX Online

Reporting standards

All reports are now being submitted in digital format and the compliance with the standards of reporting as specified in the '*Guidelines for Mineral Exploration Reports on Mining Tenements*' continues to improve. This continuing improvement is testament to the support and training provided by staff in the section. However, there is more room for improvement, particularly in the submission of tabular data for geochemistry and drilling.

WAMEX database development

The new WAMEX3 database has additional functionality, allows more effective searching, and has direct links to the digital reports and raw data within the database itself. This has improved the efficiency of processing reports and their release to the public.

Future work

- Continue the development of the WAMEX3 database.
- Continue to improve the searching capabilities of WAMEX Online, particularly the spatial front end.
- Provide all types of mineral exploration data via the Web-based WAMEX Online.
- Continue to enforce the reporting standards detailed in '*Guidelines for Mineral Exploration Reports on Mining Tenements*'.

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Commodity and industry analysis

The Commodity and Industry Analysis group provides statistics and expert analysis on mineral exploration activity, mineral resources and reserves, and mining, for all commodities. Users of the group's outputs include other divisions of the Department of Mines and Petroleum, government agencies, industry, and the community at large. The group responds to about 400 ad hoc enquiries annually.

A key component of this service is the maintenance and enhancement of Western Australia's mines and mineral deposits information database (MINEDEX), which can be accessed via the Department's website. MINEDEX data, and products derived from it, is highly valued — the database regarded as the point of truth for information on mines and deposits, their location, compilation of mineral resource estimates, and historical production data. The database is also used to efficiently produce annual or biannual updates of a series of GSWA maps and publications. MINEDEX data are displayed in the Tengraph and GeoVIEW.WA systems, and on most maps produced by GSWA.

Highlights and activities 2008–09

- On 4 June 2008, GSWA deployed the new MINEDEX database system on DMP's website, improving access to information in the three previous systems of MINEDEX (mines and deposits), WAMIN (geology of mineral occurrences), and WABMINES (inventory of abandoned mine sites). The new web application was enhanced during 2008–09 and data within the system was updated (after the emphasis in the previous year on application development).
- Fieldwork and compilation continued of the second volume of 'Dimension stone in Western Australia', concentrating on the southern, central, and northern regions.

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

Products 2008–09

- Maintenance of the mines and mineral deposits database, MINEDEX (live via the Web)
- Miscellaneous articles on dimension stone in Western Australia (external publications)
- Industrial minerals in WA: the situation in 2008 (Record and map)
- Major resource projects, Western Australia, 2009 (map)
- Iron ore deposits of the Yilgarn Craton, 2008 (map)
- Western Australian atlas of mineral deposits and petroleum fields (A4 booklet)
- Annual overview on mineral exploration and development in Western Australia (Record)
- Western Australian mines — operating and under development, January 2009 (map)
- Iron ore deposits of the Pilbara region (map and digital product compilation in progress).

Future work

- Annual updates of some of the standard products will be prepared
- Preparation of mineral fact sheets for a suite of commodities
- Compilation of the second volume of 'Dimension stone in Western Australia' will be completed
- Additional functionality of the MINEDEX system will be deployed
- A major review of gems and semi-precious stones in Western Australia will commence.

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REGIONAL GEOSCIENCE MAPPING
Geophysics and remote sensing

Highlights and activities 2008–09

- In 2008–09, two new airborne geophysical survey projects were completed in the Balladonia and Esperance regions. A total of 395 000 line-km of airborne magnetic and radiometric data were released from these two airborne surveys and from the surveys in the Kimberley, Byro, and Dumbleyung areas that commenced in 2007–08.
- New regional gravity surveys were undertaken in the Windimurra and Cunderdin areas. A total of 9200 new regional gravity stations from the Cunderdin survey and the 2007–08 West Musgrave gravity survey were added to the National Gravity Database.
- New funding from the 2009–13 Exploration Incentive Scheme saw the initiation of nine new airborne surveys in the Eucla and Canning Basins.
- During the year 196 new airborne survey datasets, containing approximately 786 000 line-km of data, were received for inclusion in the MAGIX data repository. At the end of the year, about 6.1 million line-km of private data from 1313 surveys were held in the repository.

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

Products 2008–09

See the Figures and Tables 2 and 3.

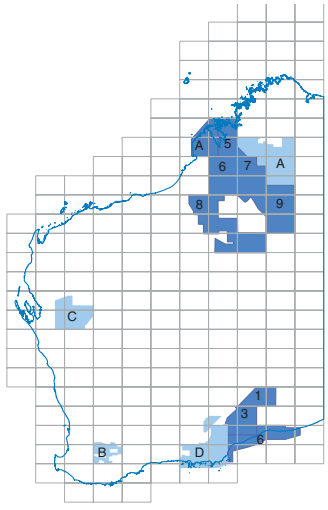
Future work

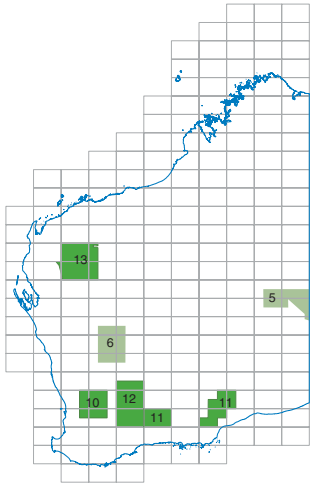
- In 2009–10, the airborne surveys being undertaken in the Eucla and Canning Basins will be completed with the acquisition and release of as much as 900 000 line-km of data.
- New gravity surveys in the Balladonia, Southern Cross, and Gascoyne areas are expected to add around 20 000 new gravity stations to the National Database. See the Figures and Tables 2 and 3.

ID	Area/Name	Size (km)	Status	Start	End	Release
Datasets released during 2008–09						
A	South Kimberley 2007	163 000	Released	Dec 07	Jun 08	20 Nov 08
B	Dumbleyung 2008	70 000	Released	Mar 08	May 08	19 Feb 09
C	Byro 2008	90 000	Released	Apr 08	Jul 08	2 Oct 08
D	Esperance 2008	84 000	Released	Sep 08	Dec 08	26 Mar 09
D	Balladonia 2008	43 000	Realesed	Dec 08	Jan 09	26 Mar 09
Surveys in progress or planned at 30 June 2009						
1	Seemore 2009	88 000	Processing	Jun 09	Sep 09	Nov 09*
2	Naretha 2009	123 000	Survey	Jun 09	Dec 09*	Feb 10*
3	Eucla Coast 2009	108 000	Contract	Sep 09*	Jan 10*	Mar 10*
4	Broome 2009	76 000	Survey	Jul 09	Oct 09*	Jan 10*
5	Yampi–Derby 2009	66 700	Processing	Jun 09	Sep 09	Dec 09*
6	Mt Anderson – McLarty Hills 2009	98 000	Survey	Jul 09	Oct 09*	Feb 10*
7	Crossland–Noonkanbah 2009	117 000	Survey	Aug 09	Nov 09*	Feb 10*
8	Central Canning 2009	92 000	Processing	Jun 09	Aug 09	Nov 09*
9	Cornish–Helena 2009	121 000	Survey	Jun 09	Oct 09*	Jan 10*

* Estimated dates. Information current at 21 September 2009

Table 2. Regional airborne geophysical surveys 2008–09





ID	Area/Name	Size (stns)	Status	Start	End	Release
Datasets released during 2008–09						
5	West Musgrave 2008	4 028	Released	Dec 07	Jun 08	7 Aug 08
6	Windimurra 2008	5 185	Released	Feb 08	May 08	20 Nov 08
Surveys in progress or planned at 30 June 2009						
10	Cunderdin 2009	7 494	Released	Jan 09	Apr 09	3 Sep 09
11	South Yilgarn Margin (2 parts)	6 500	Survey	Jul 09	Oct 09*	Dec 09*
12	Southern Cross	6 700	Planning	Jan 10*	Apr 10*	Jun 10*
13	Gascoyne North 2010	7 400	Planning	Apr 10*	Jul 10*	Sep 10*

* Estimated dates. Information current at 21 September 2009

Table 3. Regional gravity surveys 2008–09

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Lennard Shelf project

Highlights and activities 2008–09

Bulletin 145, Devonian Reef Complexes of the Canning Basin, by PE Playford, RM Hocking, and AE Cockbain, was completed during 2008–09, and released officially in early August 2009. The bulletin is a 444-page (including three paleontological appendices) guide to the field geology of the reef complexes, including more than 536 full colour figures and eight map plates — the culmination of more than 50 years work by the senior author. A field guide to the Devonian Reefs was also released.

This guide includes material from the bulletin, and additional information on geomorphological features associated with the reef complexes and the paleokarst that overprinted them during the Late Carboniferous – Early Permian glaciation of Gondwana.

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

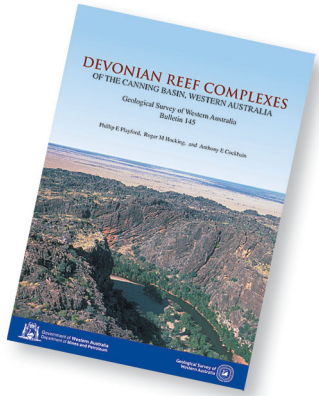

Figure 8. Cover of the Devonian reef complexes of the Canning Basin.

Products 2008–09

- GSWA Bulletin 145, Devonian Reef Complexes of the Canning Basin, Western Australia
- Record 2009/5, Guidebook to the geomorphology and geology of Devonian reef complexes of the Canning Basin, Western Australia

Future work

No future work directly related to the bulletin is planned. As time and funding permit, legacy capture of field observations may be undertaken, for incorporation in a GIS package.

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Figure 7. The Classic Face in Windjana Gorge, showing the transition from flat bedded platform on the right through massive reef facies to dipping marginal slope deposits on the left.

Pilbara Craton project

Highlights and activities 2008–09

- The second Pilbara GIS DVD, covering eleven 1:100 000 geological map sheets and including extensive geological recompilation, was released.
- Work has commenced on the third Pilbara GIS DVD, to be released in late 2010. This will provide updated geological coverage of eight additional 1:100 000 map sheets in the east Pilbara.
- In July 2008, team members led a field excursion to accompany the 2008 Australian Earth Science Convention. Various aspects of project work were described in oral presentations at this conference.
- In March 2009, two team members gave invited keynote presentations at the international geological conference Precambrian World 2009, held in Fukuoka, Japan.

