Department of
Industry and Resources

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 2003-04

Geological Survey of Western Australia

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BASE

- Laguna Green granite from near Jerramungup in the Southwest
- 2220 mm x 1280 mm x 620 mm and weighs 4250 kg
- Granitic rocks in this region are typically about 2700 million years old
- This rock is characterised by green plagioclase feldspar and is classified as a hornblende–biotite granodiorite
- Other minerals include quartz, potassium feldspar (microcline), hornblende, biotite, and minor titanite, ilmenite, apatite, zircon, chlorite and calcite
- The new Australian War Memorial in London is built from Laguna Green granite

SPHERE

- Boogardie orbicular granite from Boogardie Station, 35 km west of Mount Magnet
- 880 mm in diameter and weighs 900 kg
- Similar orbicular rock in the region is 2685 million years old
- The egg-shaped orbicules comprise concentric mineral bands of varying amounts of hornblende, biotite, ilmenite and titanite crystals, either radially or concentrically aligned
- The layers reflect a dynamic history of crystallisation with frequent changes in magma composition and cooling rate
- The rock that hosts the orbicules is classified as hornblende–biotite tonalite to granodiorite
- Late pegmatite veins of quartz and feldspar cut across the orbicular granite

GEOLOGICAL SURVEY OF WESERN AUSTRALIA

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA ANNUAL REVIEW 2003–04

Perth 2004

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The recommended reference for this publication is:

(a) For reference to an individual contribution
VAN KRANENDONK, M. J., SMITHIES, R. H., HICKMAN, A. H., BAGAS, L., WILLIAMS, I. R., and FARRELL, T. R., 2004, Event stratigraphy applied to 700 million years of Archaean crustal evolution, Pilbara Craton, Western Australia: Western Australia Geological Survey, Annual Review 2003–04, p. 49–61.

(b) For general reference to the publication
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 2004, Geological Survey of Western Australia Annual Review 2003–04: Western Australia Geological Survey, 152p.

ISBN 0 7307 8988 8

ISSN 1324–504 X

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates

Coordinating editor: J. F. Johnston
Technical papers editor: K. A. Blundell
Cartography: S. N. Dowsett
Desktop publishing: K. S. Noonan

Published 2004 by Geological Survey of Western Australia

Copies available from:
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This and other publications of the Geological Survey of Western Australia may be viewed or purchased online through the Department's bookshop at www.doir.wa.gov.au

Cover:
***Austral Juperana* granite–gneiss from Bruce Rock (photo courtesy Melocco Pty Ltd and Discovering Stone (© Discovering Stone, 2004)**

Frontispiece:
A striking entry statement to the recently opened Perth Core Library at Carlisle. Highly polished, rotating sphere of orbicular granite from Boogardie Station, 35 km west of Mount Magnet sits on a plinth of *Laguna Green* granite from near Jerramungup in the Southwest of Western Australia. Granite sphere donated to the Perth Core Library by Mark Creasy

Contents

GSWA mission statement

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

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

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

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

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

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

The year 2003–04 in review

by Tim Griffin, Director

An air of optimism surrounded the resources industry and GSWA in 2003–04. On the industry front, demand was driving mineral commodity price rises and supply concerns were driving increases in petroleum prices. These buoyed the exploration scene, with the mineral exploration sector emerging from the gloom it entered in 1997–98. Don Flint's following article *Overview of mineral exploration in Western Australia for 2003–04* provides the statistical detail on the increase in State mineral exploration — expenditure that hopefully will be maintained. Exploration was not the only highlight of the resources sector. World economic growth, particularly in China, has driven expansions in Western Australia's mineral and petroleum production capacity. Highlights during 2003–04 include the go-ahead for the Ravensthorpe Nickel Project, passage through Parliament of a State Agreement for the giant Gorgon Gas Project, and continued development of Burrup Fertilisers' ammonia project on the Burrup Peninsula. BHP Billiton and Rio Tinto also announced major expansions of iron ore production from their Pilbara operations. These developments further underscore the need to increase the level of exploration to find new deposits that will sustain the resources sector as the major component of the Western Australian economy in the long term.

Increased funding for GSWA announced by Premier Gallop

GSWA was the subject of a very welcome announcement by the Premier of a $13.2 million geoscience information stimulus package consisting of $12 million over four years for new pre-competitive geoscience information release and $1.2 million over three years for release of statutory mineral exploration reports under the provisions of the five year 'sunset clause' period of confidentiality contained in the preparation of the Mining Amendment Bill 2004 that will go to Parliament in 2004–05.

The funding increase was in response to recommendations of the State Government's Bowler Inquiry into greenfields exploration, the Federal Government's Prosser Inquiry into impediments to increasing investment in mineral exploration, and the industry-led Mineral Exploration Action Agenda process. These reviews recommended greatly increased funding for pre-competitive geoscience data acquisition, in particular the detailed aeromagnetic surveys essential for mapping prospective rocks and structures hidden beneath largely soil- and sand-covered areas of Western Australia.

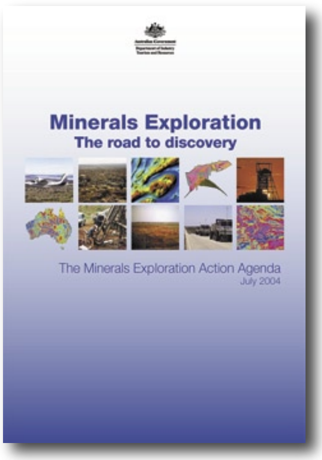
Although it was hoped that this new State funding would be matched dollar for dollar by the Commonwealth Government, as recommended by the Strategic Leaders Group for the Commonwealth's Mineral Exploration Action Agenda, the Commonwealth's 2004–05 budget was silent on an exploration stimulus package.

Western Australia's vast size presents a formidable challenge to providing detailed geophysical coverage over large areas. Some of these areas are known to be highly prospective for a variety of minerals, whereas others, because of poor outcrop, are not well understood geologically. To date, only about 25% of the State has been covered by aeromagnetic surveys of sufficient detail to be of real use to explorers. The new funding will provide coverage of up to an additional 25% of the State, concentrating on areas with the highest potential for new greenfields discoveries. The new surveys will be flown at a line spacing of 400 m, which is sufficiently detailed to assist in GSWA's regional mapping programs as well as provide the framework for mineral exploration targeting. Priority areas include the Murchison–Gascoyne region, the eastern wheat belt, the Albany–Fraser Orogen between Esperance and Warburton, the Paterson region east of the Pilbara, the Musgrave–Arunta region on the Western Australian border, and the west Kimberley. In addition to aeromagnetics, the increased funding will allow collection of other data of interest to mineral explorers, such as orthophotography and hyperspectral sensing, geochemical and gravity surveys, and, in conjunction with Geoscience Australia and the Australian National Seismic Imaging Resource, deep crustal seismic traverses in key areas of the State. Industry will have an input into how this new funding will be spent through the GSWA Liaison Committee, which meets in June and December each year.

Aeromagnetic surveys are due to commence in the Yalgoo–Kirkalocka area of the Murchison, and the Southern Cross – Lake Johnston areas of the eastern wheat belt in early 2004–05.

Mineral Exploration Action Agenda launched

The final Mineral Exploration Action Agenda (MEAA) report, entitled *Minerals Exploration — The road to discovery* released in early July 2004, initiates more process-related activity, calling on relevant government and private sector organizations to cooperate on implementing many of the report's recommendations. Canadian experience suggests fiscal reform (such as a flow-through share scheme) is the strategic imperative that will deliver a major increase in exploration expenditure in Australia.



The report includes an implementation plan for a suite of actions by industry and governments under four strategies (land access, pre-competitive geosciences, human and intellectual capital, and implementation). The implementation strategy has been named the 'Resources Exploration Strategy' and will be driven by an industry-led group, chaired by John Dow, Managing Director of Newmont Ltd.

Of particular interest to GSWA and other Australian geological survey organizations were the MEAA's recommendations under the pre-competitive geoscience strategy, as follows:

- Governments to consider a major pre-competitive geoscience survey program to achieve national coverage of basic geoscience datasets to modern standards
- Governments, in consultation with industry, to develop and implement nation-wide protocols, standards, and systems that provide internet-based access to, and effective storage and archiving of, geoscience datasets and industry-generated exploration data

In the coming year, GSWA will work in consultation with industry, and through the Chief Government Geologists' Committee of the Ministerial Council for Mineral and Petroleum Resources to begin implementing these recommendations.

GSWA production targets achieved

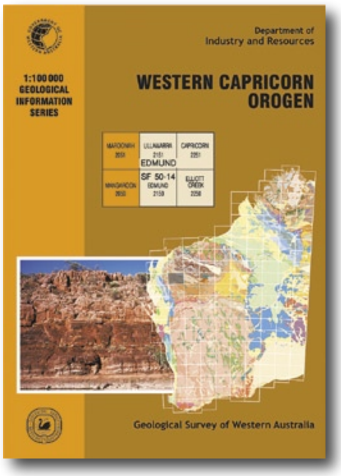
During 2003–04, GSWA published the following products:

- 14 geological maps at 1:100 000 scale
- 26 geological maps at other scales
- 43 Records, Reports and other publications
- 24 digital information products

In achieving this output of geoscience products, GSWA managed to maintain its level of productivity measured on a cost basis (output per million dollars).

I thank the hardworking members of GSWA's Liaison Committee and its two Technical Subcommittees for the feedback and guidance they provide on our annual work program and for their comments that ensure the quality of our products and services is maintained at a high level.

New geoscience map products



During 2003–04, GSWA released two new products to take us into the future with geoscience map databases. The new products are:

- the *1:100 000 Geological Information Series* (Western Capricorn Orogen, covering Mangaroon and Maroonah map sheets) on DVD in *GeoVIEWER.WA* format with all accompanying field and legacy geoscience data, geophysical and satellite images, field photographs, and photomicrographs.
- the *Geological Exploration Package* (west Musgrave area), also in *GeoVIEWER.WA* format on DVD, containing a wide range of regional geoscientific and related information (including orthorectified aerial photographs) available prior to mapping a new area.

These new products allow for the release of all legacy data, including remotely sensed data from the area, which has been assembled by mapping teams prior to going into the field. As the mapping progresses, new information is added to the product, and released as updated versions of the DVD. Once new maps of the area are completed a new 1:100 000 Geological Information Series DVD is released that includes new field observations, thin-section descriptions, mineral occurrences, geochronology etc, together with all the information originally released as the Geological Exploration Package. This is regularly updated as additional geological mapping is completed.

More-comprehensive geochronology information

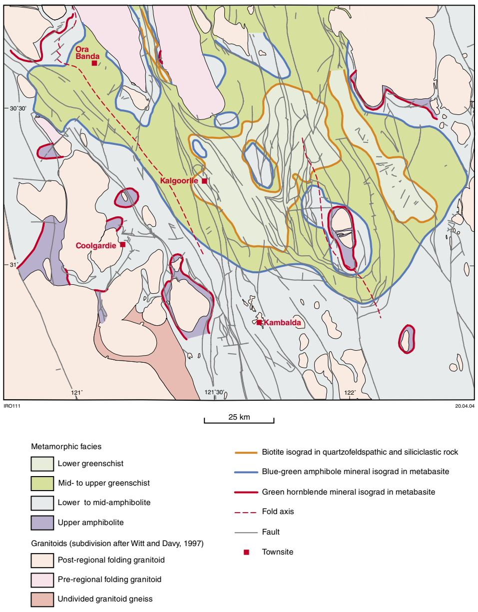
Since 1995, GSWA has been publishing the results of David Nelson's geochronology analyses in Record form each year. Now, with more than 460 analyses of rocks from all parts of the State, including dating information on samples collected by others such as Geoscience Australia, geochronology information has been compiled into a digital data package on DVD using *GeoVIEWER.WA* software. The digital data package — *Compilation of geochronology data, 1994–2001* — represents a significant change to the traditional way that geochronology information has been previously provided.

The software allows a user to view and access the data as well as build queries to identify geochronology samples that meet certain criteria, whether these be age, rock type, confidence level, type of geochronology analysis, or a combination of information. You can zoom to all the geochronology points that meet the criteria, or to a specific geochronology point. The digital data package contains GIS data layers including 1:500 000-scale geology, and PDFs of all written descriptions, discussions, tabulated data and graphs linked directly to the sample locality on screen. This product will be updated annually to include new geochronological data and information.

Kalgoorlie metamorphic study released

Record 2003/12, titled *Metamorphic petrography of the Kalgoorlie region, Eastern Goldfields Granite–Greenstone Terrane: METPET database* provides an updated metamorphic map and petrographic database for a 20 000 km^2 area covering much of the Kalgoorlie region. This study was carried out with special support from Placer Dome.

This region is host to significant gold deposits, including those at Mount Charlotte, the Golden Mile, Kanowna Belle, St Ives, and Coolgardie. Because the origin, evolution, and migration of the gold-related hydrothermal fluids are intimately associated with the thermal evolution of the Eastern Goldfields, metamorphic grade, which also reflects the thermal evolution, places constraints on ore genesis and can play an important role as a pathfinder.



One great advantage of this study over previous metamorphic studies of the region is that locality and metamorphic-assemblage data for each sample are recorded in a database that is accessible through a stand-alone version of the *GeoVIEWER.WA* GIS software package. The software facilitates analysis of this and any other spatial data, such as hyperspectral alteration mineral maps. Individual data points can be plotted together with metamorphic zone or facies boundaries, allowing direct comparison between these boundaries and the constraining data, and with hyperspectral data collected remotely. It also allows users to devise their own criteria for defining metamorphic zones or facies. Additional entries to the database can be included as new information becomes available. The Record was released as a CD-ROM containing explanatory notes, the METPET database, and the files necessary for viewing the data in a GIS environment.

Petroleum acreage release packages

In cooperation with DoIR's Petroleum Division, GSWA produced two State Petroleum Acreage Release packages during 2003–04. The specific area release system is aimed at encouraging a wider selection of companies to evaluate areas for petroleum exploration than the previous 'open' State-wide gazettal. The package for bids that closed in March 2004 covered four areas in the central Canning Basin and two in the northern Perth Basin, whereas the package for bids to close in September 2004 provides information on several areas in the State, including the northern Canning, Northern Carnarvon, the northern Perth, and Officer Basins.

Acreage release packages come on an easy-to-navigate CD to enable potential bidders to evaluate the area. The CD contains information on prospectivity, open-file data listings, land access, investment background, how to make a valid application for an exploration permit, and Departmental publications, including the Petroleum Division's Atlas of the Canning Basin fields, and GSWA reports on the stratigraphy, structure, and hydrocarbon potential of specific regions. Also available on application are information and analyses from the Western Australian petroleum information system (WAPIMS) database, seismic sections (SEG-Y format), wireline logs (LAS format), and PDF files of company well completion and permit reports.

Information on acreage releases on the CD can also be downloaded from the Department's website (www.doir.wa.gov.au) for the period of the gazettal, although most of the information is available through the website via WAPIMS, our catalogue of geoscience products, and the Petroleum and Royalties part of the DoIR website.

Improved geoscience services

During 2003–04, a major upgrade of both the web-based WAPIMS (WA Petroleum Information Management System) and GeoVIEW.WA systems was achieved. Initially launched in 2001, the GeoVIEW.WA system has evolved from a simple visualization-mapping interface into one with the capability to create a customized view of a large range of geoscientific data for querying, analysing, and extracting. About 50 geoscience, mineral, petroleum, and administrative-related layers are provided in the reference area of GeoVIEW.WA. If required, a hardcopy map of that view can be captured without the need for specialized GIS skills. A major improvement in the 2004 version of GeoVIEW.WA was the provision of two options for extracting digital data for use in one's own system. Both methods provide a zipped file containing data layers, licence agreement, and associated metadata for downloading via the web. The first is through a data download page with a complete list of various State-wide datasets in either ESRI® shapefile or MapInfo® tab file formats. The second option extracts the visible data layers clipped to the map-view extent as an ESRI® shapefile.

The upgrade of the WAPIMS database system involved changes that make it more user-friendly, with the deployment of a map interface to access spatial data using similar technology to the GeoVIEW.WA web interface. To further assist industry users, a series of training workshops were conducted.

Lancer 1 stratigraphic drillhole

GSWA Lancer 1 was successfully drilled between October and November 2003 to a total depth of 1501 m in the remote Gibson Desert, about 570 km northeast of Wiluna in the northern Officer Basin. This is an area where there hasn't been any oil exploration for 20 years.

The well was fully cored from 104 m to total depth, primarily to assess the petroleum potential of the Neoproterozoic (545–1000 Ma) rocks of the Officer Basin, but also to provide information on the underlying Mesoproterozoic (1000–1600 Ma) succession. Although the section in Lancer 1 was close to that expected from seismic interpretation, there were some surprises: a 49 m-thick basaltic unit in the Kanpa Formation; an eolian sandstone in the upper Browne Formation, rather than the expected evaporites; and the remarkable similarity of the lower part of the intersected section to Empress 1A, 260 km to the southeast. This similarity implies a low gradient across the basin during deposition as well as broad-scale tectonic controls on deposition and subsidence, and a low-relief hinterland.

Four separate zones each about 10 cm thick between 850 and 900 m depth in the Hussar Formation displayed evidence of hydrocarbon traces, but organic petrography by Alan Cook of Kieraville Konsultants found only a single oil inclusion. Although of no commercial significance, these zones indicate that hydrocarbons have migrated through the basin and may still be trapped elsewhere in greater quantities.

Archaean Biosphere Drilling Program

The first stage of the Archaean Biosphere Drilling Program was completed in late 2003, with six fully cored holes drilled in the Pilbara region. The project is investigating the nature of the atmosphere, biosphere, and hydrosphere of the early Earth.

The Archaean Biosphere project involves collaboration between the Geological Survey of Western Australia, Kagoshima University (Japan), Pennsylvania State University (United States), and the University of Western Australia. Substantial funding of about $US200 000 towards operational costs was provided by the Japanese Government and the NASA Astrobiology Institute. GSWA also collaborated with Institute de Physique du Globe de Paris (IPGP) in the Pilbara Drilling Project. GSWA played a major role in setting up the projects prior to the drilling stage, and UWA provided technical support during drilling. Drilling took place at carefully selected Pilbara sites, based on our expert field geological knowledge, to allow collection of uncontaminated rock samples up to 300 m deep from below the weathered zone . The projects aimed to drill through sedimentary rocks and basalts ranging in age from 3.5 billion years to 2.7 billion years in order to examine evidence for the evolution of the early Earth. Subsequent detailed geochemical studies will shed new light on the Earth's primordial atmosphere and hydrosphere. Other studies will involve testing for evidence of life, such as the presence of biomarkers.

Half of the core will be retained at GSWA's new Perth Core Library facility to provide reference sections.

This project, and ongoing research by the Australian Astrobiology Institute at Macquarie University represent a fascinating spin-off from GSWA's ten-year mapping program in the Pilbara that was winding down in 2004. Fieldwork in the Pilbara is now complete, although final geoscience map and report products will continue to be released over the next few years.

Summary and the future

In preparing this review, I note my last year's optimistic comments that the various reviews (Fardon in 2001, Bowler in 2002, Prosser in 2003, and the MEAA process from 2003 onwards) would culminate in an increase in resourcing for GSWA. All of these studies reached similar conclusions on a range of issues facing the mineral industry and it is pleasing that — at State level at least — there has been a recognition that governments have to invest in the industry in order to reap the considerable economic and community benefits of resource development.

However, while the mineral industry has been the primary focus of industry reviews, WA's onshore petroleum exploration industry, even in a period of high crude oil prices, is in a parlous state. The Commonwealth has injected funding into Geoscience Australia to undertake pre-competitive geoscience programs in Australia's underexplored offshore sedimentary basins, which include various projects around the Western Australian coast, in response to the decline in Australia's crude oil production. At the State level in Western Australia, the royalty receipts from oil production are set to decline dramatically. GSWA looks forward to working with industry to promote a program for increased funding for gathering new pre-competitive geoscience information relevant to petroleum exploration onshore and in State waters, increasing the amount of information held within the WAPIMS database, and for transcribing stiction-affected seismic tapes onto new media.

Overview of mineral exploration in Western Australia for 2003–04

by D. J. Flint

Overview

During 2003–04, mineral exploration expenditure* (excluding petroleum) figures for Western Australia rose by 10% ($42.2 million) to $465.8 million, which is the second year in succession where mineral exploration expenditure has risen by 10–11% in Western Australia. However, mineral exploration is still well below the peak level of 1996–97, when $825 million (in 2003–04 dollar terms) was spent (Fig. 1). Recent quarterly data show mineral exploration expenditure continuing to rise, with exploration expenditure in mid-2004 significantly above the dismal levels of mid-2002 (Fig. 2). Western Australia continues to attract the major proportion of mineral exploration expenditure in Australia (59%).

The Western Australian trend is consistent with the Australian trend. The 2003–04 level of mineral exploration expenditure within Australia is $786.7 million, which is 7.4% ($54.2 million) higher than during 2002–03. However, mineral exploration expenditure in Australia is still well below the peak level of 1996–97, when $1370 million (in 2003–04 dollar terms) was spent.

Unfortunately, the recovery in exploration expenditure in Australia and Western Australia has not been as strong as the worldwide recovery, and Australia and Western Australia have both lost market share in the expanded pool of exploration capital (Fig. 3; based on data compiled by the Metals Economics Group of Halifax, Canada, www.metalseconomics.com). During the last decade, the proportion of the world's non-ferrous mineral exploration expenditure in Australia has dropped from 23% to 15% of the total, whereas that for Western Australia has dropped from 13% to 9% of the total. The comparison with the situation in Canada is striking, with the proportion of worldwide mineral exploration expenditure spent in Canada recovering strongly after 1997, whereas the proportion has continued to fall in Australia and Western Australia (Fig. 3). This clearly illustrates what can be achieved with the combination of high-profile discoveries, ongoing exploration success, and favourable government regimes (including fiscal incentives to exploration).

Exploration and development highlights

Important gold discoveries are still being made in Western Australia, but none have been sufficiently spectacular to excite international attention. These discoveries include the gold deposits of Lord Henry and Lord Nelson (Sandstone), Williamson–Regent (Lake Way), Sickle (Laverton), Brightstar

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

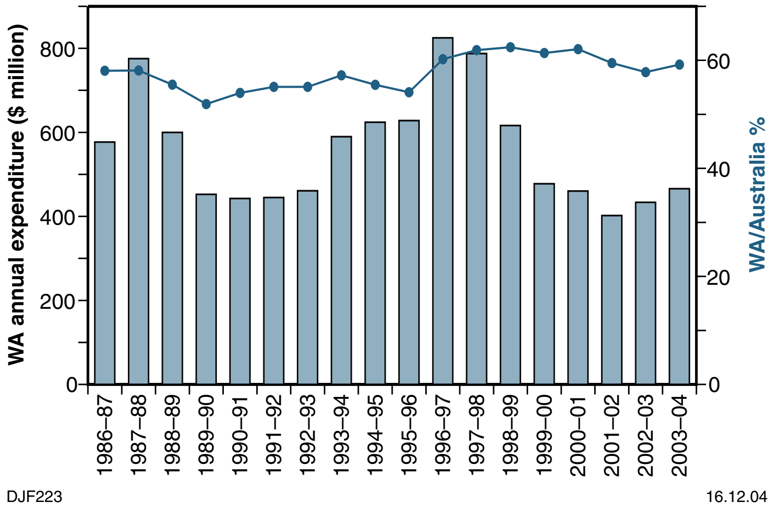


Figure 1. Mineral exploration expenditure in Western Australia, by financial year (2003–04 dollars)

(Laverton), and Withnell – Camel 1 and Wingina Well (Indee, Pilbara), and the discovery of a previously unknown gold province by Anglo Gold Ltd and Independence Group NL at Tropicana (southeast margin of the Yilgarn Craton). Development highlights for gold in Western Australia are dominated by the mine development at Telfer (Paterson Orogen), which was nearly completed by mid-2004. Telfer is a world-class deposit and contains a total of about 25 Moz of gold and 950 kt of copper within its measured, indicated, and inferred resources.

In the nickel sector, there were grassroot discoveries of nickel sulfide at Collurabbie Hills (190 km northeast of Leinster; Gerry Well greenstone belt), AK47 (130 km east of Wiluna; Mount Eureka greenstone belt), and further exploration success in the Halls Creek Orogen at Copernicus and Salk North. Significant brownfields exploration successes include those at Anomaly 1 (near Cosmos Deeps), Emily Ann (120 km west of Norseman; Lake Johnston greenstone belt), and Flying Fox (200 km west of Norseman;

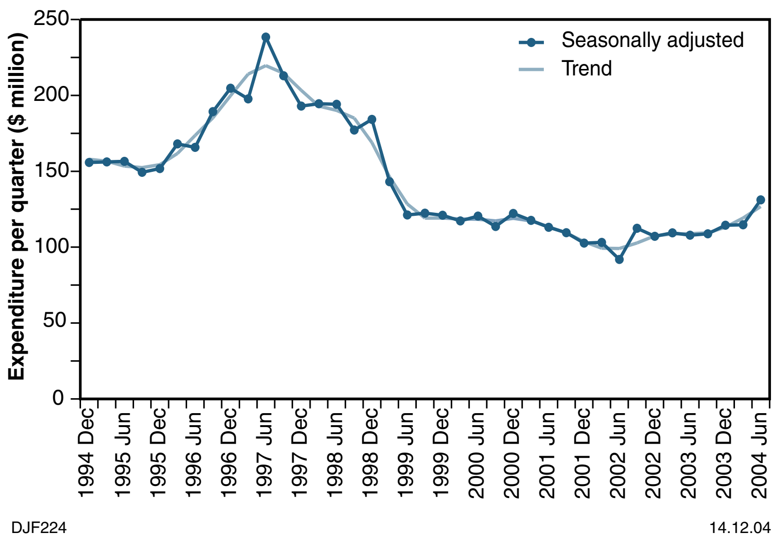


Figure 2. Mineral exploration expenditure in Western Australia, by quarter, on seasonally adjusted and trend terms (June 2004 dollars)

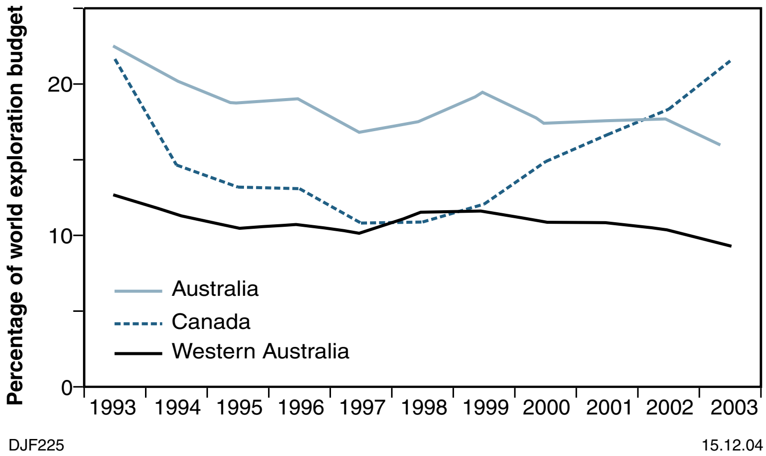


Figure 3. Non-ferrous mineral exploration expenditure — comparative market share of Canada, Australia, and Western Australia since 1993. Source: Metals Economics Group (Canada), ABS, and DoIR

Forrestania greenstone belt). The most significant mine development was the commencement of construction of BHPB's lateritic nickel project at Ravensthorpe. Development of smaller nickel sulfide mines include Sally Malay (East Kimberley), Maggie Hays (Forrestania), and numerous mines in the Eastern Goldfields Granite–Greenstone Terrane, such as Cosmos Deeps, Gibb South, Victor South, Carnilya Hill, Beta–Hunt, Spargoville 5A, Area 57 (Blair), Mariners, North Miitel, and Redross. Many of these involve the re-opening of former WMC mines.

In the iron ore sector in the Pilbara, the mines based on the Channel Iron Deposits (CID) in the Yandicoogina – Marillana Creek area are being expanded rapidly by Hamersley Iron Ltd and BHPB Ltd, and the Eastern Ranges (Paraburdoo) supergene-enriched deposits are being developed by Hamersley Iron Ltd. The go-ahead has been given by BHPB for development of Western 4 (four mesas of CID mineralization along Marillana Creek) and Newman Orebody 18 (Brockman supergene-enriched mineralization). In addition, Fortescue Metals Group (FMG) has established a substantial portfolio of exploration tenements in the east Pilbara and undertaken resource drilling at numerous sites in the Chichester Range – Mount Nicholas area (Marra Mamba supergene-enriched mineralization) and Mindy Mindy area (CID mineralization). In the Yilgarn Craton, the first ore from Tallering Peak was shipped from Geraldton during 2003–04, Portman's Koolyanobbing project was expanded — with mines opening at Windarling and Mount Jackson (BIF supergene-enriched mineralization), and there was fresh interest by numerous companies in magnetite mineralization within primary BIF throughout the craton.

At the Argyle diamond mine, a decline (costing $70 million) for exploration purposes is targeting lamproite beneath the existing openpit, with the aim of providing mining, geotechnical, and geological information. Rio Tinto Ltd is planning to complete a full feasibility study that may lead to a decision to commence underground mining during 2005.

Mineral exploration expenditure by commodity

Western Australia still accounts for the major proportion of exploration dollars expended in Australia for many of the major commodities — iron ore (99%), nickel–cobalt (84%), gold (70%), diamond (65%), heavy mineral sands (44%), silver–lead–zinc (13%), and copper (6%).

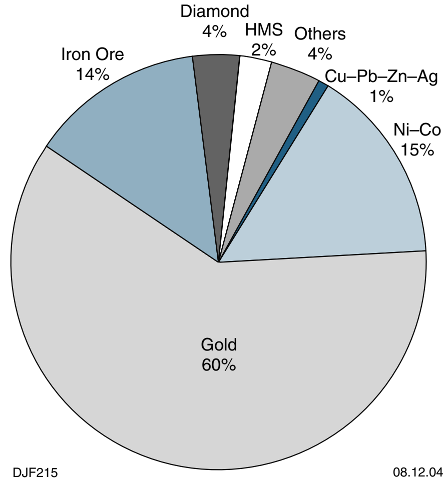


Figure 4. Mineral exploration expenditure in Western Australia, by commodity (2003–04)

Within Western Australia, gold remains the main focus of mineral exploration, accounting for about 60% of all exploration expenditure (Fig. 4). Other target commodities for exploration are nickel–cobalt (15%), iron ore (14%), diamond (4%), heavy mineral sands (2%), copper–lead–zinc–silver (1%), and 'others' totalling 4%. 'Others' include all industrial minerals, construction materials, platinum group elements, tantalite, rare earth elements, and coal–lignite.

Commodities that attracted increased exploration expenditure in Western Australia during 2003–04 were iron ore, nickel–cobalt, heavy mineral sands, and gold, whereas exploration expenditure directed at copper–lead–zinc–silver was unchanged. Commodities that attracted decreased exploration expenditure in Western Australia during 2003–04 were diamond and 'others'.

During 2003–04, $276.7 million was expended on gold exploration in Western Australia, which is only marginally up (+4.2%; $11.1 million) from the $265.6 million spent in 2002–03. The level of gold exploration expenditure has barely recovered and is still at the recessionary levels of the early 1990s and 2001–02 (Fig. 5). Gold exploration expenditure is still 56% lower (down $357 million) than the peak level of $634 million (in 2003–04 dollar terms) in 1996–97 (Fig. 5).

Exploration for nickel–cobalt recovered strongly during 2003–04, rising by 30.5% ($16.5 million) to $70.6 million. Exploration expenditure for Ni–Co has risen strongly over the last two years and there was even talk of a 'nickel boom', with the concomitant shortage of skilled personnel and available drill rigs. But a comparison with the longer term trends shows that nickel–cobalt exploration is still well below the other boom periods around 1980–81 and 1997–98 (Fig. 6). Data from the Australian Bureau of Statistics for the earlier years is for base metals generally (as an undifferentiated group), but these booms in Western Australia were undoubtedly dominated by exploration for Ni–Co. The recovery during 2002–03 and 2003–04 was principally led by junior companies exploring for and developing nickel sulfide deposits (particularly in the Kambalda area at properties previously owned by WMC) and by BHPB completing the feasibility study for the Ravensthorpe lateritic nickel project.

Iron ore exploration expenditure in Western Australia is now at the highest level ever recorded. During 2003–04, iron ore exploration expenditure jumped dramatically by 65.2%, from $24.9 million to $63.1 million (Fig. 7). This was driven by strong customer demand for iron ore, particularly from China, with the major producers in the Pilbara able to respond fairly rapidly by expanding

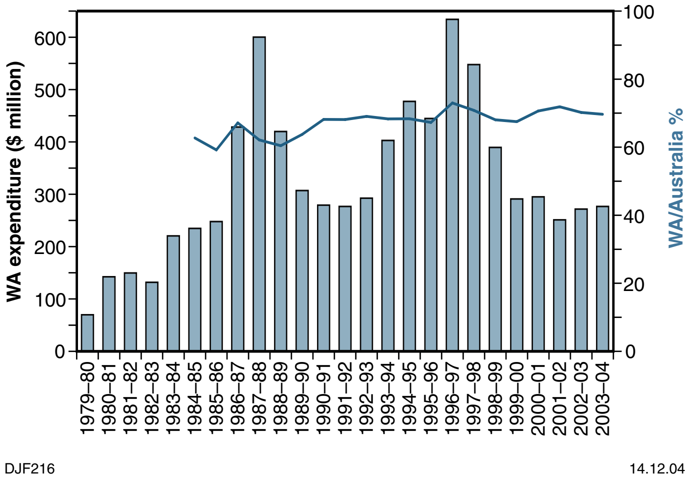


Figure 5. Gold exploration expenditure in Western Australia, by financial year (2003–04 dollars)

their operations at existing projects. In addition, the Fortescue Metals Group (FMG) emerged as a new force in the Pilbara iron ore industry, and there was renewed interest in exploration for magnetite deposits in primary banded iron-formations on the Yilgarn Craton.

Diamond exploration expenditure in Western Australia is now at its lowest level for at least 25 years, decreasing by a further 5% during 2003–04, falling by $0.9 million to only $16.9 million for the year (Fig. 8). The fall was primarily due to reduced resource–reserve drilling activities at Argyle, the Ellendale project entering the production phase, and little diamond exploration elsewhere in the State. Diamond exploration expenditure has declined gradually over the last decade, and is now far below the peak level of $134 million in 1981–82 (in 2003–04 dollar terms) reflecting the general lack of exploration success, hence investor interest, in Western Australia. Despite the success of Kimberley Diamond delineating further reserves at its Ellendale deposits, this had only

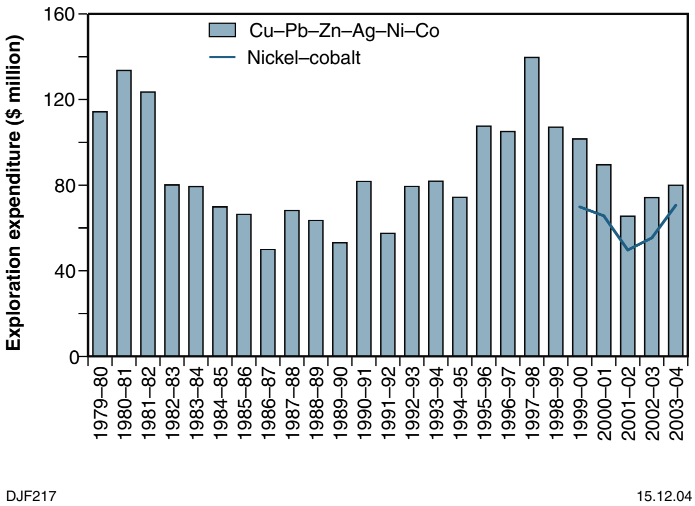


Figure 6. Base metal exploration expenditure in Western Australia, by financial year (2003–04 dollars). Base metals include copper, lead, zinc, silver, nickel, and cobalt. Note: the ABS did not separate Ni–Co data from total base metals until 1999–2000

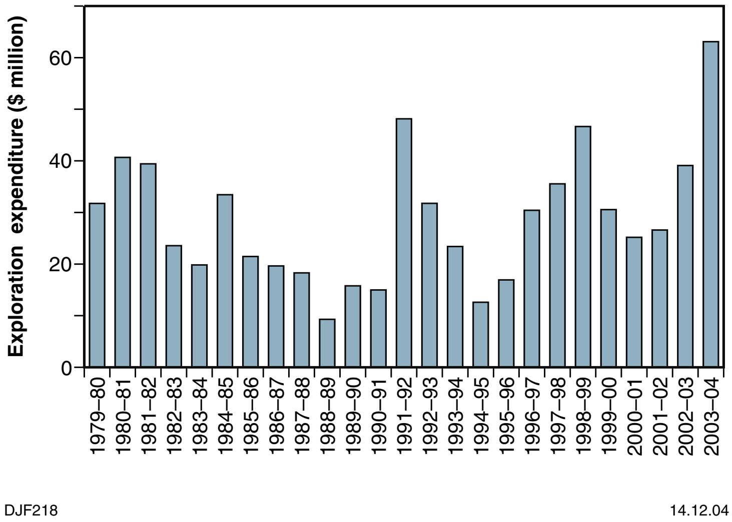


Figure 7. Iron ore exploration expenditure in Western Australia, by financial year (2003–04 dollars)

limited impact on the ability of other companies to raise capital specifically for diamond exploration in Western Australia.

Exploration expenditure for heavy minerals in Western Australia recovered strongly during 2003–04, rising by 34% ($2.4 million) to $10.6 million for 2003–04 (Fig. 9). However, this is still within the range of $8 to $11 million (in 2003–04 dollar terms) that has been the trend since 1996–97. After a switch in exploration focus to the Murray Basin in Australia's eastern states, Western Australia's share of the Australian exploration expenditure for heavy minerals has fallen from around 70% of the total in the mid-1990s to only 28% in 2002–03, but during 2003–04 the share recovered to 44% of the total. The main greenfields exploration project is Coburn (south of Shark Bay), which is at the bankable feasibility study stage.

Exploration expenditure directed at copper–lead–zinc–silver in Western Australia is unchanged at $3.9 million, with little interest in the Lennard Shelf after the mines were placed on care and maintenance by Teck Cominco Ltd.

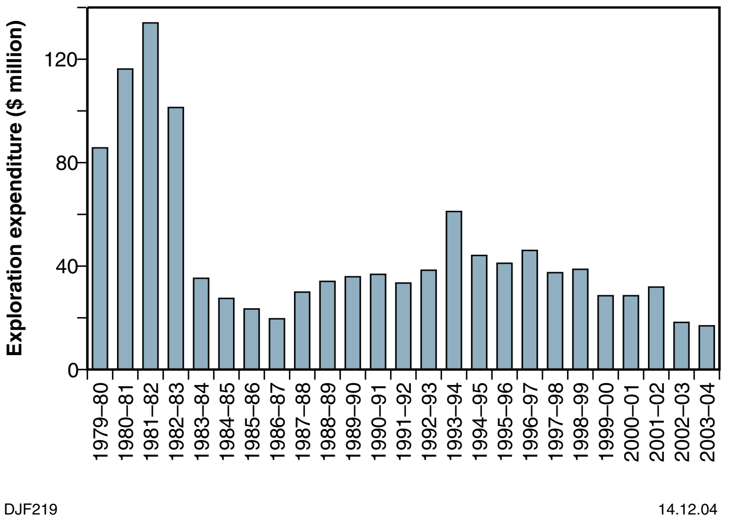


Figure 8. Diamond exploration expenditure in Western Australia, by financial year (2003–04 dollars)

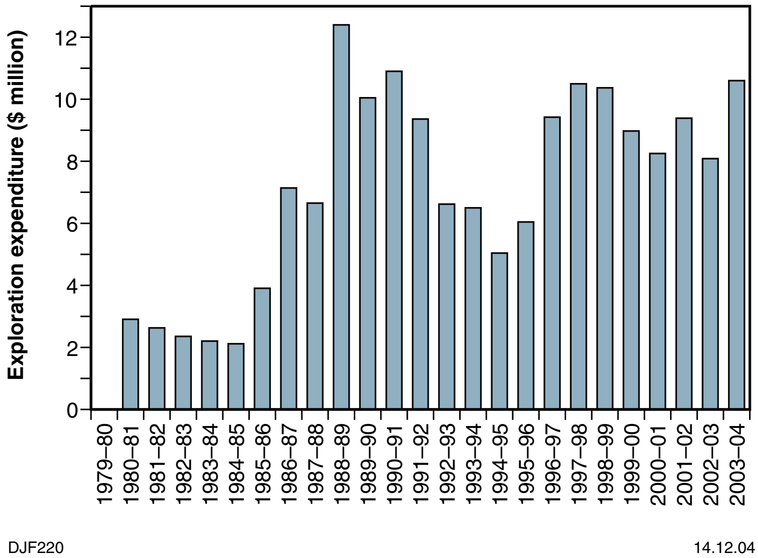


Figure 9. Heavy mineral sands (Ti–Zr) exploration expenditure in Western Australia, by financial year (2003–04 dollars)

Exploration expenditure directed at 'other' minerals in Western Australia fell by 14.4% ($3.1 million) to $18.5 million in 2003–04.