Through a number of collaborative international research projects, new geological data have been obtained on the Pilbara Craton since GSWA completed mapping in 2003. Joint authorship of resulting papers has included further examination and some reinterpretation of GSWA's mapping data. This has contributed to GSWA's ongoing program of geological interpretation of the Pilbara Craton, with highlights including:

- Further evidence that the northern Pilbara Craton is composed of two fundamentally different types of Archean crust: crust formed 3.53 – 3.23 Ga (East Pilbara and Karratha Terranes) which accumulated through repeated crustal heating events (probably related to mantle plumes) and predominantly vertical deformation; and crust formed 3.23 – 2.83 Ga (Regal, Sholl, and Kurrana Terranes, and overlying sedimentary and volcanic basins) formed by horizontal tectonic processes, including continental rifting, plate separation to form oceanic crust, and subsequent convergence with subduction, arc magmatism, plate collision, and orogeny.
- Recognition that fossiliferous horizons in the 3.53 – 3.23 Ga Pilbara Supergroup correlate directly with periods of sedimentation between major ultramafic–mafic–felsic volcanic cycles. Most of these breaks in volcanism lasted only a few million years, but the highly fossiliferous Strelley Pool Formation, which separates the Warrawoona and Kelly Groups, was deposited over 75 million years, and across an area of 30 000 km^2.

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.

Products 2008–09

- Pilbara Geological Information Series, 2008 update on DVD (spanning 11 x 1:100 000 map sheets)
- 38 external papers were published, including papers in journals, and abstracts accompanying presentations at conferences.

Figure 9. Participants of the 2008 AESC Pilbara field excursion discuss an outcrop of c. 3465 Ma pillow basalt at Marble Bar Pool.

Future work

Work during 2009–10 will include:

- Release of the Marble Bar 1:250 000 map (third edition)
- Release of three Records describing results of collaborative projects with external authors
- Work for production of a 2010–11 GIS DVD covering eight additional 1:100 000 geological map sheets in the east Pilbara
- Editorial work for the 2010–11 release of three Records on collaborative projects
- Compilation of a field guide to accompany the 5IAS field excursion to the west Pilbara, August–September 2010
- Geoscientific papers in external books and journals.

Beyond mid 2010, work will continue towards completion of the Pilbara GIS database, including production of interpreted bedrock geology maps at 1:250 000 scale for the East Pilbara Terrane. Reports on the Marble Bar and Kelly greenstone belts will be compiled, in addition to Reports on the geology and mineralization of the West Pilbara Superterrane and the East Pilbara Terrane. Geoscientific papers will continue to be published in external journals.

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Earaheedy Basin project

Objective: To increase geoscientific knowledge of the Earaheedy Basin and its mineral systems, through the collection, synthesis, and dissemination of geological information. This is to be achieved through the production of a final, seamless, geological map of the entire basin and adjacent areas, together with supporting publications, both internal and external, integrating field mapping, geochronological, petrological, geochemical, and remote sensing data.

Highlights and activities 2008–09

Completion of a final report on the geology and metallogeny of the Earaheedy Basin. The Earaheedy Basin forms part of the eastern end of the Paleoproterozoic Capricorn Orogen. The Basin has an exposed extent of approximately 32 000 square kilometres and covers large areas of Nabberu, Stanley, and Kingston 1:250 000 map sheets, and extends northward and eastward beneath Mesoproterozoic, Neoproterozoic, and Permian cover. The Earaheedy Basin hosts Mississippi Valley-Type Zn–Cu–Pb, granular iron-formations that provide a substantial iron resource, as well as a number of diamondiferous lamprophyre dykes and pipes. The sedimentary rocks of the Earaheedy Basin were deposited in a continental shelf developed on the northern margin of the Yilgarn Craton. Aeromagnetic data show that Archean granite–greenstone rocks extend from the south beneath these sedimentary rocks. The aeromagnetic data were instrumental in the discovery in 2003 of the Collurabie Ni–Cu–PGE occurrence in the Gerry Well greenstone belt, beneath the Proterozoic cover of the Earaheedy Basin. Studies of the geology and mineral systems of the Earaheedy Basin have now been finalised. These studies provide a substantial body of knowledge on the geology and geodynamic evolution of the basin and associated mineral systems.

Figure 10. Mega-ripple marks in sandstone of the Chiall Formation.

Products 2008–09

An external paper was published in Earth-Science Reviews on the geology of the Earaheedy Basin.

Future work

Publication of the final report on the geology and metallogeny of the Earaheedy Basin. No further work is planned.

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Figure 11. Outcrop of Sweetwaters Well Member stromatolite carbonate.

Mineral systems studies

Studies of mineral systems are progressing in the Gifford Creek carbonatite complex, the Minnie Spring molybdenum occurrences (both in the Paleoproterozoic Gascoyne Complex) and the Abra polymetallic deposit in the Mesoproterozoic Edmund Group of the Bangemall Supergroup. These studies aim to assess the mineral potential and to integrate genetic models with regional geology and geochronological data. Work on mineral systems involves: 1) studies of individual deposits; 2) tectonic controls of mineralization; and 3) modelling of ore systems within the framework of the geodynamic evolution of host terranes. The purpose of these studies is to provide viable genetic models that can be used to improve exploration targeting in greenfield regions.

Objective: To carry out comprehensive studies of mineral systems in Western Australia with a view to building genetic models that can provide insights into the geodynamic environment of ore formation and allow a degree of predictability that can assist in exploration targeting for greenfield areas. This is to be achieved mainly through field, geochronological, isotopic and petrological work, integrated with existing databases. The information will be disseminated by means of GIS packages, internal and external publications, for the benefit of government agencies, tertiary institutions, resource companies, and the community.

Highlights and activities 2008–09

Field and laboratory work was carried out at two giant deposits:

- The polymetallic Abra deposit in the Jillawarra Sub-basin (Edmund Basin) and the Magellan lead deposit in the Yerrida Basin. Work completed to date at these deposits provided new insights on the evolution of these mineralizing systems, leading to the establishment of genetic models, which will help exploration activity in greenfield areas. Core logging, X-ray diffraction analyses, and petrographic studies of core from the Abra deposit are still underway. A sulfide sample was dated by the Re-Os method at the Department of Earth & Atmospheric Sciences, University of Alberta (Canada).
- Re–Os dating of two samples of molybdenite from the Minnie Spring molybdenum occurrence in the Gascoyne Complex was carried out at the Institute of Mineral Resources in Beijing. Age and petrographic data are being assessed.
- Field and laboratory work was also carried out in the unusual Gifford Creek alkaline complex, which is characterized by numerous ferroan carbonatite intrusions, containing rare earth elements (REE) and uranium minerals.
- A comprehensive study of large igneous provinces and associated mineral systems in Western Australia was updated with the latest data and a report is being compiled.

Products 2008–09

- Record 2009/4 Magellan lead deposit.

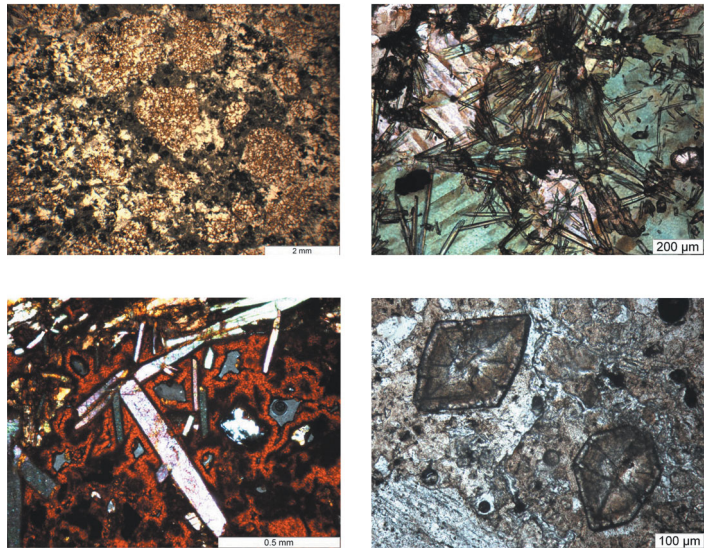

Figure 12. Photomicrographs of rocks from the Gifford Creek alkaline complex; A) Ferroan carbonatite consisting of ankerite globules, calcite blebs, and interstitial sodic amphibole; B) arferdsonite acicular crystals and sodic pyroxene plates; C) cancrinite crystals and hematite; D) Pyrochlore crystals in fenitic rock.

Future work

Studies will focus on:

- Gifford Creek Alkaline Complex, containing REE and uranium mineralization
- The Minnie Creek batholith, containing molybdenum and tungsten mineralization
- Abra breccia pipe polymetallic deposit and surrounding areas
- Field and laboratory work will continue in the Gifford Creek alkaline complex, Minnie Spring molybdenum occurrence and Abra.

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Edmund and Collier Basins project

Highlights and activities 2008–09

- During 2008–09 fieldwork and office activities have focused on detailed mapping and compilation of Bangemall Supergroup rocks on the CALYIE, TANGADEE, and MILGUN 1:100 000 map sheets.
- Edmund and Collier Basin rocks on the CALYIE and TANGADEE 1:100 000 map sheets comprise fine- to coarse-grained siliciclastic and dolomitic sedimentary rocks of the Mesoproterozoic Edmund and Collier groups (Bangemall Supergroup). The succession includes minor occurrences of felsic volcanic rocks and has been intruded by dolerite sills at 1465 Ma and 1070 Ma.
- Polymetallic mineralization at Abra is hosted by lower Kiangi Creek Formation alluvial fan deposits and the underlying Irregully Formation (low to middle Edmund Group). Stratigraphic relationships suggest that the timing of Abra mineralization coincided with a period of active growth faulting and alluvial fan sedimentation during deposition of the lower Kiangi Creek Formation.
- The Edmund and Collier Groups have been extensively deformed with regional scale folds and faulting during the Edmundian Orogeny (1030–950 Ma). Younger strike-slip faults may be part of the Mulka Tectonic Event (570 Ma).
- Felsic volcaniclastic rocks within the Ullawarra Formation on Milgun have yielded a U–Pb SHRIMP age of 1460 ± 9 Ma. Similar rocks have been mapped at the same stratigraphic level on CALYIE.
- A pilot study of gold from the Egerton and Bangemall mining centres, and Low Hill indicates that the Capricorn Orogen underwent at least two periods of hydrothermal gold mineralization during the Proterozoic, and at least one period of secondary gold formation, probably during the Phanerozoic.

Products 2008–09

- CANDOLLE, ERRABIDDY (2nd edition), and MARQUIS (2nd edition) 1:100 000 geological maps
- West Capricorn Geological Information Series: CANDOLLE, ERRABIDDY, and MARQUIS 1:100 000 sheets (digital data)
- Record describing gold mineralogy and trace element chemistry of gold deposits from the Capricorn Orogen

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

- Record describing GSWA's digital map compilation process
- Record describing GSWA's ArcGIS map compilation techniques.