Drilling activity

Exploration drilling activity throughout Australia has declined markedly from the peak reached in 1996–97. At the low point in 2001–02 activity had declined by 55% (7.120 million metres) from that peak level, but during the last two years mineral exploration drilling has started to recover slightly, and during 2003–04 mineral exploration drilling in Australia rose by 10.7% (0.554 million metres) to a total of 5.711 million metres (Fig. 10). The estimated mineral exploration drilling in Western Australia follows the same trend (the estimate is based on Western Australia's proportion of the total Australian exploration expenditure for each year).

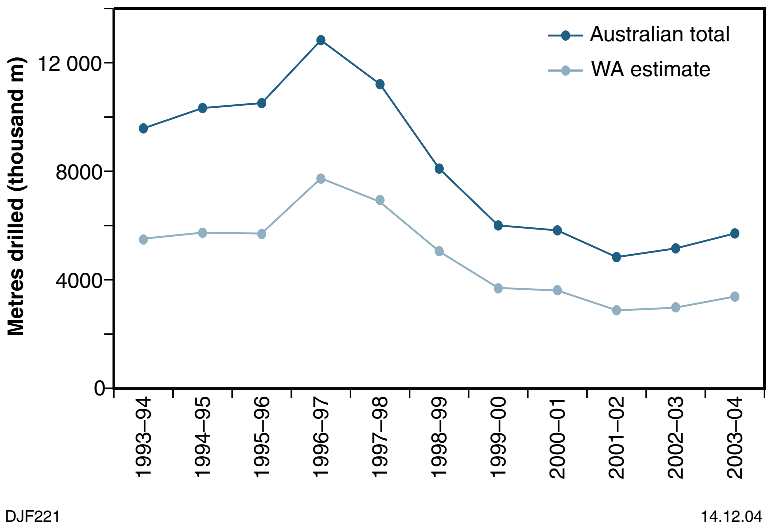


Figure 10. Mineral exploration drilling in Australia and Western Australia, by financial year (metres drilled)

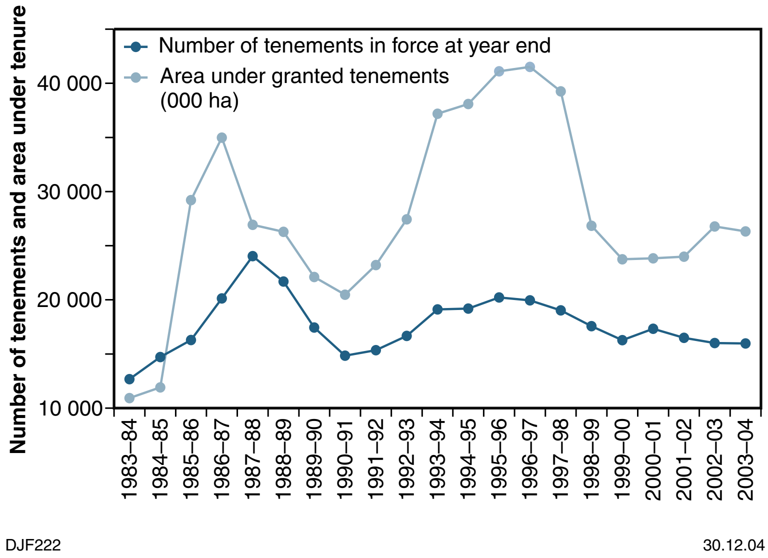


Figure 11. Tenement activity, Western Australia (1904 and 1978 Mining Acts). Source: DoIR

Mining tenement activity

The broad trends in mineral exploration expenditure (an increase of 10–11% for each of the last two years) is not reflected in the 2003–04 mineral tenement statistics*. For all tenements under the Mining Acts of 1904 and 1978, the total number of tenements in force and their corresponding area (as at 30 June 2004) exhibited very slight declines, but only of the order of 0.3% and 1.7%, respectively (Fig. 11). The trends for individual tenement types (Prospecting Licences, Exploration Licences, Mining Leases, etc.) are the same, with marginal decreases for nearly all tenement types in both number of tenements in force and area under tenure. The only increase was in the number of Exploration Licences (up by 2.0%), but the area under tenure by Exploration Licences fell by 1.1%. The distribution of tenements, both granted and under application, is shown in Figure 12.

The data suggest (but do not prove) that increasing mineral exploration expenditure is occurring mostly in brownfields areas, whereas the decline in the area of Exploration Licences under tenure is indicative of continual weakness in the level of greenfields exploration.

* Tenement data supplied by DoIR's Mineral Titles Branch and published in the Department's Annual Reports for 2002–03 and 2003–04.

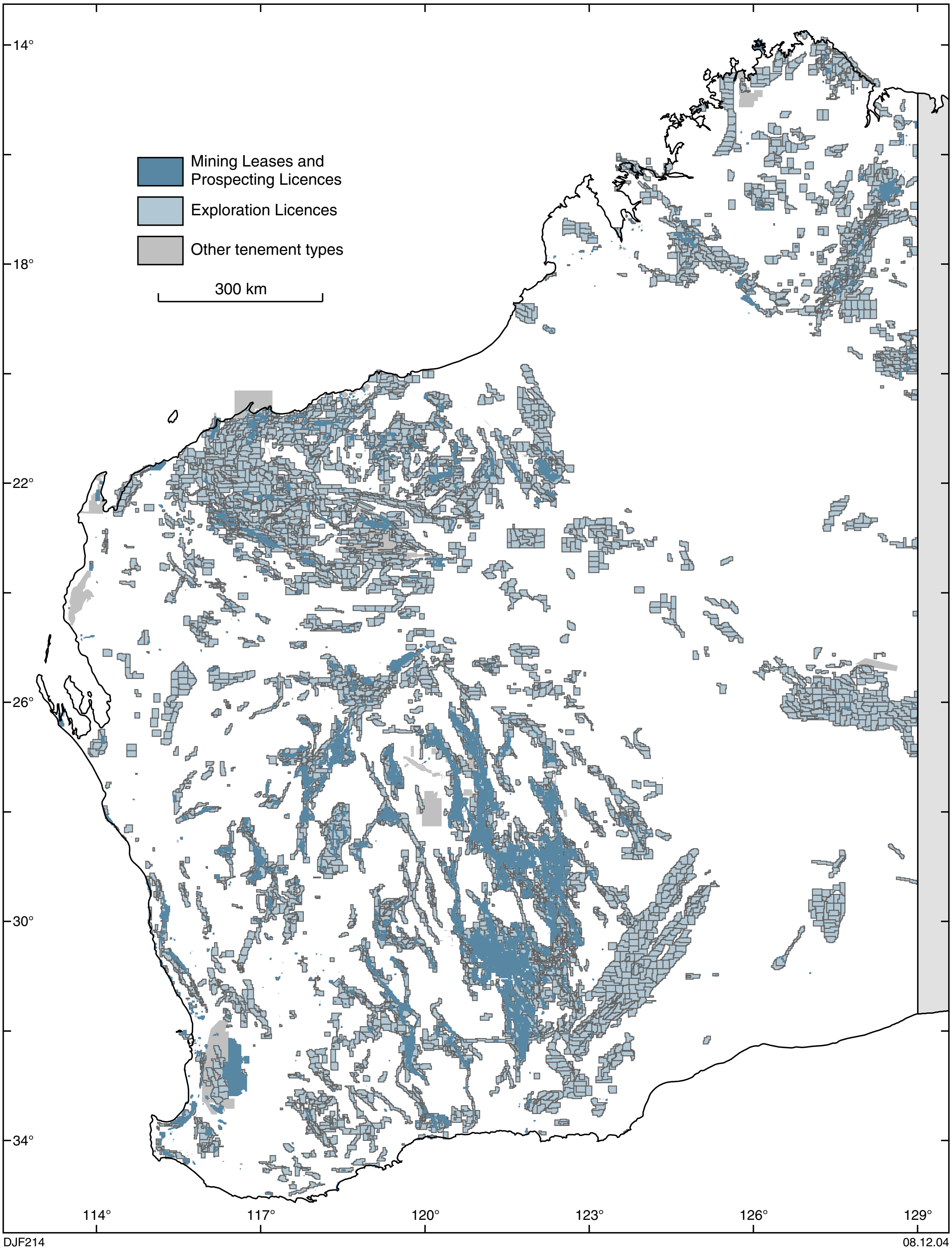


Figure 12. The distribution of mining and exploration tenements, granted and pending, in Western Australia as at 30 June 2004

Airborne geophysical coverage of Western Australia

by S. H. D. Howard

Abstract

Western Australia's vast size presents a formidable challenge to obtain statewide coverage of pre-competitive geophysical data of sufficient resolution to be of real use to explorers. The Western Australian Government's investment of $12 million, for a four-year regional geophysical survey program starting in 2004–05, is a welcome boost to the capacity of the Geological Survey of Western Australia to provide much-needed regional aeromagnetic and radiometric coverage for some of the State's most prospective areas. However, considerable additional funding will be required to complete basic data coverage of Western Australia as recommended by recent State and Federal government reviews.

While there is little doubt of the value of government investment in pre-competitive geoscience information, there is no simple solution to the trade off between extent of coverage and resolution detail in airborne geophysical surveys. In this context, the Geological Survey has adopted a strategy that seeks to optimize the effect of the present funding initiative by integrating new flying programs with the purchase of existing data. Its four-year plan seeks to complete 400 m-resolution coverage of magnetic and radiometric surveys over areas where Precambrian rocks are exposed or within 300 m of the surface. Commencing with surveys in the southern Yilgarn, priority areas for future work include the Murchison–Gascoyne region, the eastern wheat belt, the Albany–Fraser Orogen between Esperance and Warburton, the Musgrave–Arunta region on the Western Australia border, and the west Kimberley. There are also plans for collection of other data such as orthophotography and hyperspectral sensing, geochemical and gravity surveys, and some deep crustal seismic traverses in key areas of the State.

Introduction

In February 2004 the Premier of Western Australia announced his intention to invest an additional $12 million over the next four years to double the area of the State covered by modern airborne geophysical surveys. The funding was confirmed in May 2004 with the inclusion of the 'Geoscience Information Program – Minerals' in the WA State Government budget for 2004–05, and the allocation of the first tranche of $3 million as an addition to the standing budget of the Geological Survey of Western Australia (GSWA) for the provision of Geological Services (Department of Treasury and Finance, 2004).

This initiative has been welcomed by the minerals industry, and is a valuable boost to the capacity of GSWA to provide much-needed regional aeromagnetic and radiometric coverage for some of the State's most prospective areas. However, the fact remains that the present pre-competitive airborne geophysical coverage in Western Australia is still at a very low level, with only about one third of the State presently covered by non-proprietary, appropriate-resolution* surveys.

While it is easy to accuse governments of being niggardly, the vast size of Western Australia (which, at 2.5 million km^2, is one third of the total area of Australia and more than a quarter that of China, Canada, or the United States) requires a disproportionately higher level of expenditure in relation to the size of the economy for the provision of suitably detailed geophysical coverage.

Not surprisingly, it has never been an easy task to convince Western Australian State Governments and the Federal Government and their Treasury Departments to invest funds in the acquisition of regional pre-competitive geophysical data in Western Australia at a rate that might be considered desirable by explorers.

This article summarizes the background to the current state of publicly-owned airborne geophysical coverage of Western Australia, reiterates the rationale for government funding of pre-competitive information, and, in the context of the dilemma between coverage and detail, outlines GSWA's data-acquisition strategy and four-year plan.

Background to the current geophysical funding initiative

Previous airborne survey funding initiatives in WA

The latest funding boost occurs 20 years after the first such specific initiative funding in 1984–85, when, over four years, $282 000 were allocated for the purchase of about 200 000 line-km of non-exclusive, commercial airborne magnetic and radiometric data in the Eastern Goldfields and Murchison. The total area covered by these 200 m line-spaced datasets was the equivalent of about twelve 1:100 000 map sheet areas (30 000 km^2), or slightly more than 1% of the area of the State. These purchases did not include the publication rights to the digital data, only the right to publish hard-copy contour maps of the data.

1990–91 saw the first injection of Federal Government funds for an airborne geophysical survey in Western Australia at a line spacing of less than 1600 m — at that time the standard adopted for large-area government surveys — when the Bureau of Mineral Resources (now Geoscience Australia) purchased 45 000 km of existing commercial 400 m line-spaced data over the Edjudina 1:250 000 sheet area. This was followed by the next injection of State airborne survey funding of almost $250 000 in 1991–92 for the purchase of about 110 000 line-km of non-exclusive commercial data in the Kanowna and Kurnalpi regions.

In 1993, the State Government introduced a focused, longer term program for the provision of regional geoscience data with the announcement of a $20 million, four-year 'Accelerated Mapping Initiative', including $500 000 per year for airborne geophysical data acquisition. Over the course of the next four years, working in close cooperation with Geoscience Australia (then the Australian Geological Survey Organisation) to optimize the use of State and Commonwealth funds, GSWA spent $2.2 million on new airborne magnetic and radiometric surveys flown at a line spacing of 400 m, and purchases of existing non-exclusive and proprietary company survey data. By the end of 1996–97, some 1.3 million line-km of publicly owned survey data at 400–500 m line spacing or less was available over large areas of the central and northern Yilgarn, western Pilbara, and Kimberley.

The government extended the Accelerated Mapping Initiative funding for a further four years to 2000–01. With the inclusion of Commonwealth-funded surveys through Geoscience Australia, by the end of 2000–01 total public coverage had increased to 2.1 million line-km over almost 500 000 km^2 of the State.

* In this context, resolution refers to the spacing between survey lines. Although the along-line sampling rate and the flying height also affect data resolution, their impact is less important for large-area surveys until the survey-line spacing is 100 m or less. What constitutes 'appropriate-resolution' depends on a number of factors, which are discussed more fully in the text.

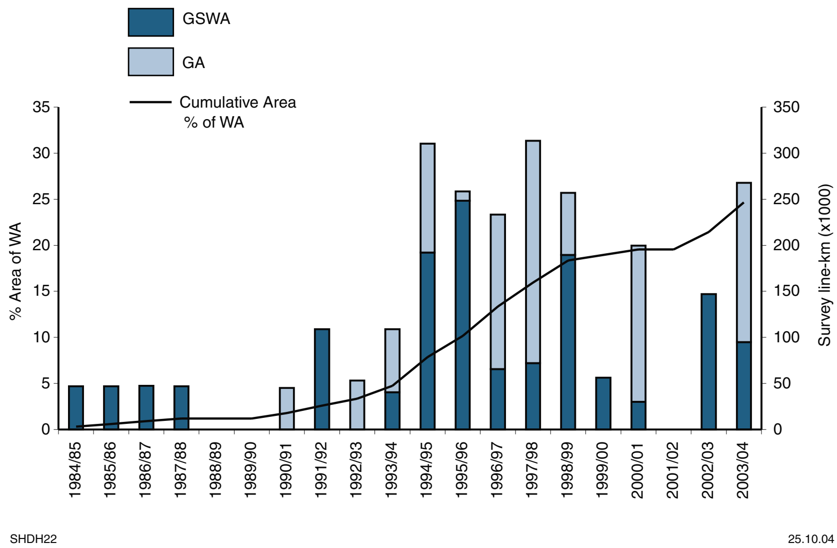


Figure 1. Annual government airborne geophysical data acquisition in Western Australia (1984–2004)

During the next three years, GSWA was able to direct a total of $1.1 million towards new surveys in the west Musgrave and west Tanami regions and in the northern Murchison. With Geoscience Australia surveys in the central and south Murchison, by the end of 2003–04 a further 415 000 line-km of data covering 128 000 km^2 had been added to the government-owned data inventory in Western Australia, taking the total to approximately 2.5 million line-km over about 600 000 km^2 (Fig. 1).

Publicly accessible data also includes proprietary data flown by commercial survey companies on a non-exclusive basis, and private exploration company data made available for public sale or, when possible, released by the Department to 'Open File' for public access.

Taking all these datasets into account, the airborne geophysical coverage of Western Australia is much improved although still well below 50% of the State's area. Figure 2 shows the spatial distribution of government-owned, commercial, and otherwise publicly available airborne geophysical datasets in June 2004.

Recent government inquiries

The Fardon Report

In mid-2000, as the four-year extension to the Accelerated Mapping Initiative was drawing to a close, the government commissioned a review of the programs and funding of GSWA. The Task Force, lead by Dr Ross Fardon and including one representative from the WA exploration industry and one from the State Treasury Department, made the primary recommendation for a 'significant increase in funding for GSWA from the current $17 million to about $40 million per annum' together with 'catch-up' of about $90 million over seven years.

Among its detailed recommendations for the application of increased funding, the Task Force proposed expenditure of $60 million over seven years ($8.5 million per year) for the acquisition of aeromagnetic and radiometric data. This, it was recommended, should include 100 m line-spaced surveys over about 750 000 km^2 of 'highly prospective areas' ($5.4 million per year; $38 million over seven years) and 400 m line-spaced surveys over the remaining 1.75 million square kilometres of the State ($3.1 million per year; $22 million over seven years).

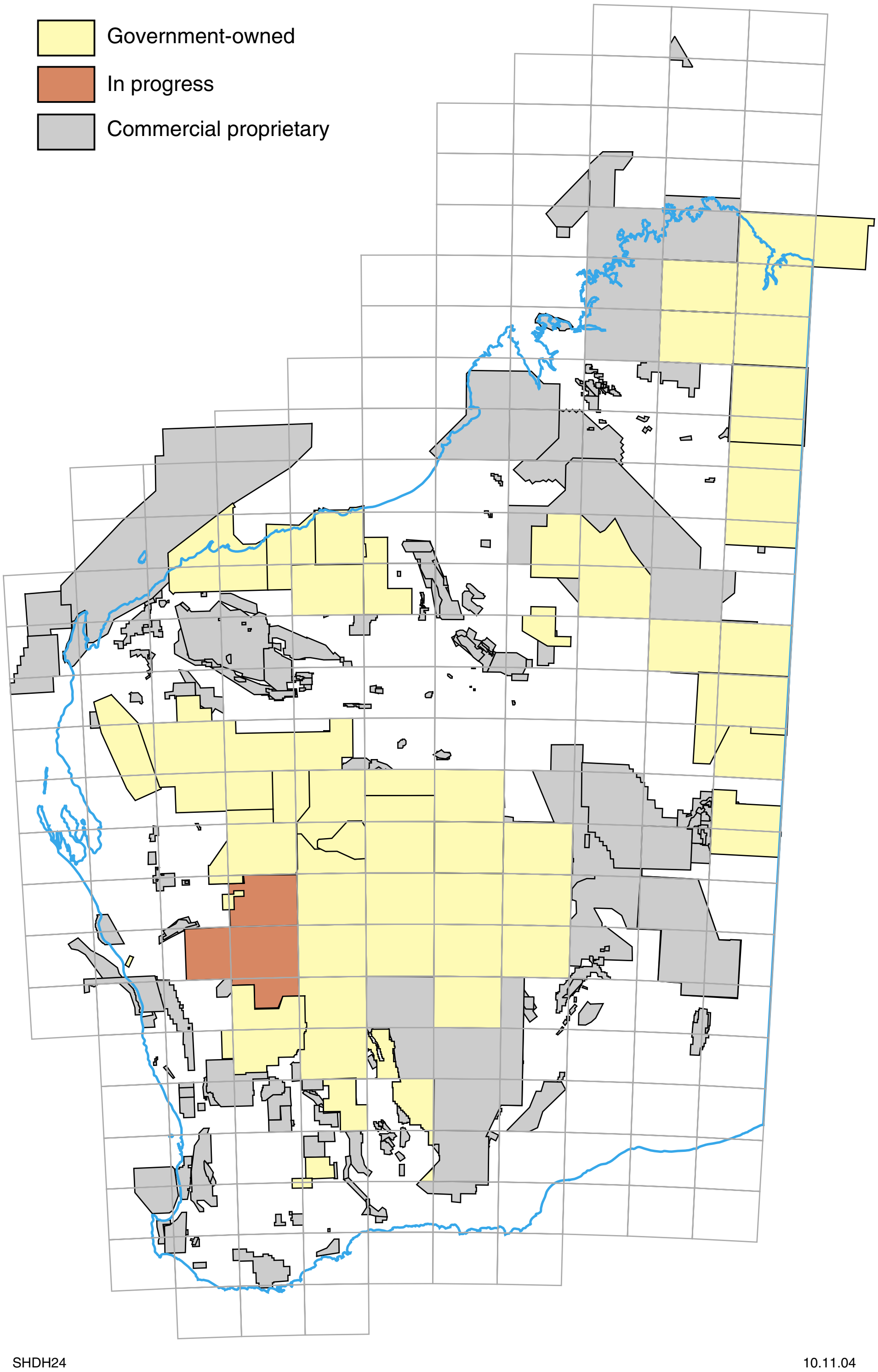


Figure 2. Publicly accessible airborne geophysical datasets in Western Australia in June 2004

The Fardon Task Force also proposed an investment of $14 million over seven years for the acquisition of 2 km × 2 km gravity data over some 25% of the State.

The Bowler and Prosser Inquiries

The State Government's response to the Fardon Task Force report was cast in the context of an extended period of low investment in mineral exploration generally and in greenfields exploration (defined as more than 5 km from existing mines) in particular. Activity data indicated that mineral exploration activity in 2001–02 had fallen 47% from its peak of $705 million in 1996–97, and there were few signs of improvement. Exploration expenditure in greenfields areas had fallen 63% during this period.

The government decided to review not only the issue of pre-competitive geoscience information in Western Australia (the primary concern of the Fardon Task Force), but also to investigate other factors that might be contributing to the exploration downturn. A Ministerial Inquiry, led by John Bowler MLA, was established in April 2002 with the objective of recommending actions to stimulate the level of expenditure necessary to sustain the future of the resources sector in Western Australia.

The woes of the mineral exploration sector were not confined to Western Australia, and concerns were also being expressed at a national level. In May 2002, the Federal Minister for Industry, Tourism and Resources referred a similar inquiry — albeit with a broader scope — to the House of Representatives Standing Committee on Industry and Resources chaired by Geoff Prosser MP.

Not surprisingly, both inquiries found there were a number of factors that impact on exploration activity and — also unsurprisingly given Western Australia's pre-eminent position in the Australian exploration sector — the factors identified in both inquiries were essentially the same (Bowler, 2002; Prosser, 2003):

- Investment attractiveness (capital raising and taxation)
- Perceptions of prospectivity (pre-competitive geoscience information)
- Geoscience education, research, and development
- Titles systems (security of tenure)
- Access to land (Native Title and environmental issues)
- Approval regimes
- Community understanding of the resources sector

While specific recommendations in the two reports (33 from Bowler; 28 from Prosser) were different both in emphasis and priority, both inquiries placed very significant emphasis on the provision of pre-competitive geoscience data.

Bowler also made the more specific recommendations that the base level of activity within GSWA should be maintained at no less than its current level, and that regional geophysical data coverage, especially in greenfields regions, should be expanded with a special allocation of $24 million over six years.

The Minerals Exploration Action Agenda

Almost in parallel with the Prosser (House of Representatives) inquiry, in September 2002 the Federal Minister for Industry, Tourism and Resources announced the development of the Minerals Exploration Action Agenda (MEAA) to address the decline in exploration in Australia. A Strategic Leaders Group (SLG) of industry and government representatives was formed to identify the priority issues and assess possible solutions. The SLG presented a report to government in July 2003.

The SLG, supported by four subsidiary working groups, identified the priority issues impacting on exploration investment in Australia: difficult access to land and finance, and increasingly inadequate geoscience data and mineral exploration research (SLG, 2003). These issues largely echoed the sentiments of the Bowler and Prosser inquiries.

Included among the SLG's 12 recommendations was a call for greater government investment in pre-competitive geoscience information. This was endorsed by the Ministerial Council for Mineral and Petroleum Resources in September 2003, with a proposal for a ten-year, $25 million per year program for pre-competitive geoscience information to be co-funded by the Commonwealth and the States.

In July 2004, as part of the Federal Government's 'Resources Exploration Strategy', the Minister for Industry, Tourism and Resources released *Minerals Exploration — The road to discovery: the Minerals Exploration Action Agenda (MEAA)*. Among the 'range of practical measures to ensure the long term sustainability of the minerals exploration industry and the mining industry which it underpins', was the call for a 'major pre-competitive geoscience survey program to achieve national coverage of basic geoscience datasets to modern standards' (Department of Industry, Tourism and Resources, 2004).

However, additional funding for such a program was not made available in the Federal budget for 2004–05; it remains to be seen whether it will be forthcoming in the next budget.

The rationale for government investment in pre-competitive geoscience information

The value of exploration

The value of exploration to the economy of the State is widely accepted not simply as an article of faith, but because:

a) it is patently obvious that — rare serendipitous finds aside — discoveries and resources development will not occur without prior exploration;

b) the correlation between exploration and resources development can be determined (at an aggregated level) by statistical and economic analyses*;

c) the impact of exploration expenditure on the economy can be readily estimated by econometric modelling†; and

d) even if the exploration is unsuccessful, there is still a contribution to the economy (and to the State coffers) from the exploration expenditure itself and its flow-on multiplier effects (e.g. Clements and Qiang, 1995).

Even taking into account concerns about any potentially negative cultural and environmental impacts, there is little argument of the value that exploration has in economic terms. It is more difficult by far to measure the effect on exploration activity of pre-competitive (geoscience) information and thus set a quantum on how much government funding should be allocated to it. While various qualitative studies have been conducted (a number are referenced in a recent review by Hogan, 2003), there appear to be very few accepted quantitative analyses.

* For example, over 17 years from 1985 to 2002, the estimated finding cost for gold in Australia was around A$60–70/oz for grassroots exploration, compared with an estimated A$12–18/oz for mine-site exploration (Schodde, 2003).

† An analysis in Appendix 3 to the Bowler Report (Bowler, 2002) suggests that an $80 million decrease in annual exploration expenditure for five years (in Western Australia) will have detrimental effects on the State Government income flows in terms of losses in payroll tax, stamp duty, royalties, and other tax incomes, resulting in a total revenue loss of more than $1.5 billion (undiscounted) over 20 years. In contrast, an annual increase in exploration expenditure of $100 million for five years is likely to have a positive impact on the State's economy, resulting in a total revenue increase of more than $1.7 billion over 20 years (Department of Mineral and Petroleum Resources and Department of Treasury and Finance, 2002).

The link between exploration and pre-competitive geoscience information

Exploration carries two inherent classes of risk. One is what may be termed 'country risk'*. As echoed by the recent government reviews, this risk includes a number of factors, the impact of which will vary from company to company and country to country. These include land access, fiscal and legal framework, mining law, negative environmental legacies, security of tenure between discovery and mining, and, in some cases, the level of corruption that is prevalent in a target country (Bavinton, 2004). But before evaluating these various risk factors, an exploration investor must select an area to assess by considering the other type of inherent exploration risk — 'geological risk', often referred to as 'perceived prospectivity' or the likelihood that an economic deposit will be found in the area.

Geological prospectivity is the first criterion for selection of a geographical location for exploration and can make a dramatic difference to the level of exploration activity. For example, in a period when global exploration expenditure dropped from US$5 billion in 1997 to US$2 billion in 2002 (and echoed in the level of exploration investment in Australia), investment in the search for deposits in Finland *increased* from 25 million euro in 1997 to over 40 million† in 2002 (Sailas, 2003).

Public or pre-competitive geoscience information is what illuminates the geological potential or prospectivity of a country or area for evaluation by explorers. It follows that the amount, quality, and accessibility of pre-competitive geoscience information for a particular area are likely to be critical determinants of exploration activity in that area. Not surprisingly, again, this was a conclusion reached by the three recent government reviews.

While the qualitative link between pre-competitive geoscience information and exploration activity is well established, less well defined is the quantitative link. Estimates provided to the Prosser Review suggest that every $1 spent by the government in the provision of pre-competitive information stimulated private exploration expenditure from $3 to $15, with an average of $5‡.

This figure is compatible with a 1999 Canadian estimate that 'every $1 million of government investment to enhance the Geoscience knowledge base will likely stimulate $5 million of private sector exploration expenditures which, in turn, will result in discovery of new resources with an average in situ value of $125 million' (National Geological Surveys Committee, 2000).

These estimates of value might well be significantly higher if they were to include a component for the value of the information for use by other sectors of the economy and by governments as a basis for decision-making support on issues of land use and infrastructure.

Of course, if it were that simple and clear-cut, government treasuries would be throwing money at pre-competitive geoscience. After all, if the models and estimates are correct, then an additional $20 million per year of government investment in pre-competitive information for five years will generate an increase in exploration expenditure of $100 million per year, which in turn will lead to an increase in (undiscounted) revenue of $1700 million over 20 years. Even undiscounted, 1700% return over 20 years is not a shabby investment.

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* Here the term 'country risk' is not used synonymously with 'sovereign risk' but includes sovereign risk, which is generally taken to mean the risk of actions by the government that might prove detrimental to a project.

† While these expenditure figures may seem small in relation to mineral exploration expenditure in Western Australia, if they are normalized in terms of currencies and the respective land areas, they translate into an increase in expenditure from about $123/km^2 to $197/km^2 for Finland compared with a decrease in Western Australia from $278/km^2 to $146/km^2.

‡ South Australia: $3–$5 (Prosser, 2003, paragraph 4.23, p. 53); Queensland: $15; Geoscience Australia: Average of $5 (Prosser, 2003, paragraph 4.24; p. 54).

These arguments about the quantitative value of pre-competitive geoscience information in attracting exploration investment are less than convincing to some of the holders of the community's purse strings.

However, because the qualitative arguments cannot be convincingly refuted, they cannot be entirely ignored. But the lack of a strong quantitative link and the fact that any returns are almost invariably long-term seem to result in an inconsistent commitment and, hence, very variable levels of funding for this purpose by most governments. Where funding boosts do occur, they often appear to be a reactive response to crises in the resources sector rather than a forward-looking approach to ensure its longer term sustainability.

Resolution and coverage in regional geoscience surveys

The resolution of a geoscientific dataset is a function of the density and precision of observations: the greater the density of observations and the better their precision, the more detailed is the scale of the geological features that can be mapped. Because precision tends to be largely a function of the available technology at any given time, resolution becomes a question of data density.

Regardless of whether governments are reluctant or lavish providers of funds for the acquisition of pre-competitive geoscience information, there is the perpetual question of what is the 'appropriate' resolution in the data. Too much detail, and the government risks becoming involved in the exploration process itself (which some governments choose to do). Too little, and it fails to have the desired effect.

The key factors governing the 'appropriate' degree of resolution are the coverage that is required and the scale of geological features that are to be mapped.

Airborne magnetic survey resolution

The observation density and, hence, the resolution of an airborne geophysical survey, particularly a survey flown with the objective of large-area mapping, tends to be almost wholly determined by the spacing between the survey lines (and the line direction in relation to the geology). Certainly the actual data resolution is a function of the flying height, the along-line sampling interval, and the measurement precision, but for the purposes of display and qualitative interpretation — except in certain specific-objective surveys — their impact is much less important until the line spacing is about 100 m or less.

In Figure 3 are shown two aeromagnetic images over the same area; the image in Figure 3a was produced from a dataset flown at one eighth of the line spacing of that in Figure 3b. The difference is stark. On the basis of the magnetic images, the two areas could almost be different. Why should one even consider spending funds on the coarser survey if it cannot decipher the detail clearly demonstrated in the higher resolution survey?

Would it were so simple. While nature contains a mind-numbing infinity of detail, our resources to gain access to that detail are all too finite (in which dichotomy lies the economist's claim to relevance). In almost all cases, the choice we are faced with is not between the 'equi-area' options illustrated in Figure 3 but the 'equi-cost' options illustrated in Figure 4; in other words, the choice between coverage and scale.

The choice between coverage and scale

Governments and explorers, both with limited funds, are faced with the same dilemma: the choice between a detailed survey in a restricted area and a coarser survey over a larger area.

Besides the community demand for equity of treatment between different areas of the country, there are some strong drivers for governments to place a higher priority on uniform coverage of a broad area at coarser resolution than on more-detailed coverage over a restricted area.

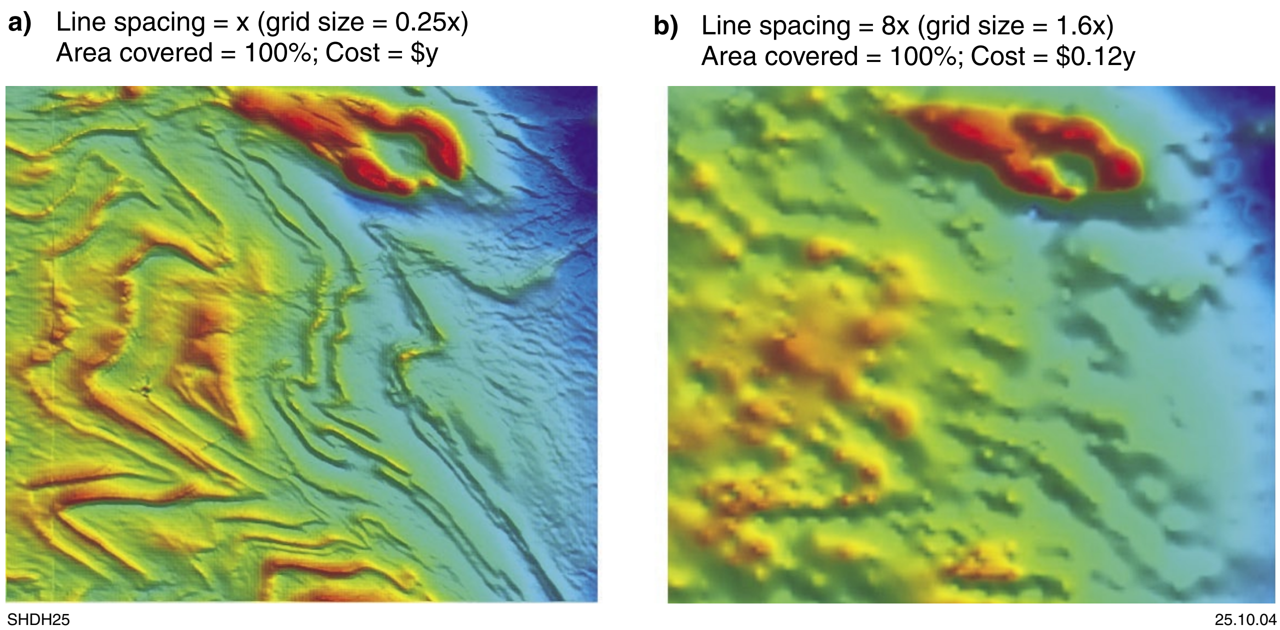

Figure 3. Illustration of equi-area aeromagnetic data coverage options. Location and scale deliberately suppressed

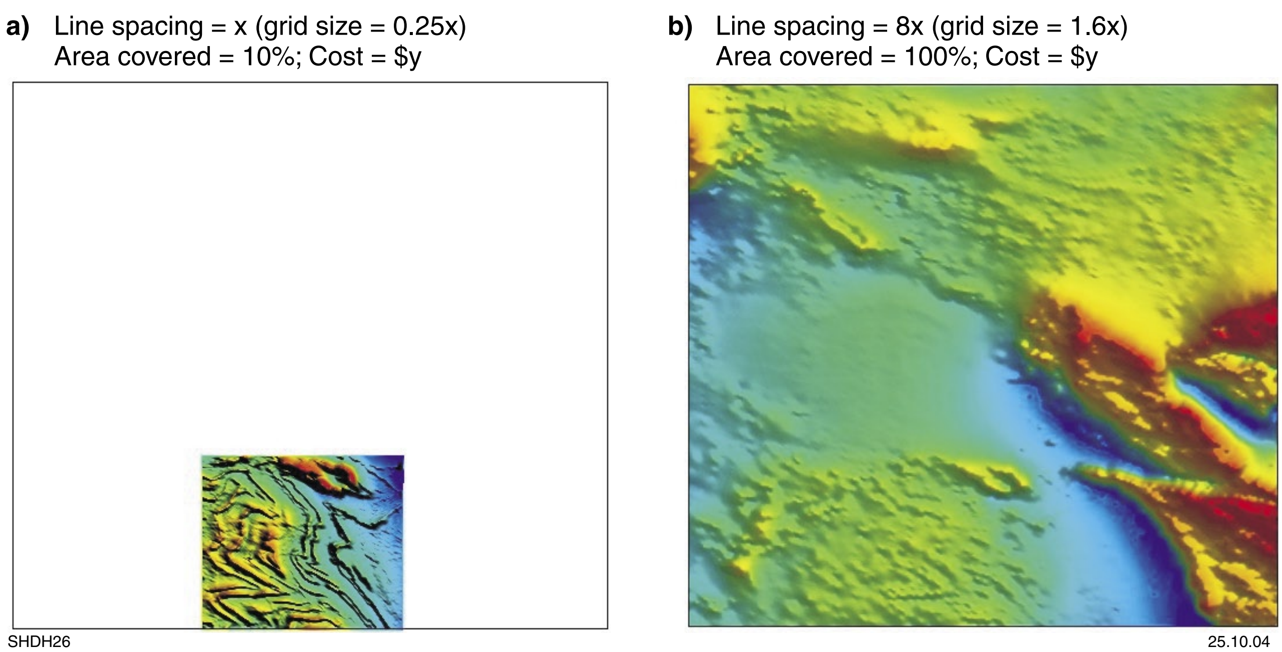

Figure 4. Illustration of equi-cost aeromagnetic data coverage options. Dataset in illustration a) is the same as that shown in Figure 3a. Processing stretches adjusted separately in each dataset

Almost all of the billions of dollars spent annually on exploration around the world are accounted for by explorers who take the approach of interpreting (coarser) datasets over larger areas to infer the location of smaller areas for targeted and detailed exploration activity (in which activity lies the geoscientist's claim to relevance). Therefore, if overview data from an area are publicly available at zero or minimal cost, the area is likely to be more attractive to an explorer than if the data were not available; it is the primary reason why government-provided pre-competitive information is so important as an incentive for private exploration*.

Another, also very strong driver is the demand for uniform regional geological coverage from the professional geoscientists and geoscience organizations who provide indispensable technical advice to governments and corporations. These professionals are well aware that in geology, as in most scientific disciplines, major new insights can be gained from the analysis of data patterns over extensive areas, thus providing a context into which detailed observations can be placed and better understood. A dramatic example of this is the impact of the 1950s measurement and discovery of the linear magnetic anomaly patterns in the North West Pacific and their interpretation in the 1960s to lend support to the revolutionary theory of plate tectonics.

Because a government-initiated program to provide large-area coverage only has any plausibility if it is programmed to be done in a specified time frame, the area, time, and budget together serve to set a limit on how detailed such a survey can be.

The situation is not stable. Once uniform pre-competitive data coverage at any particular resolution has been acquired over an area, there will be pressure to improve that resolution, either because of advances in technology or the availability of higher resolution coverage in other, competing areas for exploration investment.

Scale as a determinant of appropriate resolution

If the area that is to be surveyed is determined, the size of geological features that are to be mapped can be an absolute determinant of the required resolution, whether for exploration or regional surveys. For example, the maximum line spacing that can minimally resolve a steeply plunging stratigraphic fold closure is half the 'wavelength' or the 'amplitude' of the fold depending on the line direction relative to the strike (Fig. 5).

In practice, things are not quite as simple because geological features are not regularly defined. Nor, in exploration, can the 'size of target ore body' be used as a strong criterion unless one is confident that the target deposit is 'geologically well-behaved', which is generally not the case.

Therefore, 'map depiction scale' (i.e. the scale at which a depiction of the geology or geoscience data is to be displayed for the purposes of analyses or to make comparisons with the geology of another area) is often used as a surrogate for 'geological scale'. Thus, the detail of geological features that one might expect to find on a map at 1:100 000 scale is different from what one would expect on a map at 1:500 000 scale.

This idea of 'map depiction scale' can be used to provide a convenient rule of thumb for determining the appropriate airborne survey resolution for coverage of a given area: a line spacing that is represented by about 1 mm at the intended

* There are also economic arguments. If the data were not available and two explorers both competitively undertook an overview survey in the same area, the duplication of work would represent a decrease of economic efficiency as the total sum (of both explorers' limited funds) spent on detailed, targeted exploration would be less than that if the overview survey was conducted only once. This is further reason for government-funded pre-competitive information and is what underlies the inclusion in most countries' exploration legislation of the requirement to make previous exploration data available to subsequent explorers.

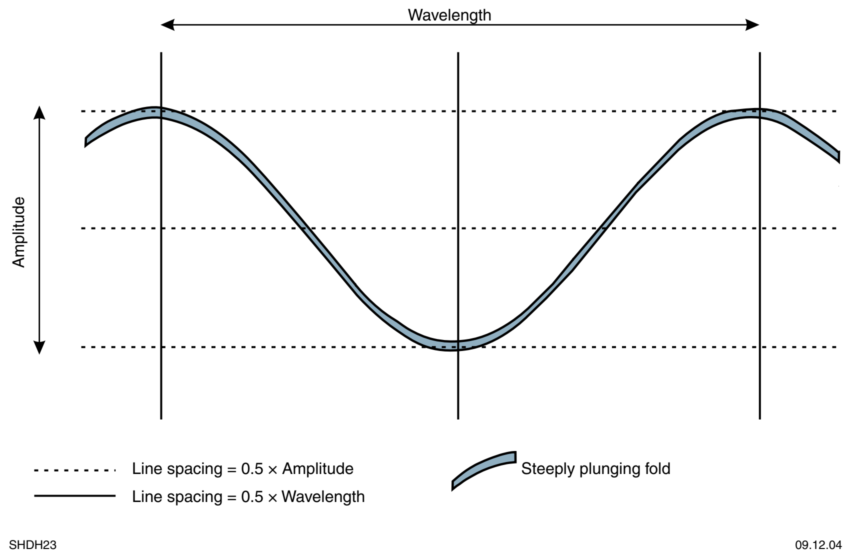

Figure 5. Survey resolution and geological scale

presentation scale. So an appropriate resolution survey for a standard 1:250 000 scale area of 1° latitude by 1.5° longitude (about 100 km × 150 km in Western Australia) might have a line spacing of about 250 m (ranging from about 100 m, or 0.4 mm at presentation scale, to about 400 m, or 1.6 mm at presentation scale).