Figure 13. Very large-scale trough cross-stratification in lower Kiangi Creek Formation fluvial facies, CALYIE 1:100 000 mapsheet.

Future work

Work to be carried out during 2009–10 includes:

- Mapping of Bangemall Supergroup rocks on TANGADEE and MT EGERTON 1:100 000 map sheets
- Compilation of 1st edition 1:100 000 hardcopy maps for CALYIE and TANGADEE, an updated hardcopy map for MILGUN, and a preliminary 1:100 000 map for MULGUL
- Western Capricorn Orogen Geological Information Series will be updated to include geological linework and supporting data from CALYIE, TANGADEE, MILGUN, and MULGUL 1:100 000 sheets, and explanatory notes for KENNETH RANGE, MOUNT AUGUSTUS, MOUNT PHILLIPS, and PEEDAWARRA.
- GSWA Record: Geochronolgy of the Abra polymetallic deposit
- External paper: Geochronolgy of the Abra polymetallic deposit — to be submitted to Earth and Planetary Science Letters
- Continuation of collaborative studies with Drs B Rasmussen and IR Fletcher at Curtin University of Technology, to use xenotime geochronology to provide age controls for selected sedimentary units in the Capricorn Orogen.

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Gascoyne Province project

Objective: To understand better the geological and metallogenic evolution of the Gascoyne Province by employing systematic regional mapping and associated geochemical, geochronological, geophysical, and petrological studies.

Highlights and activities 2008–09

During 2008–09, fieldwork on the Gascoyne Province rocks on Pink Hills and Candolle was completed. Highlights from the mapping include:

- Geochronological results that verify the presence of latest Archean to early Paleoproterozoic basement of the Glenburgh Terrane (Halfway Gneiss and Moogie Metamorphics) north of the Chalba Shear Zone on Yinnetharra and Pink Hills. These results are in accord with the interpretation from a magnetotelluric (MT) survey in 2006, that the Glenburgh Terrane floors the whole Gascoyne Province.
- Confirmation that the Ti Tree Shear Zone is an important Mesoproterozoic to Neoproterozoic structure that separates rocks with different metamorphic histories.
- Identification of an unusual belt of rocks on eastern Pink Hills and western Candolle that are interpreted as metamorphosed mylonitic granites. These rocks were previously considered metasedimentary rocks of the 'Morrissey Metamorphic Suite'.

In addition, in May 2008, Curtin University of Technology, GSWA and The University of Western Australia were awarded an ARC Linkage Grant to develop a new tectonothermal and mineralization history for the Gascoyne Province and Bangemall Supergroup. The project will be led by Prof. Birger Rasmussen at Curtin University of Technology, and will integrate his team's state-of-the-art SHRIMP phosphate geochronology with GSWA's field mapping.

Products 2008–09

- Release of a hardcopy map for Yinnetharra
- Staff from the project contributed to two GSWA Records; 2009/8 An approach to digital map compilation using ArcGIS software, and 2009/9 Tips and tricks for map compilation using ArcGIS software and Tablet PCs.

Figure 14. The Clever Mary Hills on southeastern Pink Hills. The ridges consist of quartzite of the Moogie Metamorphics.

Future work

Work during 2009–10 will include:

- Mapping of Lockier and Mount Sandiman
- Updating the Western Capricorn Orogen Geological Information Series to include digital data from Yinnetharra and Daurie Creek
- Production of hardcopy maps for Pink Hills, Candolle (version 2), and Daurie Creek
- Release of explanatory notes for all the lithostratigraphic units and tectonic events in the Gascoyne Province
- Manuscripts for two GSWA Records, the first dealing with the nature and significance of the 2005–1950 Ma Glenburgh Orogeny, and the second, a re-interpretation of the 1815–1770 Ma Capricorn Orogeny
- Follow-up studies on: (1) the nature and age of regional metamorphism in the central Gascoyne Province; (2) the age and petrogenesis of leucocratic granites; and (3) the ages of mineralizing events in the province, in collaboration with Prof. B Rasmussen, Dr IR Fletcher, and Dr CJ Gregory, all at Curtin University of Technology, and Dr JR Muhling at The University of Western Australia.

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West Musgrave Province project

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

Highlights and activities 2008–09

Fieldwork during the 2008–09 season focused on the mapping of the COOPER 1:100 000 map sheet. Completion of that sheet ends the main part of the first (eastern) phase of the west Musgrave mapping project. The project concentrates mainly on the high-grade gneiss related to the >1300 Ma Wirku Metamorphics, the rocks related to the c. 1300 Ma Mount West Orogeny, and the c. 1200 Ma Musgravian Orogeny, as well as the layered mafic–untramafic Giles intrusions that were emplaced into that gneissic terrain. Some of the highlights and activities over the 2008–09 period are listed below.

- Mapping of COOPER was completed and mapping of Mount Eveline commenced. COOPER is of particular interest in that the orthomagmatic Nebo-Babel Ni–Cu deposit is located in the central part of that sheet.
- Compilation of Finlayson was completed.
- U–Pb SHRIMP dating of detrital zircon in paragneiss from the >1300 Ma Wirku Metamorphics established slight, but persistant and significant, differences in detrital age populations between various regions of the west Musgrave Province. This has corroborated earlier suggestions that the west Musgrave Province can be subdivided into at least three different lithotectonic zones, with faulted boundaries established at least by the c. 1200 Ma Musgravian Orogeny. These zones include the Walpa Pulka zone, to the northeast, the northwest-trending Tjuni Purlka tectonic zone, and the Mamutjarra zone, to the southwest.
- U–Pb SHRIMP dating of a Cu-mineralized gabbro from the northwestern margin of the Jameson intrusion gave an age of 1067 ± 8 Ma, which is identical to the age of gabbros that host mineralization at Nebo-Babel, and is significantly younger than the main massive gabbros (c. 1075 Ma) and layered intrusions (>1078 Ma) that form the bulk of the Warakurna Supersuite.
- Two BSc. Honors students from the University of Adelaide completed projects looking at structural and metamorphic aspects of the c. 550 Ma Pertermann Orogeny and metamorphic conditions during the c. 1200 Ma Musgravian Orogeny.

Products 2008–09

- HOLT and BLACKSTONE 1: 100 000 Geological Series maps
- BATES and BELL ROCK (2nd edition) 1: 100 000 Geological Series maps
- West Musgrave Geological Information Series, 2009 update
- Record 2008/19 West Musgrave Province — new geological insights from recent mapping, geochronology, and geochemical studies
- Regional gravity data (2.5 km^2 grid) covering the entire project area (ten and a half 1:100 000 map sheets)

Future work

The following work is planned for 2009–10.

- The release of FINLAYSON and a further release of the West Musgrave 1:100 000 Geological Information Series package
- Completion of the compilation of COOPER
- Mapping of MOUNT EVELINE will continue
- BSc. Honors theses, as part of collaborative works between GSWA and the University of Adelaide, will be published as Records 2009/12–15
- Record — Age and geochemistry of the Alcurra Suite in the west Musgrave Province and implications for orthomagmatic Ni–Cu–PGE mineralization during the Giles Event
- Record — Geochemistry, geochronology, and petrogenesis of Mesoproterozoic felsic rocks in the west Musgrave Province, central Australia, and implications for the Mesoproterozoic tectonic evolution of the region.

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East Yilgarn project

This program focuses on the Eastern Goldfields Superterrane and the southern part of the Southern Cross Domain of the Youanmi Terrane in the Yilgarn Craton.

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

Highlights and activities 2008–09

- In the northeast Yilgarn Craton, compilation of the Strawbridge, Mulgabiddy Creek, Dorothy Hills, and Toppin 1:100 000 map sheets was completed, and compilation of the adjacent Jutson, Yamarna, and Lightfoot 1:100 000 map sheets was substantially completed. The new mapping, complemented by newly acquired geochronological and geochemical data, has resulted in the subdivision of the original Burtville Terrane in the northeast Yilgarn Craton into an older (>2710 Ma) greenstone terrane (the newly defined Burtville Terrane), and a younger (<2710 Ma) greenstone terrane (the Yamarna Terrane). Greenstones in the Burtville Terrane appear to have affinities with greenstones in the Youanmi Terrane in the western part of the Yilgarn Craton, while the younger rocks of the Yamarna Terrane are similar in age to, and may have affinities with, rocks in the Kalgoorlie Terrane to the west. This subdivision has significant implications for the likely distribution of gold, nickel, and base-metal mineralization in the region.
- New field mapping in the southern part of the Youanmi Terrane, with initial work in the Southern Cross and Lake Johnston greenstone belts.
- Collaboration with CSIRO on applications of the new Hychipper spectral scanning technology.
- Collaboration with Monash University and Gold Fields Ltd on a new study of the architecture of several late basins in the Eastern Goldfields, and its significance for gold mineralization.
- Results and interpretations based on recent mapping in the northeast Yilgarn Craton were presented at the 2008 Australian Earth Sciences Convention in Perth.
- GSWA in Kalgoorlie continues to provide advice and information to the general public, mining companies, and others about the geology of the Eastern Goldfields and adjacent areas.

Figure 15. Mount Charlotte goldmine

Products 2008–09

- East Yilgarn 1:100 000 GIS digital package, 2009 update
- GSWA Annual Review paper: The Yamarna Shear Zone: a new terrane boundary in the northeastern Yilgarn Craton?
- Structural and metamorphic controls on gold through time and space in the Central Eastern Goldfields Superterrane — a field guide (Australian Earth Sciences Convention).

Future work

- Publication of first-edition 1:100 000-scale map sheets, GIS layers, and explanatory notes for the new mapping in the Burtville and Yamarna Terranes in the northeast Yilgarn.
- Development of a stratigraphy-based interpretation of the geology of the Eastern Goldfields Superterrane utilizing the now-complete 1:100 000-scale mapping coverage and the most recent geophysical data. This project will also make use of new geochronological and geochemical data obtained through various pmd*CRC, AMIRA, and MERIWA projects.
- Continued mapping in the southern part of the Southern Cross Domain of the Youanmi Terrane. New 1:100 000-scale mapping will be published as hard-copy maps and in a GIS product.

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Youanmi Terrane project

This program focuses on the Murchison Domain and northern part of the Southern Cross Domain of the Youanmi Terrane in the Yilgarn Craton.