These concepts of coverage and scale are important in understanding the scope of the current funding initiative and as a basis for the GSWA data-acquisition strategy.

Scope of the current funding initiative

The present funding program of $12 million per year over four years for the provision of regional geophysical data is an order of magnitude more than previous governments' investments for this purpose. Representing an addition of about 25% to GSWA's standing annual budget, it will make a significant difference to the level of pre-competitive regional geophysical data coverage in Western Australia.

To appreciate how significant, consider that this level of funding fully applied at the current cost of airborne magnetic and radiometric surveys represents coverage of about 800 000 km^2 or about 30% of the State's total area (at 400 m line spacing). If realized, this magnitude of coverage over a four-year period would be almost the same as that achieved by the aggregated State and Commonwealth funding over the past 20 years. Its importance as a potential turning point in the government's attitude to the resources sector cannot be understated.

However, it is just as important that this level of funding be viewed in the context of the challenge faced by Western Australia in providing appropriate-resolution pre-competitive airborne geophysical data coverage over the entire state. Table 1 compares the current funding program compared with recommended levels from the recent reviews.

Although the current funding program is a necessary and welcome starting point, it is only half the lowest recommendation for pre-competitive airborne geophysical coverage of the State. It is a far cry from the proposals of the Prosser Inquiry and the MEAA SLG.

Table 1. Current WA funding program compared with recent recommended levels ($ million)

Review	*Magnetic/ radiometric*	*Gravity*	*Total*	*Timeframe (years)*	*$/year*
Fardon (2000)	$60	$14	$74	7	$10.5
Bowler (2002)	–	–	$24	6	$4.0
Prosser (2003)[a]	$22	$100	$122	10	$12.2
SLG (2003)[b]	–	–	$85	10	$8.5
Current program	**–**	**–**	**$12**	**4**	**$3.0**

NOTES: (a) The Prosser Inquiry recommendations did not mention specific dollar sums or time frames. The sums shown are estimates of the cost of the recommendations based on the following assumptions:
Rec. 6: Funds 'to accelerate onshore pre-competitive data acquisition programs'. The assumption is made that this means to complete coverage of remaining areas of the country with magnetic and radiometric surveys at 400 m line spacing or better. In Western Australia this is assumed to be 70% of the State, requiring 4.4 million line-kilometres of survey at an estimated cost of $5 per kilometre
Rec. 8: 'Conduct an airborne gravity gradiometry survey of the Australian landmass'. Gravity gradiometry surveys with the Falcon™ system mentioned by Prosser require a line spacing of not more than 500 m to be effective. Other systems may be able to utilize larger line spacings. At an assumed line spacing of 1 km, a nationwide survey would cost $600 million at present acquisition costs or $300 million allowing for a 50% reduction in cost for surveys of this size. The cost for Western Australia is assumed to be one third of this or $100 million. It is unlikely that such a program could be completed in less than 10 years with present supply capacity
(b) SLG Recommendation 8: Commonwealth/State co-funding of $25 million per year to 2014. One third for Western Australia, on the basis of its proportional area, is $85 million

But even these do not go far enough. It is not sufficient for Australia and Western Australia to simply play 'catch-up'. We must play 'leap frog'!

The dollar sums for the recommendations of the Prosser and SLG reviews were cast in a whole-of-Australia context. In contrast, the more moderate recommendations from the Fardon task force were constrained by what might be funded by the State alone. Combining the visions of all of these, Table 2 shows a coverage scenario that is challenging but achievable. The costs may seem high, but the total over eight to ten years is a fraction of the direct payments of royalties, rentals, and other taxes paid in a single year by the resources sector in Western Australia to the State and Commonwealth governments.

Table 2. Ambitious 10-year airborne geophysical coverage scenario in WA

	Magnetic and radiometric surveys[a]				*Gravity/Gradiometry*			*AEM[b]*
Resolution (m)	100	200	400	**Total**	500	1000	**Total**	**500**
Area (% of WA)	30	25	10	**65**	50	50	**100**	**50**
Area (km^2 × 1000)	750	625	250	**1 625**	1 250	1 250	**2 500**	**1 250**
Line-km (× 1000)	7 500	3 125	625	**11 250**	2 500	1 250	**3 750**	**2 500**
Cost ($ million)	38	16	3	**56**	100	50	**150**	**75**
Time frame (years)				**8**			**10**	**8**
Total cost								**$280 million**

Assumptions	*Magnetic and radiometric*	*Gravity*	*AEM*
Cost ($/line-km) (Gravity = 40% of present rates; AEM = 50%)	5	40	30
Acquisition rate (km per year per aircraft)	250 000	150 000	150 000
Survey aircraft (per year)	6	3	2

NOTES: (a) Assumes that there is existing coverage at 400 m resolution over 35% of the State
(b) AEM = Airborne electromagnetic surveys, mentioned but not recommended by the Fardon Task Force

Plainly, the scope of the current initiative is insufficient to come close to a program of this magnitude. As mentioned above, the current State funding alone will be insufficient to complete even basic 400 m-resolution magnetic and radiometric coverage of the State. While there is every hope that the MEAA will result in a major injection of Commonwealth funding, there is no guarantee that this will occur and it is critical that the limited State funding be used to optimum effect.

GSWA data-acquisition strategy

The GSWA strategy for acquisition of regional geophysical data concentrates on optimum use of the current funding while keeping options open to take advantage of any additional funding from the Commonwealth or State governments.

Complete aeromagnetic coverage of the entire State at sub-500 m resolution is a major goal of GSWA. The existing 1:250 000 geological mapping, conducted mostly in the 1960s and 70s, is nearing the end of its useful life and it will be a long time before re-mapping at 1:100 000 scale — the focus of the current GSWA field-mapping program — has sufficient extent to become the definitive coverage, except over limited areas. Airborne magnetic and radiometric data and other remotely-sensed spectral data are being used to complement and enhance the existing 1:250 000-scale geology, and geological re-interpretation on the basis of data from the newer technologies effectively extends the useful life of this mapping. It is recognized that 400 m is at the outer limits of appropriate resolution for this scale of presentation, but it is considered that the benefits to be gained from a statewide coverage will outweigh the advantages of more-detailed surveys over restricted areas.

In order to maximize data coverage, resolution, and use, the GSWA geophysical-data strategy seeks to lower the unit cost of acquisition to the State by:

- encouraging private exploration companies to make their data publicly available;
- acquiring existing commercial and proprietary data of suitable quality and integrating them with new survey data rather than over-flying these areas;
- encouraging other State agencies, land use organizations, and exploration companies to apply their funds as appropriate to in-fill GSWA regional surveys with higher resolution surveys (thus taking advantage of lower survey rates that can be obtained for large survey contracts); and
- working closely with Geoscience Australia so that State funds are combined with any Commonwealth funds that can be directed to Western Australia, in order to fly larger survey blocks at lower per kilometre rates.

Because the current funding cannot be used to complete coverage of the State with any technique at the preferred resolution, it becomes important to attain best use of the data that exist at poorer resolution. To this end, GSWA will seek to acquire complementary datasets that might provide the control for better interpretations of wider line spacing data and allow workers to extrapolate interpretations from the more detailed coverage areas to the more poorly defined areas.

GSWA four-year plan within the current funding program

The primary objective for the program is to complete 400 m-resolution airborne magnetic coverage over areas where Precambrian rocks are exposed or within 300 m of the surface. All new surveys will also include radiometric data acquisition.

The provisional flying program is shown in Figure 6 with currently planned prioritization for surveys. These priorities may be modified as the program proceeds and circumstances change.

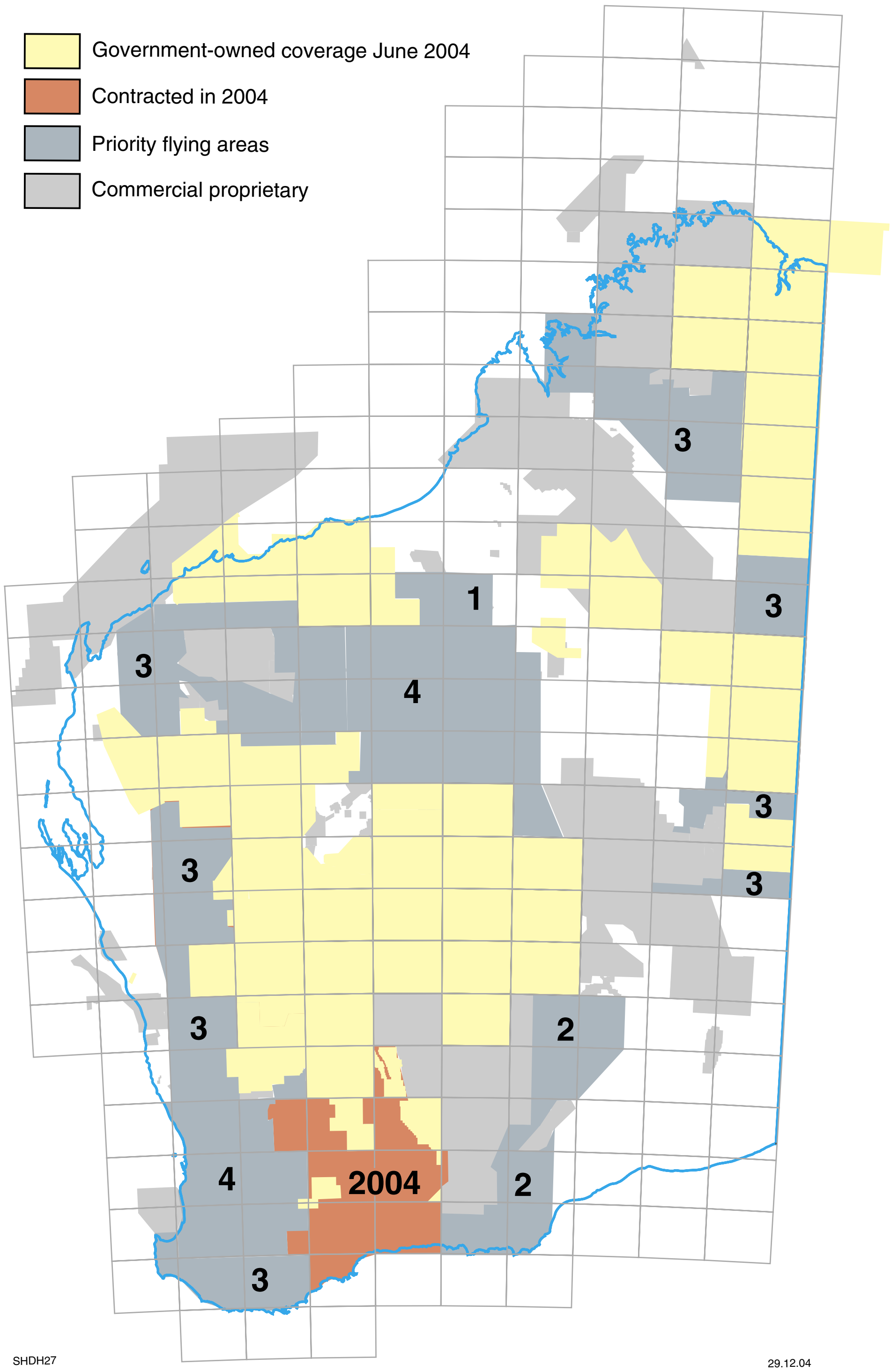

Figure 6. Priority areas for airborne magnetic and radiometric coverage 2004–2008

Survey contracts were let in July 2004 to acquire data in the southern Yilgarn. Together with the purchase and integration of existing company data, the surveys will provide coverage over an area of approximately 112 000 km^2, or 4% of the total area of the State, in a region extending from Kellerberrin to Ravensthorpe. Final data from these surveys should become available from late 2004.

Remaining priority areas include the Murchison–Gascoyne region, the eastern wheat belt, the Albany–Fraser Orogen between Esperance and Warburton, the Musgrave–Arunta region on the Western Australia border, and the west Kimberley. As funds permit, existing commercial and proprietary datasets of adequate quality will be purchased to integrate with the new data and add to the government-owned data inventory.

In addition to aeromagnetic and radiometric data, there are plans for collection of other data of interest to mineral explorers, such as orthophotography and hyperspectral-sensing, geochemical, and gravity surveys, and, in conjunction with Geoscience Australia and the Australian National Seismic Imaging Resource, some deep crustal seismic traverses in key areas of the State.

In the agricultural areas of the western wheat belt, it is hoped that additional State funds and matching Commonwealth funds from the National Action Plan for Salinity and Water Quality program might become available. If this happens, it will be possible to increase the magnetic and radiometric survey resolution in those areas for the benefit of agriculturalists, natural resource management groups, and mineral explorers alike. The target resolution in these areas is 100 m line spacing.

If matching Commonwealth funds from the MEAA become available, completion of aeromagnetic and radiometric coverage over the Phanerozoic basins becomes achievable, as does increased gravity coverage (whether ground or airborne).

The importance of the new data for enhancing existing geological mapping has not been overlooked, and new geological interpretations will be undertaken in areas of new geophysical coverage.

All data and interpretations will be released as soon as they are available.

Conclusions

Although a number of factors impact on exploration activity, there is no doubt the provision of pre-competitive, regional geoscience information is an important mechanism to attract private exploration investment to an area. The question of what constitutes the appropriate resolution for pre-competitive datasets is subjective and reduces to a trade-off between extent of coverage and degree of detail.

As a consequence, it can be difficult to determine the 'right' level of government funding for the provision of pre-competitive geoscience data. That difficulty is illustrated by the fact that four government reviews between 2000 and 2003 made recommendations for expenditure on pre-competitive airborne geophysical data over Western Australia that ranged from $24 million over six years to $122 million over ten years.

When arguments can be made for even higher expenditures than these, it is not surprising that government, when faced with such a variable response from its advisors, takes the minimal expenditure approach that has characterized Western Australian Government investment in regional geophysical surveys.

Clearly, the fact that all the recent reviews recommended dramatically increased levels of funding for the provision of statewide geophysical surveys has had an effect. The Western Australian State Government's current funding of $12 million for a four-year regional geophysical survey program is more than twice the amounts allocated by previous State Governments during the past 20 years. It will make a significant difference to the level of pre-competitive coverage of airborne magnetic and radiometric data in Western Australia. However, it is only a fraction of the sum needed to complete appropriate-resolution geophysical coverage of the State.

The reality is that investment in comprehensive, appropriate-resolution geoscience coverage is an investment in the State's infrastructure, in the same way as is investment in ports, roads, or the education system, and should be considered as such.

GSWA has a 10-year vision for pre-competitive geophysical coverage of Western Australia that includes, as a minimum:

- complete sub-500 m resolution magnetic and radiometric coverage over the entire state, and sub-250 m coverage of areas where Precambrian basement rocks are within 300 m of the surface; and
- complete 1 km-resolution airborne gravity or gravity gradiometry coverage over the entire State.

The vast size of Western Australia makes this a challenging, but achievable, goal. For it to become a reality, it requires a sustained commitment by State and Commonwealth governments; a commitment that transcends short-term political and economic cycles. It will need the Western Australian State and Commonwealth governments to have the same level of faith in the resources sector and make the same calibre of investment decisions that they are calling on private explorers to do.

Without such whole-hearted commitment, the vision of comprehensive geophysical coverage of Western Australia will remain nought but a pipe dream.

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Inside GSWA

Ivor Roberts

Ivor Roberts graduated from the University of New South Wales with an honours degree in applied geology. He then completed a doctorate on felsic volcanic rocks and associated mineralization at the University of Wollongong, after which he returned to UNSW to pursue and develop his research interest in clay minerals. The origin and mode of formation of these minerals have many implications for the interpretation of geological processes of weathering, sedimentation, diagenesis, and hydrothermal alteration. This research led Ivor to develop a speciality focused on understanding the formation of clay minerals within the regolith, an important contributor to the recognition of original rock types and the characterization of the near-surface expression of gold deposits and associated hydrothermally altered host rocks. Numerous presentations at conferences and publications resulted from this work.

Ivor moved west in 1990, accepting a lecturing position in the Department of Mineral Exploration and Mining Geology at WASM (the Western Australian School of Mines) in Kalgoorlie. The great breadth of subjects addressed in his lecturing ranged from general introductory geology to mineral analysis and computer applications in geology. He also supervised post-graduate research projects. He ran the XRD facilities at WASM and was responsible for an extensive collection of clay products and regolith materials from the Goldfields region well before the establishment of any official CRC-LEME interest in the regolith of the area.

Ivor travelled widely for academic reasons, including several visits to Vietnam to conduct intensive short courses in various aspects of geology at the University of Mining and Geology in Hanoi. He also conducted fieldwork associated with a joint research project into base metal mineralization west of Hanoi.

His considerable interaction with the minerals industry while lecturing at WASM caused a burgeoning interest in economic geology, leading Ivor to convene a series of geological symposia titled ‘Geology and mineralisation of the Eastern Goldfields’.

In 1997, Ivor deserted academia for the Geological Survey but, before leaving, he established a perpetual annual award, the ‘Dr F. Ivor Roberts Prize’, for the best pass student in first year geology at WASM. Joining the Survey as the manager of the East Yilgarn terrane custodianship, his position involved the management of the Kalgoorlie Regional Office of GSWA, and the commissioning of the Joe Lord core library in Kalgoorlie. The early part of this involved coordination of the assembly of the Eastern Goldfields digital map database and the necessary remapping and resolution of boundary discrepancies between the maps covering the 150 000 km^2 area mapped by many geologists from different backgrounds over more than ten years.

At the same time, Ivor undertook extensive liaison with the minerals industry to determine the most suitable procedures for stocking the forthcoming Joe Lord core library. His awareness of who had drilled what, and where, came to the fore when various companies were redefined (or disappeared) through mergers, as the core library was able to acquire 40 km of heritage diamond drill core very quickly.

Ivor's involvement with the mining and geoscientific profession has included committee membership of the Sydney branch of the Australasian Institute of Mining and Metallurgy (AusIMM) and chairmanship of the Kalgoorlie branch. His participation has continued in Perth, as he is now a committee member of the AusIMM Perth branch.

Ivor has always been community-minded and whilst living in Kalgoorlie was a member of the Hannans Rotary Club, which he found invaluable, both from the point of view of assisting those less well off in this mining community and for the development of friendships with community leaders.

Ivor married his childhood sweetheart, Judith, in 1980, and they have two daughters (Georgina and Briallen) and a son (Gareth).

Ann Fitton

On a hot October day in 1970, an English rose arrived in the Pilbara heat of 42°C carrying her tweed coat over her arm. Such was Australia's introduction to Ann Fitton, newly arrived from the UK with her (now ex-)husband Fritz, to take up the challenges of field geology. These were the heady days of the nickel boom and Ann and Fritz had been offered eight jobs, seven of them sight unseen. They accepted positions with Utah Development Company who had actually bothered to interview them in London.

Ann grew up in Sheffield, and graduated in 1969 from Leeds University with a BSc Hons in Geology/Geography.

Ann discovered on arrival that women geologists were still a rarity in Australia and that she had been employed only because the demand for geologists exceeded the supply of available male geologists. Despite having comparable qualifications and experience to that of her male colleagues Ann was also paid less. However, she spent five glorious years in the Pilbara running the camp for the team, which usually consisted of Ann and six blokes, and undertaking everything from geological mapping to diamond drilling. She loved the experience of camping, with the Hamersley Range at her 'back door' and interesting characters to meet in drilling teams, at the local stations, and at the Whim Creek pub.

After being made redundant when Utah closed its WA office in 1975, Ann worked in western NSW around Eleura, and then in Charters Towers in Queensland.

On returning to WA in 1976, Ann worked as a geological writer and co-editor of the first two editions of the *Register of Australian Mining*. It was interesting and challenging to play an integral role in the foundation of a publication, which has now become an icon in the industry.

From 1979 to 1990 Ann worked for CRAE and then Metana Minerals as an Administrative Geologist. In the 1990s she set up her own consultancy and continued her previous role of coordinating exploration reporting for submission to the department on behalf of a number of exploration companies. In 1997 Ann 'jumped the fence' and joined the Geological Survey in the role of Senior Geologist — Review. In this role she has been responsible for evaluating the reports submitted by industry — the very reports that she had previously prepared for submission. In the Survey, she has been a vital player in the development of the Digital Reporting Guidelines for submission of exploration reports to the WAMEX system in digital form, and in the redevelopment of the exploration information database.