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

Highlights and activities 2008–09

- Publication of new stratigraphy for the northern part of the Murchison Domain of the Youanmi Terrane, Yilgarn Craton.
- Completion of field mapping on the Cue and Reedy 1:100 000 sheets.
- Commencement of field mapping on the Reedy, Nowthanna, and Wynyangoo 1:100 000 sheets.
- Data compilation and field mapping on the large layered mafic–ultramafic intrusions (the Windimurra, Narndee, and Youanmi Igneous Complexes) in the eastern part of the Murchison Domain. New mapping and geochronological work has been able to demonstrate that these intrusions represent a major magmatic pulse that is coincident with one of the volcanic cycles identified in the more broadly regional mapping studies.
- Results and interpretations based on recent mapping in the central and western parts of the Yilgarn Craton were presented at the 2008 Australian Earth Sciences Convention in Perth.

Figure 16. Geochronologist using a portable XRF device to determine zirconium content in a dyke in the Murchison region.

Products 2008–09

- Central Yilgarn 1:100 000 GIS, 2008 update
- Tieraco, Koonmarra, and Madoonga 1:100 000 geological series maps
- GSWA Annual Review paper: A new lithostratigraphic scheme for the northeastern Murchison Domain, Yilgarn Craton
- Kalgoorlie, Youanmi and Narryer Terranes of the Yilgarn Craton — a field guide (2008 Australian Earth Sciences Convention).

Figure 17. Granite outcrop in the Murchison region.

Future work

- Continuation of field mapping in the Meekatharra–Wydgee greenstone belt to complete mapping on the Meekatharra, Gabanintha, and Nowthanna 1:100 000 sheets
- New mapping in the Meekatharra–Wydgee greenstone belt on the Wynyangoo, Austin, and Mount Magnet 1:100 000 sheets
- Continuation of mapping over the Windimurra, Narndee, and Youanmi Igneous Complexes including parts of the Wynyangoo, Woodley, Challa, Windimurra, Coolamaninu, Youanmi, Bungar, and Malgar 1:100 000 sheets
- Collaborative project with Dr Ben Goscombe of the University of Adelaide to generate a detailed metamorphic map and GIS layer, along with associated analytical data, over the whole of the Yilgarn Craton. Data collection commenced in 2008–09, and will cover the Murchison Domain in 2010.

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SCIENTIFIC, TECHNICAL, AND FIELD SUPPORT
Chief Geoscientist and Terrane Custodianships

Highlights and activities 2008–09

Ongoing work is related to quality control, geological consistency, database development and direction, and capture of legacy data in current and future mapping areas. A significant portion of workflow is devoted to review and approval of manuscripts, maps, and digital products. Cataloguing and spatial referencing of stromatolite specimens in the GSWA Fossil Collection commenced in 2008–09.

Expansion and validation of the geological content in the MS Access prototype of the Western Australian Geology Online database has continued, with the goal of assembling a significant, validated, consistent dataset that will be used to test the forthcoming production version of the database. Extractions from the database prototype are now routinely used to construct look-up tables that accompany digital GSWA products. To meet the need for a hardcopy form of Explanatory Notes prior to the release of the production version database, an extraction routine to combine and format data from spreadsheets and prototype forms has been developed and is being tested for the Gascoyne and Musgrave projects.

Work on the Albany–Fraser Orogen is now focused on the eastern half of the orogen looking at margin relationships with the southeastern Yilgarn Craton. Geophysical data interpretation has been combined with field studies and a substantial geochronology and geochemistry program.

Team members are working on ARC Linkage projects on the late basins of the eastern Yilgarn Craton and their relationship to mineralization and on chronostratigraphic correlation in Devonian reef complexes of the northern Canning Basin focused on describing and sampling platform facies. They are also involved in the development and implementation of 3D interpretive methodologies in GSWA.

Products 2008–09

- Record 2007/13 Interpreted Bedrock Geology of the South Yilgarn and central Albany–Fraser Orogen, Western Australia. Report relating to the South Yilgarn Geological Exploration package, including new interpretations and geochronology.
- Geoscientific papers in external journals and public presentations.

Objectives

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

Future work

The 2009–10 period will see progress towards a populated, public version of the virtual geology database and its front end, Western Australian Geology Online. The Chief Geoscientist's team is responsible for validation and consistency of this database, and the design and development of the new-style Explanatory Notes. Interim Explanatory Notes drawn from the trial database will be released, along with Records providing geological overviews and progress reports.

A planned Geological Exploration Package covering the Eastern Albany–Fraser Orogen and southeastern Yilgarn margin will include a new interpreted bedrock geology map based on field studies, targeted geochronology, geophysical data, and legacy data capture, and new imagery from geophysical data that is either currently being collected, or has recently been released. A new program of geochemical and isotope data collection has also begun, which will help define the rock suites and their evolution.

Still planned is a revised State 1:2 500 000 geology map in both digital and hard copy formats, to be derived from the released State 1:500 000 interpreted bedrock geology and regolith digital map layers — resources were not available to progress this map significantly in 2008–09. The 1:500 000 linear structures digital map layer needs revision and alignment with the current 1:500 000 interpreted bedrock geology and tectonic units layers. A revised 1:2 500 000 tectonic units layer will follow on from the 1:2 500 000 bedrock geology and linear structures layers.

Work related to quality control, uniformity of approach and data coverage, and state-wide issues will continue for the foreseeable future. Incremental updates of the 1:500 000 interpreted bedrock geology layer will continue as new mapping is completed in project areas. Review of GSWA manuscripts and graphic products will continue as usual, to maintain the quality and consistency of GSWA products. Advice will be provided to GA and other state geological surveys, and to academic researchers for a coordinated approach to national geoscience initiatives, and for geological terranes that extend across state borders.

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Geochronology

Highlights and activities 2008–09

Western Australia is principally composed of Precambrian rocks; hence few lithologies contain biological material suitable to place precise age constraints on rock units. Thus, the use of isotopic techniques to date rocks and minerals is of significant importance for understanding stratigraphic relationships and ages of mineralization. In particular, the zirconium-bearing minerals zircon and baddeleyite, and phosphate minerals monazite and xenotime, are suited to dating by the U–Th–Pb decay system. The Sensitive High-Resolution Ion Microprobe (SHRIMP) at Curtin University is used to date these minerals at high spatial resolution, supported by world-class mineral separation facilities at GSWA's Carlisle laboratory. So far, in excess of 800 dates have been produced in support of GSWA's geoscience programs.

In 2008–09, over 100 samples were processed at GSWA's laboratory for SHRIMP dating, and more than 90 samples were dated by ion microprobe. These samples are in large part supporting GSWA programs in the west Musgrave, Murchison, Eastern Goldfields, Capricorn Orogen, Albany–Fraser Orogen, and southeast Yilgarn Craton. The effect on geological knowledge of progressively collecting geochronological data is illustrated by progress made in the west Musgrave. Mapping in this area commenced in 2004, and by the end of 2008–09, SHRIMP geochronology has been completed on more than 70 samples, providing new insights into both geological and mineralization events. For example, it has been generally thought that Ni–Cu–PGE mineralization at the Nebo-Babel prospect corresponds to the c. 1075 Ma Giles event. However, SHRIMP U–Pb dating of a copper-mineralized dyke indicates that this type of mineralization is probably confined to a narrower and younger time period closer to 1067 Ma.

Although SHRIMP U–Pb dating of zirconium-bearing minerals provides important age constraints, separation of the dated minerals destroys any textural relationships. The in-situ dating of phosphate-bearing minerals by SHRIMP (e.g. allanite, monazite) offers textural control that enables relationships between deformation and mineral growth to be understood and allows mineral grains below the size limit for hand picking to be dated. GSWA has collaborated with staff and research students at Curtin University and the University of Adelaide, extending its dating program using this approach. This has led to new understanding of tectonic events in the Gascoyne Province and Bangemall Supergroup in the Capricorn Orogen.

Objectives: To acquire precise and accurate geochronological data, in order to date geological events, hence better understand the geological history (including the timing and process of mineralization) of the State. This information has a direct bearing on enhancing mineral prospectivity.

Apart from providing direct evidence of crystallization ages, zircon grains can also be used to elucidate the isotopic composition of the magma from which it crystallized through the Lu–Hf isotopic system. Laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) can be used to determine the hafnium isotope composition of zircons from the same position that has been previously dated. Thus, for single zircon grains that preserve evidence of several different geological events, corresponding hafnium isotope data can be generated, producing time-composition relationships. These hafnium isotope data are a complement to whole-rock neodymium isotope data that have proven valuable in delineating different crustal age domains on a regional scale. Acquisition of the Lu–Hf data requires no additional sample preparation and adds value to existing collections.

The success of the GSWA geochronology program can be gauged by the high level of use of geochronology data in nearly all survey project areas, and the requirement by industry and academia that these data are made available as soon as possible. Accordingly, GSWA continues to explore and develop new Web-based delivery systems for its geochronology, extending the current GeoVIEW.WA system. Reports generated in a standard format for each sample that is dated are available on the Department's Website at <www.dmp.wa.gov.au/geochron>.

Products 2008–09

- Compilation of geochronology information 2009 update (on CD)
- Record 2008/19 The west Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies
- Record 2009/10 Interpreted bedrock geology of the southern Yilgarn and central Albany–Fraser Orogen, Western Australia.

Future work

- Acquisition of geochronology data in the Murchison Province, northeastern and southeastern Goldfields, Southern Cross domain, west Musgrave, east Yilgarn / Albany Fraser and Capricorn Orogen.

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Geochemistry

Highlights and activities 2008–09

- Discussions with representatives from both industry and academia have shown that there is increasing usage of GSWA's online geochemical data delivery system (Geochem Extract), which was activated in June 2008.
- The available data in September 2009 comprise 27 905 individual analyses drawn from 108 1:250 000 map sheets, compared to 19 418 analyses in September 2008, representing a 43% increase in available data over the 12-month period.
- In 2008–09, the database structure was expanded to allow the capture of neodymium isotope data. Regional compilations of these data for the Yilgarn Craton, compiled by Geoscience Australia (GA), have been effective in outlining different age crustal domains, some of which are related to mineralization. Currently, GSWA's geochemical database contains 349 neodymium isotope determinations on a variety of rock types, in large part from the Pilbara Craton and west Musgrave area. All these data are available online through Geochem Extract.
- The majority of whole-rock geochemical analysis has involved the determination of major, trace, and rare earth element chemistry by X-ray fluorescence (XRF) spectrometry, and inductively coupled plasma mass spectrometry (ICP-MS) at GA's laboratory. In 2008–09, 477 samples were sent to GA for analysis.
- Two hundred and seventy one additional samples have been analysed by Perth-based commercial laboratories. These samples were either visibly mineralized, suspected of being mineralized, or contained concentrations of species that are not determined by GA (e.g. precious metals).
- Regional-scale multi-element geochemical analysis of regolith from different parts of the State has been a feature of GSWA's geochemistry program. Refining the analytical approach to regolith has become more important, as GSWA's programs increasingly focus on greenfield areas, where regolith cover is thick and heterogeneous. In these cases, there is a higher probability that regolith at the surface does not preserve as much information about the underlying bedrock, compared to areas where the regolith is thin and of more uniform composition.
- To further understand how regolith chemistry can help in mineral exploration, a variety of regolith samples from the southeastern part of the Yilgarn Craton and Albany–Fraser Orogen have been examined in terms of different grain size fractions and analytical approaches.
- In late 2007–08, GSWA acquired a field-portable X-ray fluorescence (XRF) analyser. Throughout 2008–09, this equipment has been widely used by different groups within GSWA to screen samples for geochronology (i.e. selecting the samples with the highest Zr content, in order to maximize zircon or baddeleyite yield), evaluate likely parent rock compositions from saprolite and saprock, and determine the level of mineralization in fine-grained lithologies. Improvements in field-portable XRF hardware and software have meant that analysis of lower atomic number members of the periodic table ('light elements') including P, Mg, Al, and Si is now possible. In order to ensure that field-portable XRF technology is fully utilised in GSWA, it is necessary to monitor changes in both the hardware and software associated with this technology.