In order to maintain her sanity Ann has always been active in a number of pastimes. She has been a 'folkie' since the 'Ban the Bomb' days and has been very active in the folk music scene in Perth, running folk clubs, concerts, and festivals. She is also a spirited dancer, having been known to dance on tabletops, tango in the streets of Buenos Aires, and play the fool at Morris dancing. She is a member and dance teacher of the Maids of Perth Morris dancing group, which she co-founded in 1978, and which still performs at fetes and fairs.

Another passion is Western Australian wildflowers. She enjoys wandering around the bush identifying and photographing wildflowers, particularly native orchids. To compensate for the relatively flat Western Australian countryside, Ann also has a passion for mountains and their spectacular scenery. She has trekked in the Himalayas, done the four-day walk to Machu Picchu in the Peruvian Andes, and earlier this year visited the Andes of Southern Chile.

She is currently working hard so that she can finance her next adventure.

Brian Dawson

Brian Dawson, affectionately known as 'Stoves', with more than 47 years of service, is the Geological Survey's, and possibly the Department's, longest serving employee.

Born in England, Brian and his family emigrated to Western Australia, arriving in December 1953. The family settled in the suburb of East Fremantle where he attended Fremantle Boys High School and later John Curtin High School.

After leaving high school Brian started in the Department of Mines as a temporary file clerk in the Inspection of Machinery Branch in November 1956. He hated doing paperwork and has never been able to file a piece of paper since. The current state of Brian's desk attests to this aversion and his office has been voted the messiest in the Survey for two years running.

From 1957 to 1960 Brian was a trainee/cadet in what came to be known as the Surveys and Mapping Division, and received a Diploma of Cartography from Perth Technical College in 1961. It was during this time that Brian received the nickname 'Stoves'. This alias was derived from 'Smoky' (as all Dawsons are labelled) and 'Smoky Stover' (a cartoon character at the time).

From 1961, as a qualified draftsman, Brian worked in a variety of areas within the Surveys and Mapping Division. It was not until the mining boom in the late 1960s that Brian specialized in the survey side of the Division's activities and by 1978 he was promoted to the position of Senior Cartographer supervising a surveys section of the Survey Services Branch. During this time Global Positioning System technology had emerged and Brian became the first person in the Department to test the new equipment in anger on a field trip to the Pilbara.

In 1991 he again had a career change and was moved to supervise the Geological Mapping Section of the Cartographic Services Branch. In the first six months of 1991 a pilot project to test new mapping technologies was trialled — to produce the first computer-assisted map in GSWA — which was the Cheritons Find 1:100 000 geological map. After the success of the pilot project, Brian was assigned the task of implementing the new technology in a production capacity, which gave rise to what is still the Computer Assisted Map Production (CAMP) Section.

Brian's career continued to evolve as he had commenced part-time studies in 1988 to gain a Bachelor of Science (Cartography) from Curtin University. On completion of his degree course in 1993 he was awarded the Alcoa prize for the best major project of the final year.

In 1995, as a result of the disbanding of the Surveys and Mapping Division, Brian joined the Geological Survey Division as a Senior Cartographic Officer supervising the Computer Assisted Map Production Section and was a Project Coordinator. His current title is Manager, Graphic Products, and under his guidance the CAMP area has continued to develop and flourish and today is a very well-oiled machine producing high-quality mapping products.

In recent years, Brian has managed the production, both inhouse and through the private sector, of orthorectified aerial photographs, which are the foundation stone of the new, improved geological mapping process.

Outside work Brian has been involved in diverse activities. From 1976 to 1980 he was Commodore of the 'East of Perth Yacht Club', organizing Friday lunchtime yacht racing. He was also a 'Weekend Warrior' in the Army Reserve for 28 years, rising to the rank of Major before retirement in 1988.

In 1997, a number of GSWA staff members started a project to hike along the entire Bibbulmun Track, a 963-km trek, to be done in stages. Over the years the group's enthusiasm waned and in 2004 Brian was the only member to complete the journey.

Brian's interests and hobbies include military history, sailing, and bushwalking. In preparation for his retirement he has also taken up watercolour painting. Brian has been married to Norma for 22 years (but it is Norma's assertion that it has been 23!) and has four children and two grandchildren.

Staff list (30 June 2004)

GRIFFIN, Tim (Director)

Regional Geoscience Mapping Branch

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

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

Edmund and Collier Basins
MARTIN, David
THORNE, Alan

Gascoyne
BAGAS, Leon
FARRELL, Terry

Earaheedy Basin
JONES, Amanda

West Musgrave
HOWARD, Heather
PIRAJNO, Franco
SMITHIES, Hugh

Eastern Goldfields (Kalgoorlie Office)
GROENEWALD, Bruce
GOSCOMBE, Ben
HALL, Charlotte
JONES, Sarah
RIGANTI, Angela

Central Yilgarn
CHEN, She Fa
WYCHE, Stephen

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

Lennard Shelf
PLAYFORD, Phillip

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

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

Publications and CAD
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DOWSETT, Suzanne
EDDISON, Fiona
HARTLEY, Gary
HOFFMAN, Arthur
JOHNSTON, Jean
JONES, Murray
KUMAR, Manjeet
LENANE, Tom
MARON, Marcel
MIKUCKI, Jennifer
MULLIGAN, Sue
NASH, Margie

NOONAN, Kath
PIZZI, Trevor
PRAUSE, Michael
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1 On secondment

Staff movements (1 July 2003 to 30 June 2004)

Internal reclassifications
COLLOPY, Sean — to Level 4
GOSCOMBE, Ben — to Level 5
HARTLEY, Gary — to Level 5
HOWARD, Heather — to Level 5
JONES, Sarah — to Level 5
LOCKWOOD, Andrew — to Level 5

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EVANS, David
FERGUSON, Andrew
HAINES, Peter
HO, Susan
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DOYLE, Mark
EASTMAN, Rachel
FOGARTY, Louise
HALL, Glennis
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RISBEY, Stephen
VICENTIC, Milan

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STAPLETON, Gladys — to Mineral Titles Division
LANGFORD, Richard — to Safety, Health and Environment Division
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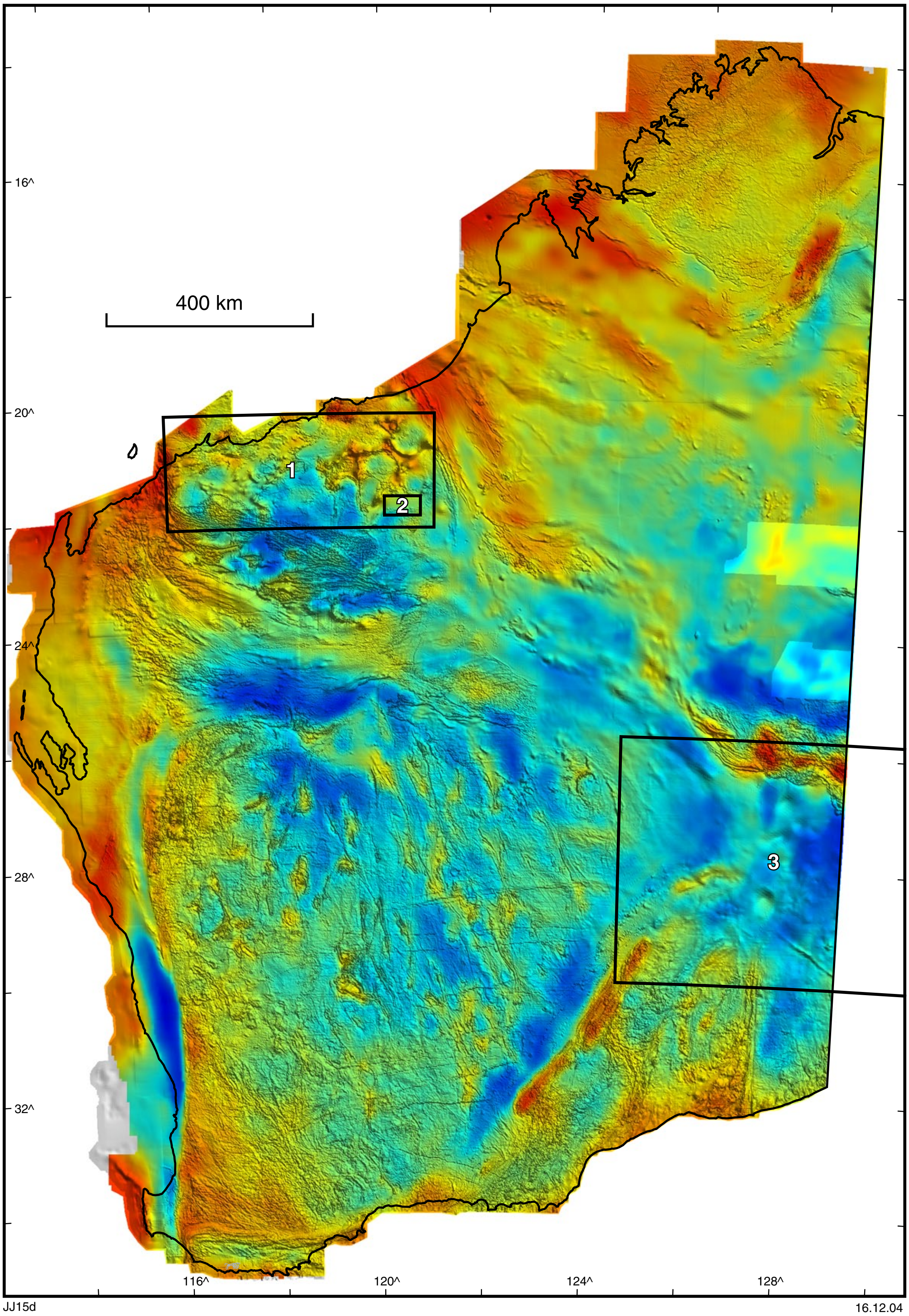

Map of Western Australia showing the locations discussed in three of the six technical papers on the following pages (Papers 4 to 6 cover the whole of Western Australia). Pseudo-colour Bouguer gravity and grey-scale Total Magnetic Intensity image. Blue = gravity low; TMI highlights structural information. Data courtesy of Geoscience Australia

Technical papers

Event stratigraphy applied to 700 million years of Archaean crustal evolution, Pilbara Craton, Western Australia

by M. J. Van Kranendonk, R. H. Smithies, A. H. Hickman, L. Bagas, I. R. Williams, and T. R. Farrell

Abstract

New geochronological and geochemical data from the pre-2.80 Ga granite–greenstone basement of the northern Pilbara Craton have been used to (a) erect a formal suite/supersuite stratigraphic scheme for its intrusive igneous rocks, and (b) revise the lithostratigraphy of its supracrustal succession. Previous divisions of the chiefly granitic intrusive rocks were informal, very generalized, and almost entirely based on intrusive and structural relationships. The three generations of granitic rocks recognized previously have now been replaced by eight supersuites and three suites. Four mafic intrusive suites have also been defined. Advances in the interpretation of the lithostratigraphy have come from a combination of detailed mapping and the acquisition of a large amount of precise geochronological data (chiefly from SHRIMP U–Pb zircon dating). Intrusive, volcanic, and mineralization events can be correlated with tectonic events, and major differences between the crustal evolution of the component terranes of the craton are recognized.

The pre-2.80 Ga basement in the northern Pilbara Craton evolved in four main phases: an early, largely cryptic phase of crust formation from 3.72 to 3.53 Ga; a major phase of crustal development from 3.52 to 3.24 Ga, involving construction of a volcanic plateau from a succession of mantle plumes; a period of rifting of the margins of the nucleus of the craton at c. 3.24 – 3.16 Ga; and a late phase of crustal growth involving horizontal (arc-accretion) tectonics from 3.13 to 2.90 Ga. Several distinct tectono-thermal events are recognized from 3.53 Ga onwards. These include: partial convective overturn of the middle and upper crust during mantle plume events at 3.43, 3.31, and 3.27 Ga; rifting of the Pilbara crust between 3.24 and 3.16 Ga to produce three separate granite–greenstone terranes; intra-oceanic arc construction at 3.12 Ga (Whundo Group); terrane accretion at c. 3.07 Ga; episodes of arc–continent collision between 3.02 and 2.90 Ga; and emplacement of post-tectonic granites at 2.89 – 2.83 Ga.

KEYWORDS: Archaean, Pilbara Craton, lithostratigraphy, suite, supersuite, event stratigraphy.

Introduction

This paper presents the latest lithostratigraphic scheme for Archaean granite–greenstone rocks of the northern Pilbara Craton, and the first suite/supersuite scheme for its intrusive igneous rocks. The new interpretation is based on information from geological mapping, geochronology (more than 200 precise SHRIMP U–Pb zircon age dates), and geochemical studies. These new data have been mainly acquired since 1995 during a joint Geological Survey of Western Australia (GSWA) – Geoscience Australia (GA) project, with additions from external researchers. All ages, except where specifically referenced, are from GSWA records published by D. R. Nelson, as cited in Van Kranendonk et al. (2002), and in Geological Survey of Western Australia (2004).

Geology of the Pilbara Craton

The Pilbara Craton comprises two major tectonic units: an assemblage of pre-2.80 Ga granite–greenstone terranes, and an unconformably overlying succession of volcanic and sedimentary rocks that were deposited in the 2.77 – 2.40 Ga Hamersley Basin (Trendall, 1990). About 65% of the granite–greenstone basement is concealed by the generally flat-lying Hamersley Basin succession; only in the northern part of the craton is this basement exposed over a very large area (Fig. 1). Here,

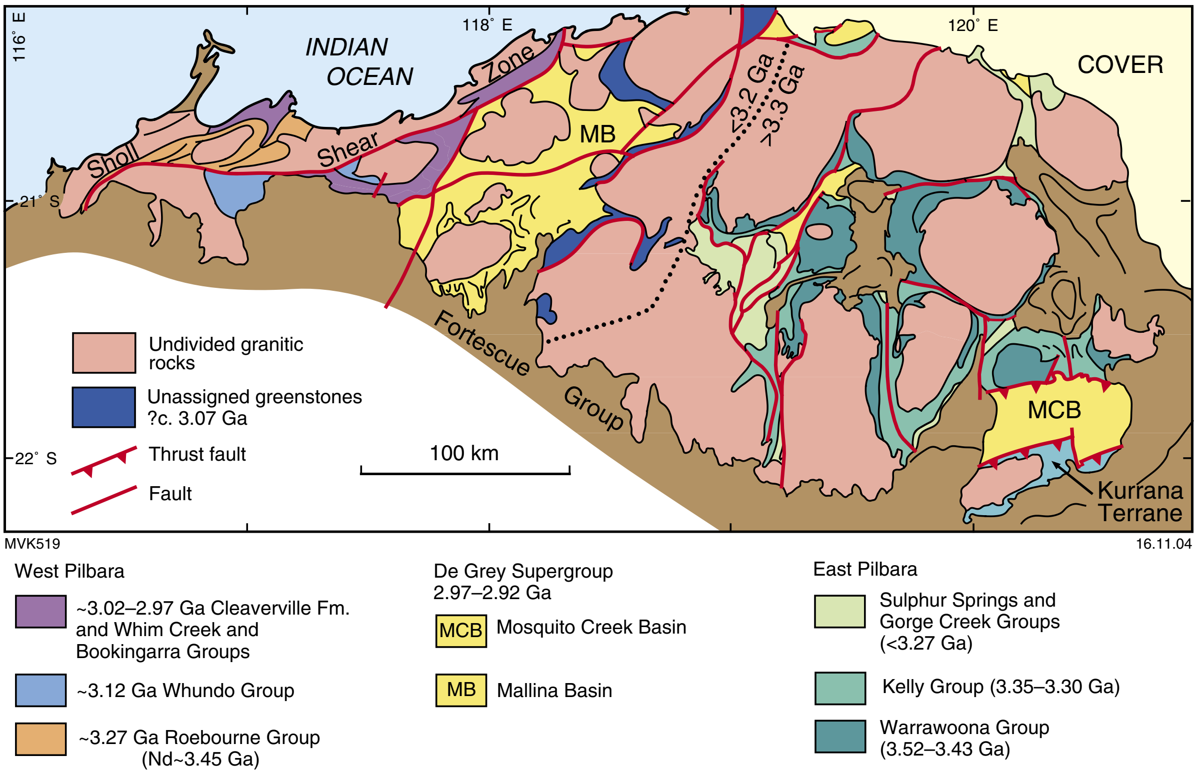

***Figure 1.** Generalized geology of the northern Pilbara Craton, showing main lithostratigraphic divisions of the West Pilbara and East Pilbara Granite–Greenstone Terranes and Kurrana Terrane, and the distribution of the De Grey Supergroup. Dotted line indicates a change in Nd-model age values within the east Pilbara (D. Champion, Geoscience Australia, 2004, written comm.)*

the craton contains three granite–greenstone terranes separated by younger clastic sedimentary basins (Hickman, 2001; Van Kranendonk et al., 2002.). The c. 3.27 – 2.92 Ga West Pilbara Granite–Greenstone Terrane (WPGGT) is separated from the c. 3.72 – 2.83 Ga East Pilbara Granite–Greenstone Terrane (EPGGT) by the c. 2.97 – 2.94 Ga Mallina Basin. Southeast of the EPGGT, the c. 2.95 – 2.92 Ga Mosquito Creek Basin is faulted against the dominantly granitic, and as yet poorly documented, Kurrana Terrane.

Previous models of Pilbara evolution

Hickman (1983, 1984) interpreted the granite–greenstone basement of the northern part of the Pilbara Craton as a single coherent crustal unit that had been deformed in episodes of vertical tectonics (D_1, D_2), and a late phase of horizontal deformation (D_3). Based on intrusive relationships and their structural history, Hickman (1983) recognized three main generations of granitic rocks, but further subdivision and detailed correlations between the various domical granitic complexes was prevented by a lack of precise radiometric age dating and geochemical data.

Tectonic models for the Pilbara Craton have evolved from the original concept of dominantly vertical tectonics (Hickman, 1983, 1984), to models of dominantly horizontal tectonics (Bickle et al., 1985; Krapez, 1993; Barley, 1993, 1997; Krapez and Eisenlohr, 1998; Smith et al., 1998), to more complex models involving intervals of both vertical-dominated (i.e. mantle-plume driven: Hickman and Van Kranendonk, 2004; Sandiford et al., 2004; Van Kranendonk et al., 2004a) and horizontal-dominated tectonics (e.g. Van Kranendonk et al., 2002; Hickman, 2004).

Van Kranendonk et al. (2002) described the EPGGT as the ancient nucleus of the craton, with a geological history from 3.72 to 2.83 Ga. The structural style of this terrane, dominated by ovoid granitoid complexes mantled by synclinal greenstone belts, has been attributed to several episodes of partial convective overturn of middle and upper crust (Collins et al., 1998; Hickman and Van Kranendonk, 2004; Sandiford et al., 2004; Van Kranendonk et al., 2004a).

Granitic rocks in the Pilbara Craton outcrop within large, domical areas that were referred to as 'batholiths' by Hickman (1983), although he emphasized that these structures were tectonically domed complexes containing granitic intrusions of widely differing ages. Griffin (1990) referred to these structural domes as 'granitoid complexes'. Van Kranendonk (1998) described the domical granitic complexes as litho-tectonic elements that did not necessarily reflect the original distribution of multi-component granitic rocks prior to deformation, as shown in a subsequent compilation of age data (Van Kranendonk et al., 2002, fig. 5).

Stratigraphy

The lithostratigraphy of the Pilbara Craton has been divided into two supergroups and several unassigned groups and formations, as shown in Figure 2. The Pilbara Supergroup is developed in the EPGGT, where autochthonous relationships can be demonstrated through unconformable contacts and precise age dating. The WPGGT contains groups and formations that are not assigned to a supergroup, although the Roebourne Group is provisionally correlated with the Pilbara Supergroup for reasons described below. The De Grey Supergroup is correlated across the entire Pilbara Craton, as it lies with an unconformable basal contact on rocks of the EPGGT and WPGGT (Fig. 1).

Pilbara Supergroup

The Pilbara Supergroup in the EPGGT comprises four groups deposited between c. 3.52 Ga and c. 3.0 Ga. The oldest group is the Warrawoona Group, which spans 100 m.y. from 3.52 to 3.43 Ga. The group is herein defined as comprising four subgroups: the Coonterunah (previously Coonterunah Group), Talga Talga, Coongan (new name), and Salgash Subgroups (Fig. 2).

Previously, the uppermost part of the Warrawoona Group included the Strelley Pool Chert, Euro Basalt, Wyman Formation, and Charteris Basalt in the Kelly Subgroup (Van Kranendonk et al., 2002), but these formations are now collectively ascribed to the Kelly Group because the base of the Strelley Pool Chert is a regional unconformity (Van Kranendonk et al., 2002 and M. Van Kranendonk, unpublished data). The rocks of these two groups contain inherited and detrital zircons as old as 3.72 Ga (Van Kranendonk et al., 2002, fig. 4), and basaltic rocks show geochemical evidence for crustal contamination (Green et al., 2000; Van Kranendonk and Pirajno, 2004), indicating the presence of an older basement.