Objectives: To generate and collate geochemical data for both regolith and bedrock throughout the State, and disseminate these data from a central repository in order to enhance prospectivity.

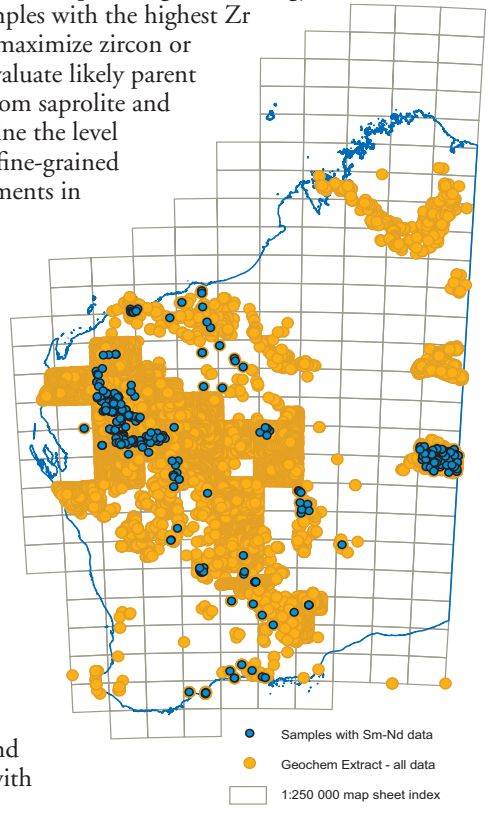

Figure 18. Results of data from Geochem extract, September 2009.

Products 2008–09

- Record 2009/7 Field-portable X-ray fluorescence analysis and its application in GSWA

Future work

- Incorporation of open-file geochemistry in GSWA's geochemical database, and making these data available via Geochem Extract
- Publication of a record on the geochemistry of different grain size fractions and analytical approaches for regolith.

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Biostratigraphy and paleontological services

Objective: To provide biostratigraphic, paleoenvironmental, paleobiological and paleontological 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 2008–09

- Digital data entry of miscellaneous macrofossils and the stromatolite collection is in progress. The stromatolite database already lists some 1500 specimens from nearly 1000 localities in Western Australia and also includes significant sites (such as type localities) from other parts of Australia for comparative purposes. There are still about 500 more records to be entered, and as with the Phanerozoic macrofossil collection, the tracking down of collecting sites is time-consuming. Nevertheless, the effort is worthwhile as preliminary results from the Neoproterozoic record have allowed the identification of key taxa useful for correlation (Fig. 19). When used in conjunction with palynological markers (Fig. 20) and stable isotope chemostratigraphy, considerable progress has been made on Australia-wide correlation. Biostratigraphic correlation has proved particularly valuable for this late Proterozoic succession that is poorly constrained by geochronology, but which has considerable hydrocarbon potential. The biostratigraphic model will be thoroughly tested in the next 12 months as the western Amadeus Basin project gets underway. Will the stromatolite succession determined for the Officer, central Amadeus, and Georgina Basins match predictions?
- Visiting scientists have been fewer this year, probably reflecting the global financial crisis and subsequent reduction in funding. However, the level of requests for information from both academics and industry remains high and covers a diversity of topics ranging from Archean stromatolites and microfossils, through late Proterozoic biostratigraphy to modern lacustrine and marine stromatolite environments. The section continues to provide advice on the export of fossils and rocks, and, in connection with efforts to protect some of the State's most vulnerable and significant geoheritage sites, a management plan is being prepared for several newly created State Geoheritage Reserves.
- Spindle-shaped and spheroidal microstructures were extracted using palynological techniques from <2.9 Ga black chert in the Farrel Quartzite of the northern Pilbara, adding considerably to other evidence that these structures are biogenic. Results were presented at a 'World Summit on Ancient Microfossils' held at the University of California, Los Angeles, a visit funded by UCLA. The financial assistance provided made it possible to also visit the University of California, Santa Barbara, to continue work on the microbialite handbook (nearing completion), and to Uppsala University in Sweden to run an international workshop on Neoproterozoic acritarchs, with the aim of improving international correlation.

Products 2008–09

- Record 2009/11 Microbialites of Lake Thetis, Cervantes, Western Australia — a field guide
- A review of Neoproterozoic glacial successions in central Australia

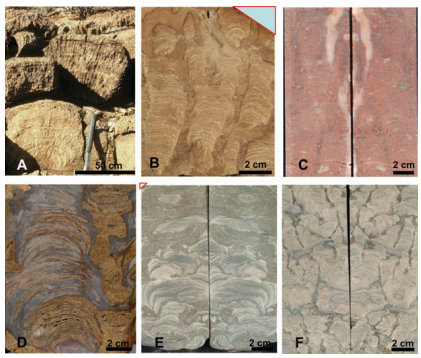

Figure 19.

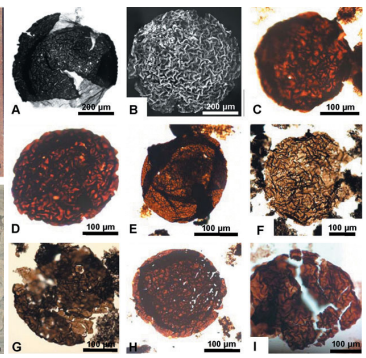

Figure 20.

Figure 19. ***A–C,* Acaciella australica*, A. outcrop, Skates Hills formation, Skates Hills, Officer Basin; B, polished slab, Jay Creek, Amadeus Basin; C, drillcore split, Lancer 1, Officer Basin. D–F,* Baicalia burra*; D, outcrop, upper Buldya Group, Lake Throssell, Officer Basin; drillcore splits; E, Kanpa Formation and F, Steptoe Formation, Empress 1A, Officer Basin. First appearance of* B. burra *and associated taxa at c. 750 Ma.***

Figure 20. ***A–I,* Cerebrosphaera buickii*. A, B, Spitsbergen, Svanbergfjellet Formation (photo N Butterfield); Officer Basin, Hussar Formation C, Empress 1A; D, Lancer 1 and E, Pirrilyungka Formation, Vines 1; Stuart Shelf, F, Skillogalee Dolomite, BLD 4; G, Anama Siltstone, PP12; Amadeus Basin, H, 'Finke beds', Wallara 1; Grand Canyon, I, Chuar Group (photo S Porter). First appearance of* C. buickii *at c. 705 Ma.***

Future work

- Preparation of more than 22 manuscripts on a range of topics continues and several should be submitted in the next 12 months.
- Analysis of stromatolite samples from the western Amadeus Basin is underway.
- Paleontological collection and database work will continue.

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Logistics support and core library services

Perth and Kalgoorlie core libraries

The downturn in the resources industry has not affected the Perth Core Library, which has been at near full capacity for most of the year. Due to the ongoing high workload, a new full-time staff member was employed. Offshore petroleum exploration clients continue to maintain a high demand for viewing and/or sampling of core and cuttings in the Perth facility. A steady number of industry clients and research groups are also using the Kalgoorlie core library facilities.

The new HyLogger, one of six instruments funded by AuScope to be provided to Australian Geological Surveys, was installed at the Perth Core Library and began its commissioning phase at the end of the year. An earlier version has been successfully trialled in the Kalgoorlie Core Library, with results gaining acclaim from local industry. The HyLogger system uses a visible and infrared spectrometer and high-resolution camera to log drillcore at a rate of up to 500 m per day. All data from these instruments will feed into a national database to form a National Virtual Core Library.

During the year, a total of 1618 clients viewed and/or sampled core or cuttings at the Perth and Kalgoorlie facilities. Clients spent a total of 7181 hours viewing core and cuttings and took 3168 samples. Over 70 km of core and 307 ditch cutting boxes were accessed by these visitors. A total of 6880 metres of core, 2825 boxes of cuttings and 992 sidewall cores were accessioned into the collection.

Field logistics

The specialized 4WD fleet continues to satisfy all divisional field transport requirements. Air transport between Perth and regional centres for breaks during the field season ensures efficient use of the fleet.

Additional field assistants required for field mapping programs continue to be sourced from an employment agency, allowing flexibility in meeting short-term needs for field staff. Two permanent field staff moved to other areas of government and one position was filled.

Continuous improvement of work practices and training remain a priority for field safety. High Frequency radios have been installed in all field vehicles, and at the Carlisle base station leading-edge HF technology is used including Automatic Link Establishment. All field staff are also issued with a satellite telephone and personal EPIRBs. Vehicle tracking units using satellite technology have also increased the safety of field staff.

GSWA publication store at Carlisle continued to supply Reports, Bulletins, and other publications and maps to the point of sale at the Information Centre in Mineral House. A total of 21 749 publication items were dispatched from Carlisle to the sales counter on the first floor of Mineral House.

Objectives:

- To manage core library facilities in Perth and Kalgoorlie to service the needs of industry, researchers and GSWA
- To manage field support services, including the provision of transport and other equipment, field assistants and communication links for all GSWA field parties
- To manage inventory services for all GSWA publications.

Figure 21. Drillcore ready for viewing at Carlisle.

Figure 22. Storage of drillcore at Carlisle.

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National Virtual Core Library (HyLogger)

Highlights and activities 2008–09

GSWA is the repository for more than 200 kilometres of mineral and petroleum drillcore, which is held in either its Perth or Kalgoorlie core libraries. This valuable resource is continually added to by submission of material required by law under the *Mining Act (1978)*, and by the co-funded drilling program which forms part of the Exploration Incentive Scheme.

GSWA, along with other Australian State and Territory geological surveys, is a participant in the National Collaborative Research Infrastructure Scheme (NCRIS) 'Structure and Evolution of the Australian Continent' known as AuScope, in particular the National Virtual Core Library (NVCL) component. The NVCL project will deliver high resolution pictures and mineral composition data for drillcore throughout Australia, thereby providing important information on the upper two kilometres of the Australian continent. These data are generated by a new and innovative spectral scanning system developed by CSIRO, known as HyLogger. Data generated from the NVCL project will be available via the Web, providing worldwide accessibility to this important information.

A primary goal of the NVCL project is to improve the objectivity of drillcore logging, and increase the amount and quality of information (and thus the value) returned from drilling. HyLogger is a new, highly automated logging method designed by CSIRO to determine core and chip mineralogy using rapid reflectance spectroscopy, where derived mineral spectra are compared to a spectral library, resulting in identification of mineral species. The HyLogger system uses a visible and short-wave infrared spectrometer and high-resolution camera to log drillcore at a rate up to 500 metres per day. These data can provide new insights into alteration mineral assemblages, vectors to mineralization, objective determination of lithostratigraphic units and their boundaries, and refined inputs to resource block modelling and mineral processing characteristics. The resulting databases thus provide a valuable resource for the study of historic mining operations, and classic mineral deposit styles and characteristics.

The HyLogger 2-2 was built at CSIRO in Sydney and was delivered to the Perth Core Library in July 2009. A custom-built container was design to accommodate the HyLogger and provide a dust-free and temperature-controlled workspace. Preparatory work involved induction to the HyLogger operating system using the CSIRO HyChips at the Kalgoorlie core library in March 2009, and compilation of a list of drillcore (both mineral and petroleum) that could be used to test the HyLogger technology, and demonstrate its use. Prioritization of core to be scanned was made to support mapping and research projects undertaken by GSWA on representative geotransects through important metallogenic provinces and mineral deposits.

Objectives: To provide high resolution imagery and mineralogical data for drillcore throughout Western Australia using HyLogger technology.

Figure 23. The GSWA HyLogger 2-2

All results are kept on the instrument hardware and departmental intranet and will be released through the AuScope database next year.

Future work

- Acquisition of spectral data from petroleum core in the Canning Basin to provide objective information of lithostratigraphic units that can assist in exploration targeting in the area.
- Analysis of core provided as part of the Co-funded Drilling Program (EIS).
- Scanning of historical Capricorn Orogen drillcore to increase the knowledge of alteration mineralization styles in the area that can provide insights into the fluids source and vectors to gold mineralization.
- Scanning of core relevant to current GSWA projects.

Commissioning of a Thermal Infrared (TIR) spectrometer will take place in April 2010, which will increase the range of target minerals.

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Geoscience information

Products 2008–09

The Geoscience Information Branch continued to produce high-quality geological and geophysical maps, printed and digital reports, and digital data packages (see Appendix Planned achievements and publications released for details of products).

Geological and geophysical maps

31 maps and images at various scales were published including:

- 14 1:100 000 and 250 000 geological series maps
- 17 project maps and geophysical images at various scales.

Geoscientific digital data packages

- 19 geoscientific digital data packages were released including digital datasets, miscellaneous data packages, and exploration packages.

Geoscientific publications

- 26 manuscripts were edited, illustrated, and published including Records, Reports, Bulletins and non-series books.

External publications

- 119 external publications (journal papers, abstracts) were published.

Airborne magnetic and radiometrics line-km

- 398 470 line-km were flown.

Objectives:

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

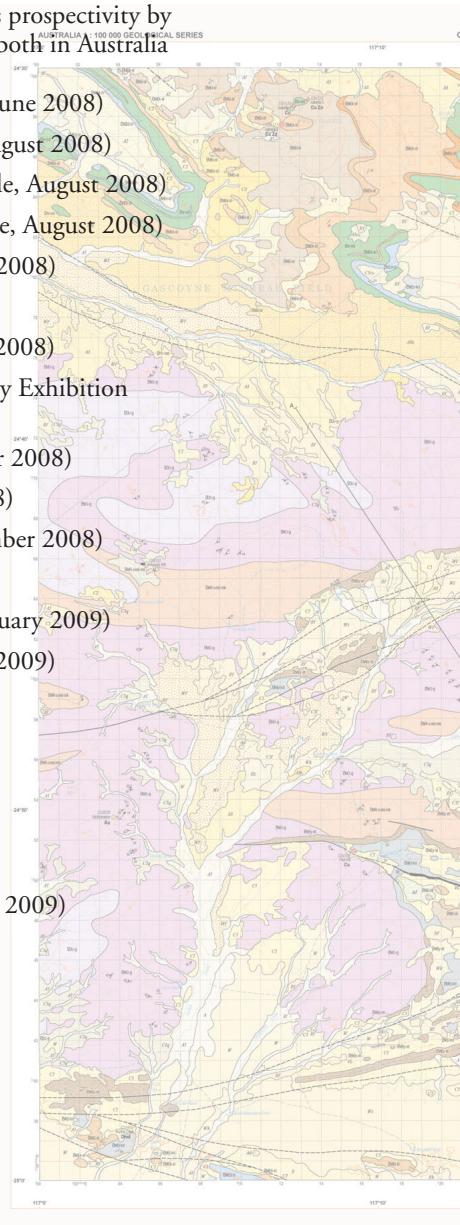
Other activities

Promotional activities

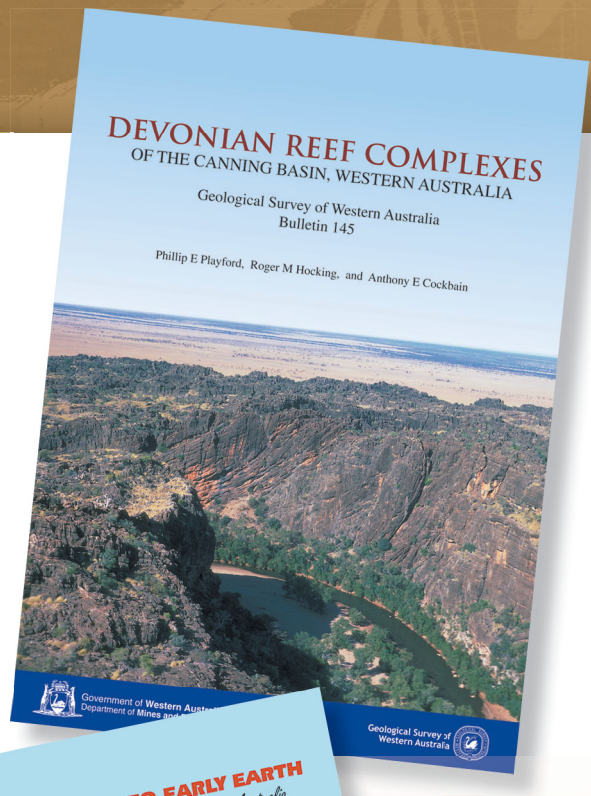
Publication of *Fieldnotes* (the GSWA quarterly newsletter) continued during 2008–09 and provided a medium for informing customers about our activities, and promoting newly released maps, publications, and datasets. During the year, advertisements and short articles publicizing the release of GSWA's products were placed in a number of newspapers, industry magazines, and journals, and ad hoc email newsletters were used to inform interested customers of recent and imminent releases and GSWA events. In particular, the branch released the long-awaited Bulletin 145 Devonian Reef Complexes of the Canning Basin with a ministerial launch. The branch also held its regular technology training sessions for internal and external clients every two months to provide information on DMP website, WAMEX, MINEDEX, WAPIMS, and GeoVIEW.WA.

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

- Australian Earth Sciences (Perth, June 2008)
- Diggers & Dealers (Kalgoorlie, August 2008)
- Geotourism Conference (Fremantle, August 2008)
- Australian Geothermal (Melbourne, August 2008)
- Good Oil (Fremantle, September 2008)
- Nickel (Perth, October 2008)
- Mining 2008 (Brisbane, October 2008)
- International Mining & Machinery Exhibition (Kolkata, November 2008)
- China Mining (Beijing, November 2008)
- PETEX (London, November 2008)
- Mines & Money (London, December 2008)
- NAPE (Houston, February 2009)
- Explorers Conference (Perth, February 2009)
- Tokyo Seminar (Tokyo, February 2009)
- PDAC (Toronto, March 2009)
- APPEX (London, March 2009)
- NW Expo (Broome May 2009)
- AMEC (Perth, May 2008)
- APPEA (Darwin, June 2009)
- Tight Gas Alternative (Perth, June 2009)



Program review



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

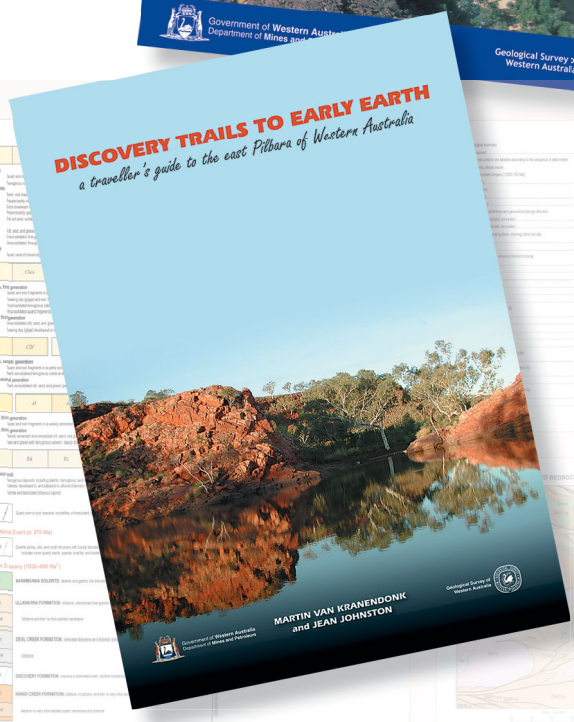
- Petroleum Open Day — showcasing recent work by DMP and issues of interest to petroleum explorers (Perth, September 2008)
- GSWA 2009, which was again held in February to hook up with the RIU Explorers Conference conducted at the same venue in Fremantle.

In 2008–09 GSWA continued to improve its provision of data online by introducing a new geochemistry download service on the Internet. This new online facility allows clients to download geochemistry data that is available for a given 1:100 000 map sheet or by project area. Clients have the ability to download geochemistry data for Western Australia.

In addition, we have continued to add new map sheet data and other datasets to the GSWA Data and Software Centre as they become available. Google Earth, KML\KMZ files, and ESRI SDE export files have been included with the MapInfo TAB files, ESRI shape files, and CSV files already available.