The c. 3.25 – 3.24 Ga Sulphur Springs Group was deposited unconformably on the Kelly Group (Van Kranendonk, 2000; Buick et al., 2002), and comprises, from base to top, the Leilira Formation, Kunagunarinna Formation, and Kangaroo Caves Formation (Van Kranendonk et al., 2002). The Six Mile Creek Formation of Van Kranendonk and Morant (1998), formerly included at the base of the group (Van Kranendonk, 2000), is now considered to belong to the Euro Basalt, based on similar geochemistry between these units and the fact that the unconformity marking the base of the group elsewhere is well defined as the base of the Leilira Formation (Van Kranendonk, 2000).

The Gorge Creek Group (Lipple, 1975; Hickman, 1983, 1990; Van Kranendonk and Morant, 1998) is herein redefined as consisting of, from base to top, the Tank Pool Quartzite, Nimingarra Iron Formation, Pincunah Hill Formation, Corboy Formation, Paddy Market Formation, Honeyeater Basalt, and Pyramid Hill Formation (Fig. 2). The age of the group is unconstrained other than the base of the formation, which is gradational with the Sulphur Springs Group at Sulphur Springs, indicating a lower age of c. 3.235 Ga (Buick et al., 2002). The basal contact of the group varies from conformable to unconformable on older rocks. The top contact of the group is an unconformity with either the De Grey Supergroup or Mount Bruce Supergroup (Hamersley Basin).

The Golden Cockatoo Formation in the southwestern part of the EPGGT consists of metamorphosed clastic sedimentary rocks and banded iron-formation (BIF) that lie in (probable) unconformable contact with basement rocks of the Yule Granitoid Complex and in faulted contact with the Sulphur Springs Group (Van Kranendonk, 2003). Unpublished geochronological data from a quartzite horizon near the base of the formation suggest a maximum depositional age of 3192 ± 74 Ma (Nelson, D. R., Geological Survey of Western Australia, 2004, written comm.), which is close to the age of the Flat Rocks Suite of granitoid rocks emplaced during an interpreted rifting event (see **Events in the northern Pilbara Craton**) and within the age range of the Gorge Creek Group (Fig. 2).

The Budjan Creek Formation in the southeastern part of the EPGGT is a succession of clastic and felsic volcaniclastic rocks that unconformably overlies the Kelly Group (Bagas et al., 2004b). A volcaniclastic sample of the formation contains detrital zircons as young as 3228 ± 6 Ma, which is slightly younger than the age of the youngest components of the Sulphur Springs Group (c. 3235 Ma; Buick et al., 2002).

The undated Copper Gorge Formation is also restricted to the southeastern part of the EPGGT (Bagas, in prep.). The formation consists of pillowed basalt and komatiitic basalt. It lies in unconformable contact with rocks of the Warrawoona and Kelly Groups to the north and is in fault contact with the younger De Grey Supergroup of the Mosquito Creek Basin to the south (Bagas, in prep.).

West Pilbara Granite–Greenstone Terrane

Supracrustal rocks in the WPGGT range in age from 3.27 to 3.01 Ga (Fig. 2). The WPGGT has a distinctly different structural style than the EPGGT, characterized by a prominent northeasterly structural grain (Fig. 1; Krapez, 1993; Hickman, 1997; Smith et al., 1998; Van Kranendonk et al., 2002; Hickman, 2004). This terrane is a collage of three separate, fault-bounded tectono-stratigraphic domains, each of which contains a unique stratigraphic succession and structural history that differs from that of EPGGT (Hickman, 2004), as well as two overlying sedimentary

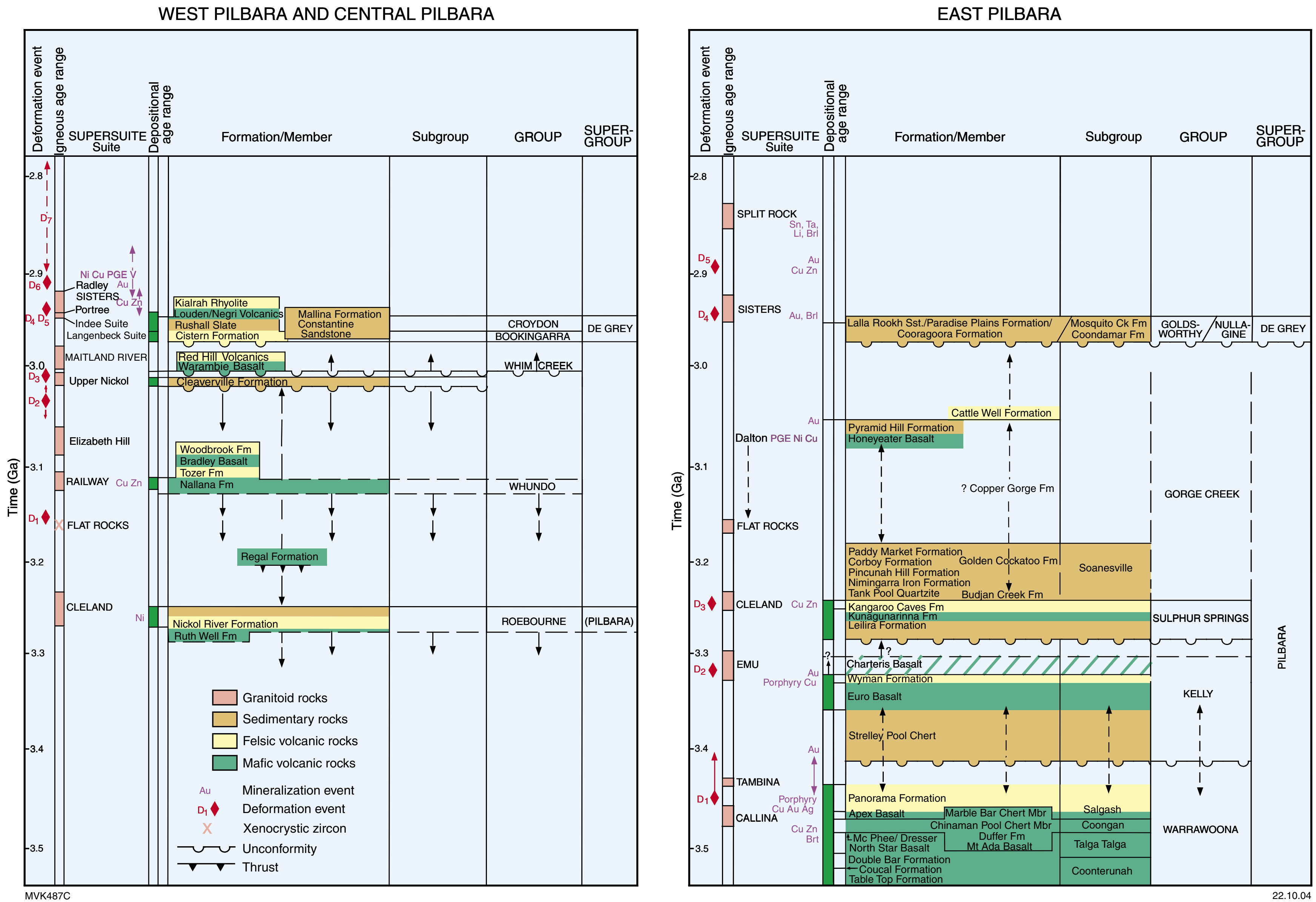

Figure 2. Event histories for the West Pilbara and East Pilbara Granite–Greenstone Terranes and central Pilbara, showing deformational events, igneous supersuites and suites, lithostratigraphic units, and mineralization events

basins, the Cleaverville and Whim Creek Basins. Designation of the Whim Creek Basin to the WPGGT is new, and based on geological data outlined below.

The main part of the terrane is transected by the 1 km-wide Sholl Shear Zone (SSZ) — a long-lived zone of early sinistral, and later dextral, transpressional shear strain (Hickman, 2004). North of the SSZ is the c. 3.28 – 3.25 Ga Roebourne Group, which is an ultramafic–felsic volcanic succession with overlying, subordinate clastic metasedimentary rocks. Isotopic data indicate that the group was deposited on c. 3.48 Ga crust, or was derived from a source region of this age (Sun and Hickman, 1998), but the basal contact of the group is obscured by intrusive 3.27 Ga tonalite and granodiorite, including the Karratha Granodiorite (K on Fig. 3).

South of the SSZ is the c. 3.13 – 3.11 Ga (Horwitz and Pidgeon, 1993; Smith et al., 1998) Whundo Group — a juvenile stratigraphic assemblage of bimodal basaltic and felsic volcanic rocks that shows no evidence of contamination by crust older than 3.28 Ga (Smith et al., 1998; Sun and Hickman, 1998) and that has no equivalent in the EPGGT succession. The Whundo Group (Fig. 2) is at least 10 km thick (Hickman, 1997), but neither the base nor the top is preserved. Hickman (1997) divided the group into four formations, based on lithostratigraphy. However, detailed geochemical analysis shows that the group consists of a much more complex volcanic succession, including a basal package of boninites that is interbedded with two distinct assemblages of calc-alkaline basalt to andesites (Smithies et al., in press). This package is overlain by a thick pile of tholeiitic basalts with arc to back-arc compositions. The tholeiites are in turn overlain by further calc-alkaline lavas with well-defined negative correlations between large ionic lithofile elements (and La/Sm) and high field strength elements (Smithies et al., in press). Calc-alkaline andesites are overlain by rhyolites, derived primarily through prolonged fractionation of tholeiitic magmas, and interbedded with adakitic lavas and Nb-enriched basalts — an association characteristic of arcs where slab melting contributes to metasomatism of the mantle wedge. This compellingly arc-like association, combined with the absence of felsic basement, the lack of any continental influence, the persistence of low Th/La ratios, and the faulted margin with a distinct terrane (Roebourne Group), points to an intra-oceanic arc setting for the Whundo Group.

The Roebourne Group is in tectonic contact across the Regal Thrust with the third domain, consisting of oceanic-type crust of the Regal Formation. Both the Roebourne Group and the Regal Formation include rocks at amphibolite facies metamorphic grade and were affected by D_1 deformation (Hickman, 2001; Kiyokawa et al., 2002).

Cleaverville Basin

The Regal Formation and the Whundo Group are unconformably overlain by BIF, chert, and clastic sedimentary rocks of the c. 3.02 Ga Cleaverville Formation, which is unaffected by D_1 deformation. The Cleaverville Formation lies both north and south of the SSZ, and thus provides a minimum age for the juxtaposition of the two domains and early sinistral shear deformation across the SSZ (Hickman, 1997, 2004; Kiyokawa et al., 2002). The Cleaverville Formation was previously correlated with the Gorge Creek Group of the EPGGT (Hickman, 1997), but new isotopic evidence for a c. 3.18 Ga crustal break in the western part of the EPGGT — an interpreted rift margin (see **Events in the northern Pilbara Craton**) — casts doubt on east–west correlations of any units deposited after this rifting event and prior to collision at c. 2.99 Ga. Thus the Cleaverville Formation is now interpreted to have been deposited in a separate basin, immediately preceding deposition of the Whim Creek Group.

Whim Creek Basin

The Whim Creek Group is a succession of a c. 3.01 Ga volcano-sedimentary rocks deposited unconformably on the Cleaverville Formation and the Whundo Group in the Whim Creek Basin (Fig. 2; Smithies et al., 2001). The Whim Creek Group represents an arc-related basin fill deposited on continental crust (Pike et al., 2002), and has no known counterparts in the EPGGT. These rocks are unconformably overlain by the volcanic Bookingarra Group and clastic sedimentary rocks of the De Grey Supergroup within the intracratonic Mallina Basin (see below).

Kurrana Terrane

The Kurrana Terrane, immediately south of the Mosquito Creek Basin, includes undated greenstones within granitoid orthogneiss dated at c. 3.18 Ga. These rocks are tightly folded and are faulted against the Mosquito Creek Basin. Only the northernmost exposures of the Kurrana Terrane are shown on Figure 1, and larger exposures of the same terrane are interpreted to be present 150 km to the south within the Sylvania Inlier (Hickman, 2004). The Sylvania Inlier was not remapped during the GSWA–GA project, and precise geochronological and geochemical data are very limited.

De Grey Supergroup

The c. 2.97 – 2.92 Ga De Grey Supergroup (redefined from the De Grey Group, as used by Van Kranendonk et al., 2002) is an intracontinental succession that was unconformably deposited on deformed and deeply eroded rocks of the Pilbara Supergroup and rocks of the WPGGT across the Pilbara Craton. Rocks of the supergroup are present in three major depositional basins, including the Lalla Rookh Basin in the EPGGT, the Mallina Basin between the EPGGT and the WPGGT, and the Mosquito Creek Basin that separates the EPGGT from the Kurrana Terrane (Fig. 1).

Lalla Rookh Basin

Eroded and deformed remnants of the supergroup in the EPGGT are referred to as the Goldsworthy Group (Van Kranendonk et al., 2002), and consist dominantly of

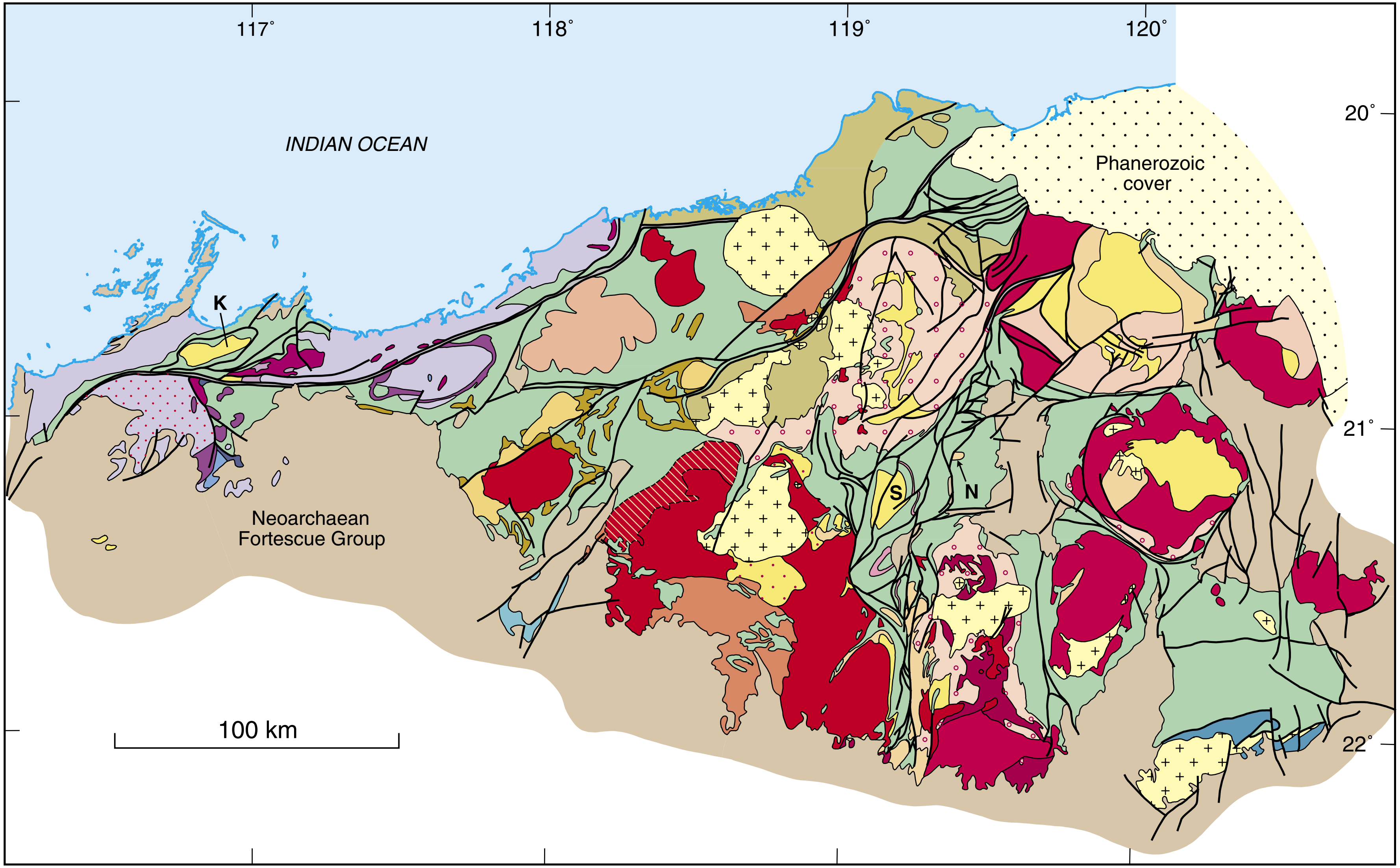

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Figure 3. Simplified geological map showing the distribution of igneous suites and supersuites in the northern Pilbara Craton. N = North Pole Monzogranite, S = Strelley Monzogranite, K = Karratha Granodiorite

Phanerozoic cover

Neoarchaean Fortescue Group

Greenstones, undivided 3515–2940 Ma

SPLIT ROCK SUPERSUITE 2880–2830 Ma

SISTERS SUPERSUITE 2970–2925 Ma

Undivided

Radley Suite ultramafic layered intrusions 2925 Ma

monzogranite 2945–2930 Ma; with inclusions of TAMBINA SUPERSUITE

monzogranite 2955–2945 Ma

Portree Suite 2946 Ma (alkaline granite)

Indee Suite 2954–2945 Ma (high-Mg diorite)

Langenbeck Suite (intrusive equivalent of Bookingarra Group)

MAITLAND RIVER SUPERSUITE 3006–2970 Ma; with SISTERS SUPERSUITE

Upper Nickol Suite 3024–3012 Ma

ultramafic intrusions

Dalton Suite (?3070 Ma)

Elizabeth Hill Suite 3093–3068 Ma

RAILWAY SUPERSUITE 3130–3114 Ma

FLAT ROCKS SUPERSUITE 3170–3160 Ma

Golden Eagle Orthogneiss c. 3178 Ma

CLELAND SUPERSUITE 3270–3235 Ma

CLELAND SUPERSUITE and SISTERS SUPERSUITE

EMU SUPERSUITE 3324–3292 Ma

leucogranite 3445–3410 Ma

CALLINA and/or TAMBINA SUPERSUITES

TAMBINA SUPERSUITE 3435–3420 Ma

CALLINA SUPERSUITE 3490–3450 Ma

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coarse-grained clastic sedimentary rocks. It is uncertain to what degree these sequences originally formed parts of a single intracratonic basin. Van Kranendonk and Collins (1998) presented evidence from structural geology for deposition of the Lalla Rookh Sandstone of the group during regional sinistral transpression dated at c. 2.940 Ga, but otherwise the Goldsworthy Group is undated.

Mallina Basin

The north-northeasterly trending Mallina Basin is more than 200 km long and up to 90 km wide (Fig. 1) and consists of the c. 2.97 – 2.94 Ga Bookingarra and Croydon Groups. The basal c. 2.97 Ga Bookingarra Group consists of volcaniclastic sedimentary rocks, siliciclastic sedimentary rocks, and basalts that unconformably overlie the Whim Creek Basin of the WPGGT (Pike and Cas, 2002). The overlying Croydon Group consists of largely siliciclastic rocks of the Constantine Sandstone and the Mallina Formation, and is dated at c. 2.95 – 2.94 Ga (Smithies et al., 1999, 2001).

Mosquito Creek Basin

The Nullagine Group, comprising the 2.95 – 2.92 Ga Mosquito Creek and Coondamar Formations (Fig. 2), was deposited in the shallow- to deep-water Mosquito Creek Basin between the EPGGT and the Kurrana Terrane (Fig. 1), possibly in a rift setting analogous to that of the Mallina Basin (see below). The group lies with unconformable contact on the EPGGT (Kelly Group) and Copper Gorge Formation along the northern margin of the basin, but is in faulted contact with the Kurrana Terrane to the south. Bagas (2004a — this Annual Review) discusses the composition and provenance of the Mosquito Creek Basin.

Intrusive rocks

Granitic rocks of the Pilbara Craton are herein divided into supersuites and suites, based on crosscutting relationships and structural fabric elements, geochronology, and geochemistry (Fig. 3; Van Kranendonk et al., 2004b). A supersuite scheme has been introduced following isotopic confirmation that different domical granitic complexes in the EPGGT contain similar age plutonic components (Van Kranendonk et al., 2002; Hickman and Van Kranendonk, 2004). The granitic complexes of the WPGGT lack evidence for tectonic doming, but are also multi-component bodies containing intrusions of similar age and chemistry. In addition to the multi-component granitic complexes, both terranes contain examples of single-component, subvolcanic intrusions (e.g. 3.46 Ga North Pole Monzogranite and 3.24 Ga Strelley Monzogranite in the EPGGT, and 3.27 Ga Karratha Granodiorite in the WPGGT — N, S, and K respectively on Fig. 3). Significant results from the suite/supersuite classification scheme include the recognition that the 3.48 – 3.45 Ga Callina Supersuite, the 3.44 – 3.42 Ga Tambina Supersuite, and the 3.32 – 3.29 Ga Emu Supersuite are exposed only in the EPGGT. The 3.27 – 3.24 Cleland Supersuite is present in both the EPGGT and the WPGGT, north of the SSZ, further supporting continuity of the two terranes at c. 3.24 Ga.