GSWA publications and WAMEX reports continued to be scanned and uploaded to GSWA's new online document-delivery system. At 30 June 2009, the system contained 48 464 WAMEX online reports and 4345 GSWA publications for a total of over 69 Gb of online data.

Figure 24. Director General Richard Sellers and Hon Norman Moore at the launch for Bulletin 145.



Future work

The following products and projects are planned in 2009–10:

- 31 publications
- 22 maps
- 14 digital data packages
- Publish Key Markup Language (KML) and Web Feature Service web services for a range of geoscientific datasets
- Redevelop GeoVIEW.WA in new technology and provide mapping facility.

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EXPLORATION INCENTIVE SCHEME (EIS)

Highlights and activities 2008–09

The Exploration Incentive Scheme (EIS), funded from the Royalties for Regions initiative, is a major five year $80 million scheme that commenced in April 2009. A full description of the scheme is provided elsewhere in this Review. The Scheme comprises six programs with the following broad themes:

- Program 1 Exploration and environmental co-ordination
- Program 2 Innovative drilling
- Program 3 Geophysical and geochemical surveys
- Program 4 3D geological mapping
- Program 5 Promoting strategic research with industry
- Program 6 Sustainable working relationships with Indigenous communities.

These programs are further subdivided into a total of 20 activities which are managed as independent projects with dedicated teams and specific funding. As the scheme commenced in April, 2008–09 expenditure was only $2.1 million. Highlights of the year were as follows:

- The Mining Tenement Application and Approvals Tracking Maintenance Module (for internal DMP use) was integrated with eMiTS (mining tenement register) and went into production on 25 June 2009. This allows DMP officers to track the approval of mining tenement applications online and will form the basis of an application on DMP's website that will allow tenement applicants to track their applications through the approvals processes within DMP.

Objective: To increase greenfields exploration and new mineral discoveries in Western Australia's more remote and regional areas, and send a clear signal to resource investors around the world that Western Australia is serious about attracting exploration investment.

- Exploration companies submitted 168 applications for financial support in 2009–10 under the Co-funded Exploration Drilling program. The program funds, on a competitive basis, drilling projects involving innovative exploration targeting geoscience or technologies. Thirty-five applications were successful in their bids for the $3 million available in 2009–10.
- The entire Terra Search surface and downhole geochemical database for WA was purchased and released to the public. Large areas of the State are included in the dataset which consists of more than 1.1 million sample locations. Multi-element geochemistry from drillholes dominates the dataset, which includes capture of 69 597 drillhole collars, 596 448 drillhole assays, and 136 343 drillhole geology observations.
- A ground-based gravity survey involving approximately 7500 stations over an area of 22 500 km^2 in the Cunderdin area was completed in late April 2009.
- Planning of the EIS airborne geophysical survey program commenced in 2008–09 leading to the award for 2009–10 of nine survey contracts for the acquisition of a total of approximately 900 000 km of data.

Future work

The 2009–10 to 2012–13 work program under the Exploration Incentive Scheme is outlined elsewhere in this Review and is fully documented in GSWA Record 2009/1.

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Program review

Appendices

Products and services 2008–09

GSWA continued its geoscience work program for 2008–09 focusing primarily on promoting Western Australia's mineral and petroleum prospectivity. This was achieved by the provision of publications and information services relating to Western Australia's geological framework and resources potential.

The planned achievements for 2008–09 were:

- release of 19 geological maps at various scales
- publication of 31 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers
- publication of 17 digital information packages
- release of 344 400 line-km of airborne geophysical data.

In 2008–09 GSWA published:

- 31 geological maps, including 14 1:100 000 Geological Series maps
- 26 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers
- 19 digital information packages
- 398 470 line-km of airborne geophysical data.

GSWA was highly productive in 2008–09 with 14 series maps produced, the highest number for at least five years. This suggests that GSWA is at last gaining efficiencies from standardizing map unit codes across the State and having field geologists digitally compile their own series maps. Several projects are also at a mature stage where knowledge of the geological framework increases rapidly and mapping is more efficient. The large number of external papers and extended abstracts reflected GSWA's strong contribution to the technical program at the 2008 Australian Earth Science Convention held in Perth.

Geophysical data were released from airborne geophysical surveys over the southern Kimberley region and the Yilgarn – Albany–Fraser margin. Ground-based gravity surveys over the west Musgrave and Windimurra areas were also made available. In total, almost 399 000 line-km of airborne magnetics and radiometrics data and 9213 ground gravity stations were released.

Transcription of legacy round seismic tapes continued with only 10% remaining to be transcribed by the end of June 2009. In addition, the ongoing scanning of open file mineral exploration reports meant that only 4000 remain to be scanned in 2009–10.

Maps, books, and datasets

Maps, books, and datasets released in 2008–09

Geological maps

1:100 000 Geological Series Maps

Bates 1:100 000 Geological Series map 2nd edition by HM Howard, RH Smithies, P Evins, F Pirajno, and MS Skwarnecki
Bell Rock 1:100 000 Geological Series map 2nd edition by HM Howard, RH Smithies, P Evins, F Pirajno, and MS Skwarnecki
Blackstone 1:100 000 Geological Series map by RH Smithies, HM Howard, WD Maier, and P Evins
Candolle 1:100 000 Geological Series map by AM Thorne, DMcB Martin, and HN Cutten
Eudamullah 1:100 000 Geological Series map 2nd edition by S Sheppard, TR Farrell, HM Howard, and RM Hocking
Errabiddy 1:100 000 Geological Series map by SA Occhipini, S Sheppard, HN Cutten, and AM Thorne
Holt 1:100 000 Geological Series map by P Evins, RH Smithies, WD Maier, and HM Howard
Koonmarra 1:100 000 Geological Series map by SF Chen and T Ivanic
Madoonga 1:100 000 Geological Series map by T Ivanic
Marquis 1:100 000 Geological Series map 2nd edition by S Sheppard, CP Swager, SA Occhipinti, AM Thorne, and HN Cutten
Mount Augustus 1:100 000 Geological Series map 2nd edition by DMcB Martin, AM Thorne, and S Sheppard
Mount Phillips 1:100 000 Geological Series map 2nd edition by S Sheppard, TR Farrell, DMcB Martin, AM Thorne, and L Bagas
Tieraco 1: 100 000 Geological Series map by SF Chen and T Ivanic
Yinnetharra 1:100 000 Geological Series map by S Sheppard, SP Johnson, P Groenewald, and TR Farrell

Resource Potential for Land use Planning

Established and proposed Aboriginal land, conservation estate, mineral and petroleum titles, and geology, Western Australia — 2009 by FI Roberts
Northwest Kimberley bauxite province, Western Australia by FI Roberts
Titanium–zircon mineralization, Bunbury 2nd edition by L Hassan
Titanium–zircon mineralization, Busselton–Clairault 2nd edition by L Hassan
Titanium–zircon mineralization, Donnelly–Meerup 2nd edition by L Hassan
Titanium–zircon mineralization, Donnybrook 2nd edition by L Hassan
Titanium–zircon mineralization, Fremantle–Jarrahdale 2nd edition by L Hassan
Titanium–zircon mineralization, Leeuwin–Tooker 2nd edition by L Hassan
Titanium–zircon mineralization, Pinjarra 2nd edition by L Hassan

Non-Series Maps

Bulletin 145 Devonian reef complexes of the Canning Basin, Western Australia — Plate 8 by PE Playford
Industrial minerals in Western Australia May 2008 — Plate 1 by JM Fetherston
Industrial minerals in Western Australia May 2008 — Plate 2 by JM Fetherston
Iron ore deposits of the Pilbara region 2009 by RW Cooper and DJ Flint
Iron ore deposits of the Yilgarn Craton by RW Cooper and DJ Flint
Major resource projects map 2009 by RW Cooper and DJ Flint
Mines — operating and under development — Western Australia 2009 by RW Cooper and DJ Flint
Western Australian atlas of mineral deposits and petroleum fields 2009 by RW Cooper and DJ Flint

Books

Bulletin

Bulletin 145 Devonian reef complexes of the Canning Basin, Western Australia by PE Playford, RM Hocking, and AE Cockbain

Reports

Report 105 The Carribuddy Group and Worral Formation, Canning Basin, Western Australia: Stratigraphy, sedimentology, and petroleum potential by PA Haines

Records

2008/1 Geological Survey work program 2009–10 and beyond
2008/16 Industrial minerals in Western Australia: the situation in 2008 by JM Fetherston
2008/19 The west Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies by RH Smithies, HM Howard, P Evins, CL Kirkland, S Bodorkos, and MTD Wingate
2009/2 GSWA 2009 extended abstracts: promoting the prospectivity of Western Australia
2009/3 Geology and petroleum prospectivity of state acreage release areas L09–1 to L09–3, Broome Platform and Kidson Sub-basin, Canning Basin by P Haines
2009/4 The Magellan non-sulfide lead deposit, Yerrida and Earaheedy Basins, Western Australia by F Pirajno
2009/5 Guidebook to the geology and geomorphology of Devonian Reef Complexes by PE Playford
2009/6 Mineralogy and trace element chemistry of lode and alluvial gold from the western Capricorn Orogen by EA Hancock, AM Thorne, PA Morris, RJ Watling, and HN Cutten
2009/7 Field-portable X-ray fluorescence analysis and its application in GSWA by PA Morris
2009/8 An approach to digital map compilation using ArcGIS software by AM Thorne, SP Johnson, A Riganti, P Evins, T Ivanic, and R Maas
2009/9 Tips and tricks for map compilation using ArcGIS software and Tablet PCs by SP Johnson, AM Thorne, T McDonald, T Ivanic, A Riganti, HN Cutten, P Evins, and RW Page
2009/10 Interpreted bedrock geology of the southern Yilgarn and central Albany–Fraser Orogen, Western Australia by C Spaggiari, S Bodorkos, IM Tyler, and MTD Wingate

Non-series books

Catalogue of geoscience products 1980–2009 (updated to February 2009)
GSWA Annual Review 2007–08
GSWA Fieldnotes v. 48, 49, 50
GSWA guide for editing digital data packages
Overview of mineral exploration in Western Australia for 2007–08 by DJ Flint and PB Abeysinghe
Review of the Geological Survey of Western Australia
Self-guided geological walk of Perth CBD by J Johnston and A Riganti
Spelling and other useful stuff (GSWA Spelling Guide)
Summary of petroleum prospectivity, onshore Western Australia and State waters 2009: Bonaparte, Canning, Officer, Perth, Southern Carnarvon, and Northern Carnarvon Basins
Western Australia atlas of mineral deposits and petroleum fields 2009 by RW Cooper, PB Abeysinghe, and DJ Flint

Datasets

1:100 000 Geological Information Packages

Pilbara 1:100 000 Geological Information Series 2008 by AH Hickman
Central Yilgarn 1:100 000 Geological Information Series (NEARANGING) update by A Riganti and S Wyche
West Musgrave 1:100 000 Geological Information Series 2009 update by RH Smithies and HM Howard

Maps, books, and datasets

Data Packages

Compilation of geochronology data, 2008 update
Compilation of geochronology information, June 2009 update
Geothermal Acreage Re-release (Perth) March 2009 by J Haworth

Non-Series Digital Products

Canning Basin — merged well logs by J Haworth
East Yilgarn Geological Information series update 2009 by S Wyche
Eastern Canning SMT project by J Haworth
Geothermal Acreage Release (Southeast) June 2009
GSWA 2009 Poster Display CD
GSWA 2009 products CD
GSWA 2009 promotional CD
GSWA products DVD 2008–09
Iron ore deposits of the Pilbara region 2009
Petroleum acreage release June 2009 by J Haworth
Prospectivity of state acreage release areas L08–8 to L08–10, Broome Platform, Munro Arch, Kidson Subbasin, Anketell Shelf, and Waukarlycarly Embayment, Canning Basin by J Haworth
Western Australian geothermal acreage release, No 2 of 2008
Western Australian petroleum acreage release, September 2008

Geophysics

Musgrave gravity (4028 stations)
Windimurra gravity (5185 stations)

Aeromagnetics

Byro 2008 (83 666 km)
South Kimberley 2007 East Block (166 700 km)
SWCC/Dumbleyung 2008 (filler areas)
Esperance (82 674 km)
Balladonia (43 948 km)

Other

EIS Exploration Geochemistry of Western Australia

External publications

External publications by GSWA authors 2008–09

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West Musgrave geology east: GSWA Seminar and Poster Display, February 2009.

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Central Yilgarn 09: GSWA Seminar and Poster Display, February 2009.

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Southern Cross mapping: GSWA Seminar and Poster Display, February 2009.

The Yamarna Shear Zone: GSWA Seminar and Poster Display, February 2009.

West Yilgarn: GSWA Seminar and Poster Display, February 2009.

New Murchison stratigraphy 09: GSWA Seminar and Poster Display, February 2009.

Sea to scarp: GSWA Seminar and Poster Display, February 2009.

East Yilgarn Albany Fraser: GSWA, Seminar and Poster Display, February 2009.

Interpreted bedrock geology: GSWA Seminar and Poster Display, February 2009.

TMI image: GSWA Seminar and Poster Display, February 2009.

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Pilbara 09: GSWA Seminar and Poster Display, February 2009.

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Field portable XRF: GSWA Seminar and Poster Display, February 2009.

GSWA and Curtin University, WAERA tight gas: GSWA Seminar and Poster Display, February 2009.

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The Geological Survey Liaison Committee (GSLC) meets twice a year to review progress and advise on future work programs for GSWA. The two technical subcommittees provide comment and advice in each of the special areas for consideration by the GSLC. Membership shown as of 30 June 2009.

Geological Survey Liaison Committee members

Richard Sellers (Chair)	Director General, DMP
Bryan Smith	AMEC
Robbie Rowe	CME
Mike Sayers	APPEA
Tim Shanahan	The University of Western Australia
Mark Woffenden	Curtin University of Technology
Peter Onley	Golder and Associates Pty Ltd
Steve Harvey	CSIRO
Neil Williams	Geoscience Australia
Tim Griffin	GSWA
Rick Rogerson	GSWA
Ian Tyler	GSWA
Stephen Bandy	GSWA

Technical subcommittees

Mineral exploration technical subcommittee

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Richard Blewett	Geoscience Australia
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Liaison committee

Mineral exploration technical subcommittee (continued)

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Petroleum exploration technical subcommittee

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Raj Singh	Origin Australia
Rick Rogerson	GSWA
Jeff Haworth	GSWA
Felicia Irimies	GSWA
Reza Malek	Petroleum Division, DMP

Acronyms and abbreviations

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AAPG	American Association of Petroleum Geologists
ABS	Australian Bureau of Statistics
AGSO	Australian Geological Survey Organisation, now Geoscience Australia
AIG	Australian Institute of Geoscientists
AMEC	Association of Mining & Exploration Companies (Inc.)
ANU	Australian National University
APPEA	Australian Petroleum Production & Exploration Association Limited
ASEG	Australian Society of Exploration Geophysicists
ASX	Australian Securities Exchange
ArcIMS	Arc Internet Map Server
AusIMM	Australasian Institute of Mining and Metallurgy
BHPB	BHP Billiton
BRGM	Bureau de recherches géologiques et minières
CME	Chamber of Minerals and Energy of Western Australia Inc
CRC LEME	Cooperative Research Centre for Landscape Environments and Mineral Exploration
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSIRO-AGE	CSIRO-Australian Geochemical Exploration joint venture
DEC	Department of Environment and Conservation
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
EXACT	Western Australian mineral exploration activities database
GA	Geoscience Australia
GeoVIEW.WA†	GSWA's integrated geoscience information system
GeoVIEWER.WA†	GSWA's CD- and DVD-based visualization, query, and integration tool
GIS	Geographic Information System
GPS	Global Positioning System
GSA	Geological Society of Australia
GSLC	Geological Survey Liaison Committee
GSWA	Geological Survey of Western Australia
IUGS	International Union of Geological Sciences
JORC	Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists, and Minerals Council of Australia

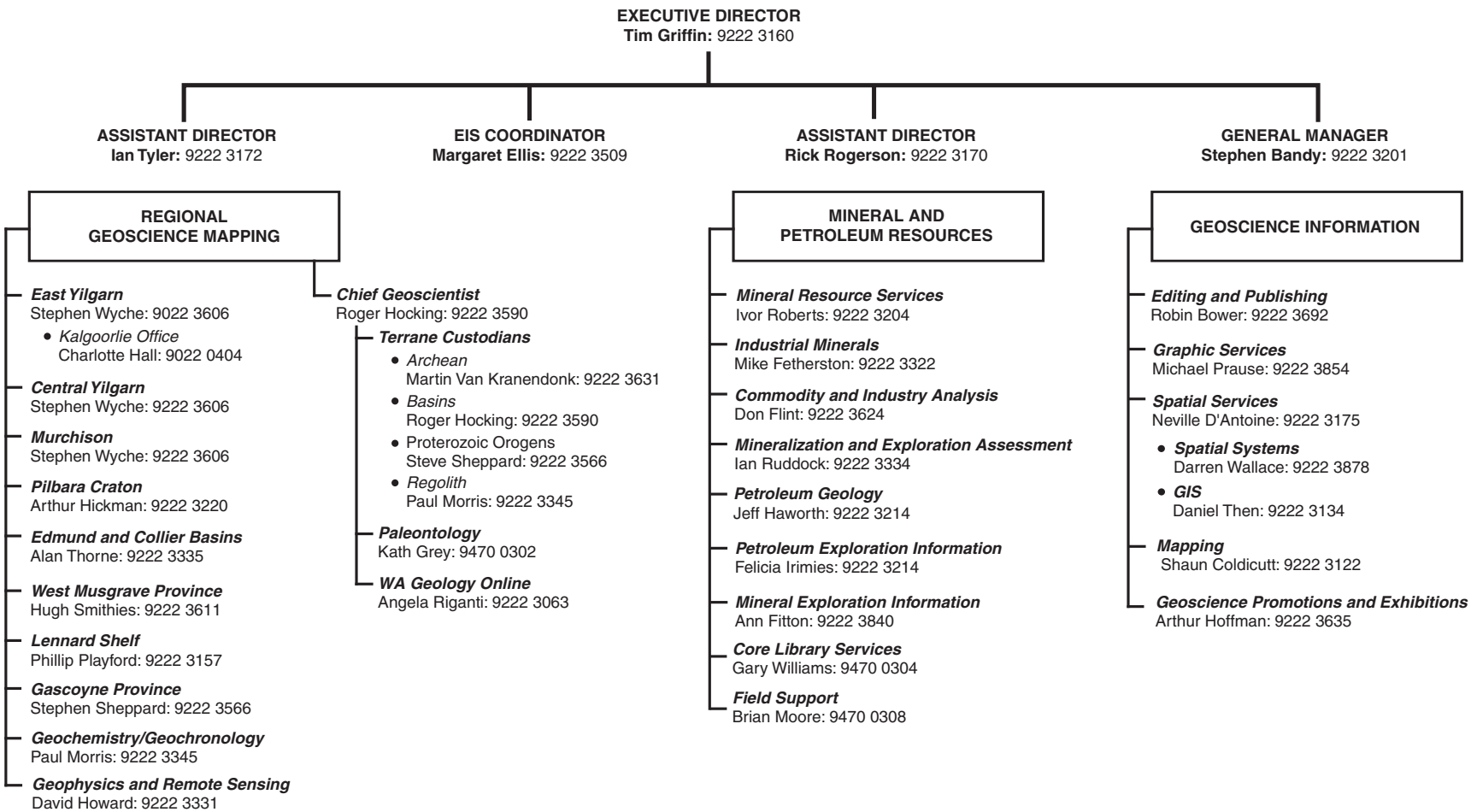
Acronyms and abbreviations (continued)

Landgate	Department responsible for land and property information in Western Australia
Landsat TM	Landsat Thematic Mapper
MAGIX	Mineral Airborne Geophysics Information eXchange
MERIWA	Minerals and Energy Research Institute of Western Australia
MINEDEX	DMP's mines and mineral deposits information database
MCMPR	Ministerial Council for Mineral and Petroleum Resources
NASA	National Aeronautics and Space Administration
NCRIS	National Collaborative Research Infrastructure Strategy
NGA	National Geoscience Agreement
NTGS	Northern Territory Geological Survey
PDAC	Prospectors and Developers Association of Canada
PESA	Petroleum Exploration Society of Australia
pmd*CRC	Predictive Mineral Discovery Cooperative Research Centre
SGTSG	Specialist Group on Tectonics and Structural Geology of Geological Society of Australia
SHRIMP	Sensitive high-resolution ion microprobe
SLIP	Shared Land Information Platform in Western Australia
SRTM	Shuttle Radar Topography Mission
TENGRAPH†	DMP's electronic tenement-graphics system
UWA	The University of Western Australia
WACHEM	GSWA's inorganic geochemistry database
WAMEX†	Western Australian mineral exploration database
WAPIMS	Western Australian petroleum information management system database
WAROX	GSWA's field observation database
WASM	Western Australian School of Mines

NOTE: †GeoVIEW.WA, GEOVIEWER.WA, WAMEX, and TENGRAPH are registereed trademarks of DMP.

Organizational structure

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA



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