Granitic rocks with intrusive ages of 3.18 – 3.16 Ga (Flat Rocks Supersuite and Golden Eagle Orthogneiss) are restricted to the margins of the EPGGT and in the Kurrana Terrane, and probably relate to early rifting of the margins of the EPGGT in the present areas of the Mallina and Mosquito Creek Basins respectively (see **Events in the northern Pilbara Craton**).

A widespread suite of granitic rocks emplaced in the WPGGT at c. 3.01 – 2.97 Ga (the Maitland River Supersuite) is probably cogenetic with arc volcanism of the Whim Creek Group (Pike and Cas, 2002; Hickman, 2004) and subsequent collision between the WPGGT and EPGGT (Fig. 4). Intrusive rocks within the Mallina Basin include a 2.95 Ga suite of high-Mg diorite (sanukitoid) intrusions (Smithies and Champion, 2000), now collectively referred to as the Indee Suite, and widespread c. 2.95 Ga mafic–ultramafic sills and rocks with boninite-like compositions (Smithies, 2002), now assigned to the Langenbeck Suite. Light rare earth element enrichments in the parent magmas of these intrusions cannot be explained through assimilation of crust, and have been attributed to a mantle source. Smithies and Champion (2000) suggested that the mantle source was metasomatically enriched during a pre-3.00 Ga subduction event; subduction processes have previously been applied to both the c. 3.01 Ga Whim Creek Group (Pike and Cas, 2002) and the c. 3.12 Ga Whundo Group (Smith, 2003). Both groups are interpreted to underlie parts of the Mallina Basin.

Late- to post-tectonic (2.89 – 2.83 Ga), Sn–Ta–Li bearing monzogranites of the Split Rock Supersuite form a northwest–southeast linear array of intrusions across the Kurrana Terrane and EPGGT (Fig. 3). These intrusions were emplaced immediately following north–south compressional deformation and gold mineralization in the Kurrana Terrane in the southeast at c. 2.90 Ga (Huston et al., 2002).

Events in the northern Pilbara Craton

The recent advances in subdivision of the supracrustal and intrusive igneous rocks across the northern Pilbara Craton has led to a much better understanding of the event history of the craton, as summarized in Figures 2 and 4. Events prior to 3.27 Ga are restricted to the EPGGT.

Following an early, largely unpreserved history from 3.72 to 3.53 Ga, the main phase of crustal construction in the EPGGT began at 3.52 Ga with the development of a thick volcanic plateau (Warrawoona Group), founded on crust to 3.72 Ga (Van Kranendonk et al., 2002; Van Kranendonk and Pirajno, 2004). Volcanic plateau formation was the result of nearly 100 m.y. of nearly continuous, dominantly basaltic volcanism that was erupted in mafic–felsic cycles of about 15 m.y. duration (Hickman and Van Kranendonk, 2004). Within this history, felsic volcanism at 3.47 – 3.46 Ga was

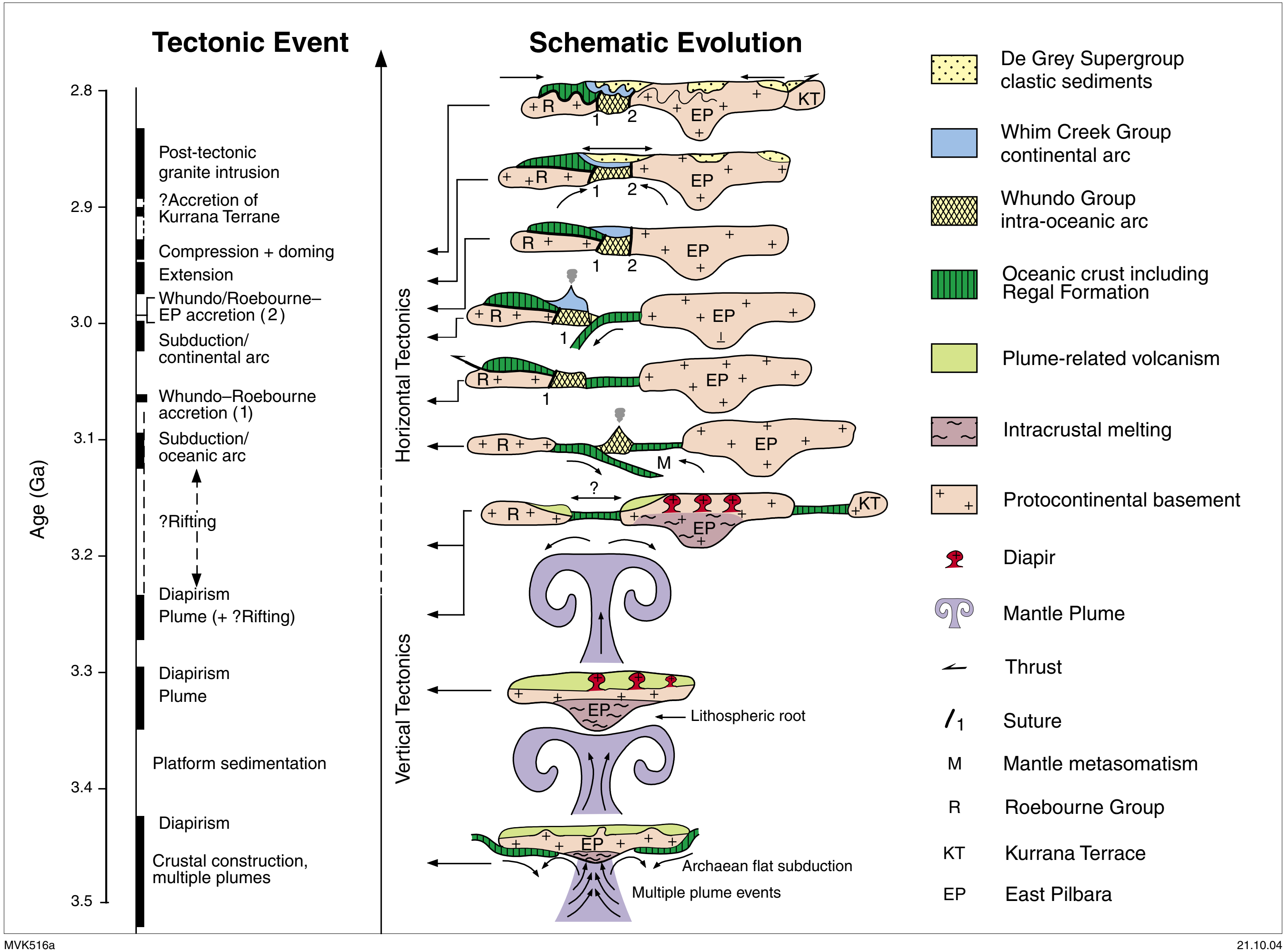

Figure 4. Schematic event history for the northern Pilbara Craton between 3.5 and 2.8 Ga

accompanied by the intrusion of Callina Supersuite tonalite–trondhjemite–granodiorite (TTG) magmas as a sheeted sill complex to produce local crustal thickening and instigate the development of volcanic domes. Magmas were derived through melting of basalt, possibly during flat subduction around the margins of the developing plateau (Fig. 4; Smithies et al., 2003). The final stages of plateau construction at 3.46 – 3.43 Ga involved early stages of doming of some of the granitoid complexes, high-pressure melting of mafic crust (Cullers et al., 1993), and resultant felsic magmatism including intrusive rocks of the 3.44 to 3.42 Ga Tambina Supersuite (TTG) and rhyolites of the Panorama Formation. This felsic magmatism was followed by regional subaerial erosion (Buick et al., 1995) over a 75 m.y. period, in the absence of volcanism (Fig. 4). Quartz sandstone and stromatolitic carbonates of the Strelley Pool Chert were deposited on a regional unconformity as Earth's oldest continental-shelf sequence at this time (Lowe, 1983; Buick et al., 1995; Van Kranendonk et al., 2002).

Volcanism recommenced at c. 3.35 Ga and continued to 3.31 Ga with eruption of the Kelly Group, which is a sequence, more than 8 km thick, of basal olivine-spinifex-textured komatiite, middle tholeiitic and komatiitic basalt, and upper K-rich rhyolite. The components of this succession are typical products of a mantle plume erupted through pre-existing continental crust. Widespread melting of pre-existing granitic rocks and the generation of the voluminous Emu Supersuite accompanied the end of Kelly Group volcanism at 3.32 – 3.29 Ga, and accompanied major doming at c. 3.31 Ga (Collins et al., 1998; Van Kranendonk et al., 2004a).

The third major event in the Pilbara commenced at c. 3.27 Ga with deposition of the Sulphur Springs Group above a regional unconformity. As with the Kelly Group, the Sulphur Springs Group consists of a komatiite–basalt–rhyolitic succession that is interpreted to represent the product of a mantle plume erupted through, and contaminated by, continental crust. Heat from this event caused widespread melting of pre-existing granitic rocks, generation of the 3.27 to 3.24 Ga Cleland Supersuite, and local high-amplitude doming of granitic complexes. Volcanogenic massive sulfide deposits were also developed at this time (Morant, 1998).

Rifting may have commenced at this time (Vearncombe et al., 1998; Hickman, 2004), and by c. 3.16 Ga had probably evolved to produce northwest–southeast separation of the older part of the WPGGT (Roebourne Group) and possibly the Kurrana Terrane. Evidence for this event comes from a distinct supracrustal succession; and the Flat Rocks Supersuite in the southwestern part of the EPGGT: and Nd-isotope data that show a distinct change in Nd-model ages obtained from dominantly 2.9 – 2.8 Ga granites down the middle of the Yule and Carlindie Granitoid Complexes of the EPGGT (Fig. 1). The data indicate that granitoid rocks to the west of this line were generated from crust younger than 3.2 Ga, as opposed to granitoid rocks to the east that have model ages generally in the range 3.4 – 3.7 Ga, with a few that have slightly younger ages to c. 3.3 Ga (Champion, D., Geoscience Australia, 2004, written comm.). The data also imply that greenstones of the Pilbara Well and Wodgina greenstone belts may not be part of the Pilbara Supergroup, and thus they have been left as unassigned on Figure 1 until more information is obtained from these rocks.

Isotopic evidence indicates involvement of a c. 3.5 to 3.4 Ga crust in the evolution of the 3.28 to 3.25 Ga Roebourne Group and the Karratha Granodiorite of the WPGGT north of the SSZ (Sun and Hickman, 1998). On this basis, and because of similarities in the broad stratigraphy and age of eruption, the Roebourne Group and the Karratha Granodiorite of the WPGGT have been interpreted to be a rifted segment of the Sulphur Springs Group and Cleland Supersuite of the EPGGT (Hickman, 2004).

From 3.24 Ga, the WPGGT evolved in isolation from the EPGGT, and underwent a different geological history (Smith et al., 1998; Van Kranendonk et al., 2002; Hickman, 2004). At c. 3.13 Ga, the Whundo Group was erupted as an intra-oceanic arc (Smithies et al., in press). This exotic terrane was subsequently juxtaposed with the Roebourne Group and Karratha Granodiorite along the SSZ probably at c. 3.07 Ga, prior to deposition of the Cleaverville Formation. The continental-arc volcanism of the c. 3.01 Ga Whim Creek Group marks a period of subduction preceding oblique collision between the WPGGT and the EPGGT (Fig. 4). Smith et al. (1998) proposed subduction from the west during arc accretion, but an alternative possibility is closure of the ocean between Roebourne/Whundo amalgam and the EPGGT through west-dipping subduction. Collision between the WPGGT and the EPGGT is interpreted to have occurred at c. 2.99 Ga, which is the age of widespread granitoid rocks in the WPGGT (Maitland River Supersuite) and abundant detrital zircons in the Mallina Basin (Smithies et al., 2001). Subsequent phases of extension and compression from 2.97 to 2.94 Ga were accompanied by deposition of the clastic rocks of the De Grey Supergroup in the Mallina Basin, and intrusion of the geochemically varied rocks of the Sisters Supersuite across the central Pilbara and western parts of the EPGGT. This series of events was accompanied by diverse mineralization, including platinum-group elements and gold.

Compressional deformation continued to c. 2.90 Ga along both the northwestern and southeastern margins of the EPGGT. During this period the Kurrana Terrane was tectonically juxtaposed against the Mosquito Creek Basin flanking the southeastern margin of the EPGGT. Isoclinal folding and thrusting within the basin was accompanied by epigenetic gold mineralization, and was followed by the emplacement of post-tectonic, highly fractionated, Sn–Ta–Li bearing granites of the 2.89 to 2.83 Ga Split Rock Supersuite. The linear northwest–southeast trend of these intrusions suggest emplacement within a failed rift in the foreland to compressional orogeny across the Mosquito Creek Basin.

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The age and provenance of the Mosquito Creek Formation

by L. Bagas, T. R. Farrell, and D. R. Nelson

Abstract

Sensitive high-resolution ion microprobe (SHRIMP) U–Pb detrital zircon ages and galena Pb–Pb model ages from the Mosquito Creek Formation indicate an age of deposition between c. 2926 Ma and c. 2905 Ma. Comparison of detrital zircon data with the age-distribution patterns for other Pilbara terranes indicate that conglomerate at the base of the formation had a provenance that included the East Pilbara Granite–Greenstone Terrane. However, a significant component of the upper part of the formation must have had a source from elsewhere, possibly either from the Sylvania Inlier to the southwest or an unknown terrane to the east.

KEYWORDS: North Pilbara Craton, Archaean, Mosquito Creek Formation, detrital zircon geochronology.

Introduction and regional setting

The Mosquito Creek Formation (Maitland, 1908; Noldart and Wyatt, 1962; Hickman, 1983) is a succession of Archaean siliciclastic rocks that occupies much of the central part of the Mosquito Creek Basin in the northern part of the Archaean Pilbara Craton of Western Australia (Fig. 1). The formation is multiply deformed and has been metamorphosed under low-grade conditions.

Hickman (2001) subdivided the north Pilbara Craton into the c. 3270–2920 Ma West Pilbara Granite–Greenstone Terrane (WPGGT), Central Pilbara Tectonic Zone (CPTZ), c. 3650–2830 Ma East Pilbara Granite–Greenstone Terrane (EPGGT), the Mosquito Creek Basin, and the little-known Kurrana Terrane (KT). The CPTZ and EPGGT include the c. 2970–2920 Ma De Grey Supergroup (Van Kranendonk et al., 2004 — this Annual Review). The exposed part of the Mosquito Creek Basin is approximately 60 km long and 30 km wide (Figs 1 and 2).

The De Grey Supergroup was deposited in a number of isolated but broadly contemporaneous clastic sedimentary packages across the north Pilbara Craton (Fig. 1). This supergroup includes rocks of the Mallina Basin in the northwest, Paradise Plains Formation in the north, Lalla Rookh Sandstone in the central part of the EPGGT, and the Mosquito Creek Basin in the southeast (Fig. 1). To the south, the Mosquito Creek Basin is wedge shaped in cross section (S. Shevchenko, GSWA, unpublished data), and is separated from the c. 3200–2840 Ma Kurrana Granitoid Complex by the Kurrana Shear Zone (Bagas, in prep.).

Hickman (1984) interpreted the Mosquito Creek Basin to have formed through subsidence during the later stages of granitic diapirism in the east Pilbara, but Eriksson et al. (1994) interpreted it as a forearc basin and accretionary complex situated to the north of a subduction complex. Tyler et al. (1992) interpreted the Kurrana Shear Zone as a suture between two distinct terranes that amalgamated between 3000 and 2760 Ma (Fig. 2). Krapez and Eisenlohr (1998) suggested that the Mosquito Creek Basin is equivalent in age to the c. 3240 Ma Gorge Creek Group, but Witt et al. (1998) interpreted it to be contemporaneous with the De Grey Supergroup.

This study presents new constraints on the age and provenance of the Mosquito Creek Formation based on SHRIMP U–Pb dating of detrital zircons. Zircons are durable and can survive the processes of weathering and erosion, are largely unaffected by metamorphism below amphibolite facies, and can survive transport over distances of many hundreds or even thousands of kilometres (e.g. the Amazon deltaic fans of South American with sediments derived from the Andes). The distribution of U–Pb ages of detrital zircons can also give valuable clues to provenance (e.g. Bagas et al., 2002).

Mosquito Creek Basin

In the Mosquito Creek Basin (MCB) the Coondamar Formation is present along its southern and northeastern margins (Bagas, in prep.; Farrell, in

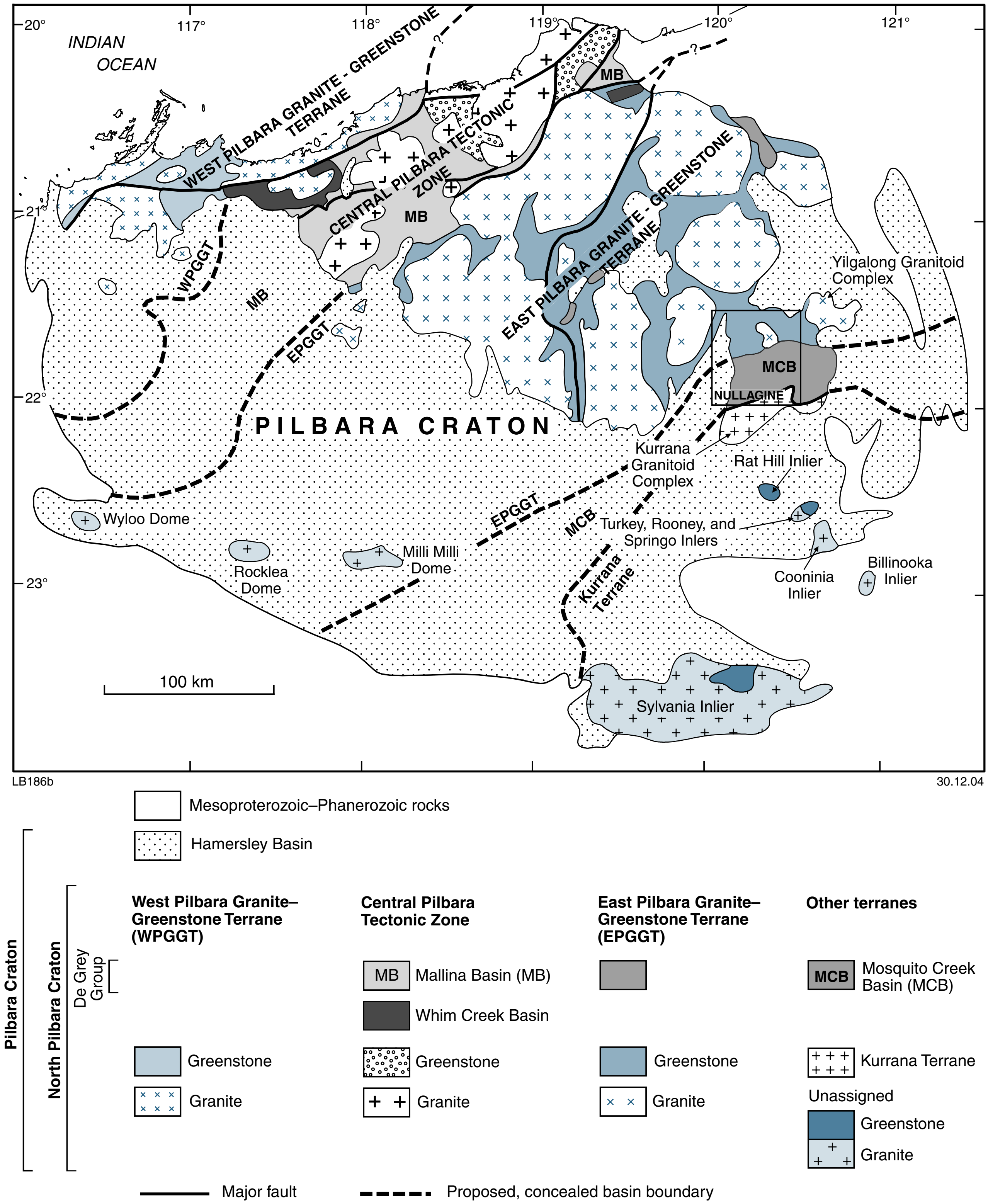

Figure 1. Regional geological setting of the Mosquito Creek Basin in the northern Pilbara Craton. The figure shows the proposed easterly to northeasterly configuration of the basin beneath the Hamersley Basin, which is based on an interpretation by Hickman (2004) using published regional-scale gravity and magnetic data (Blewett et al., 2000)

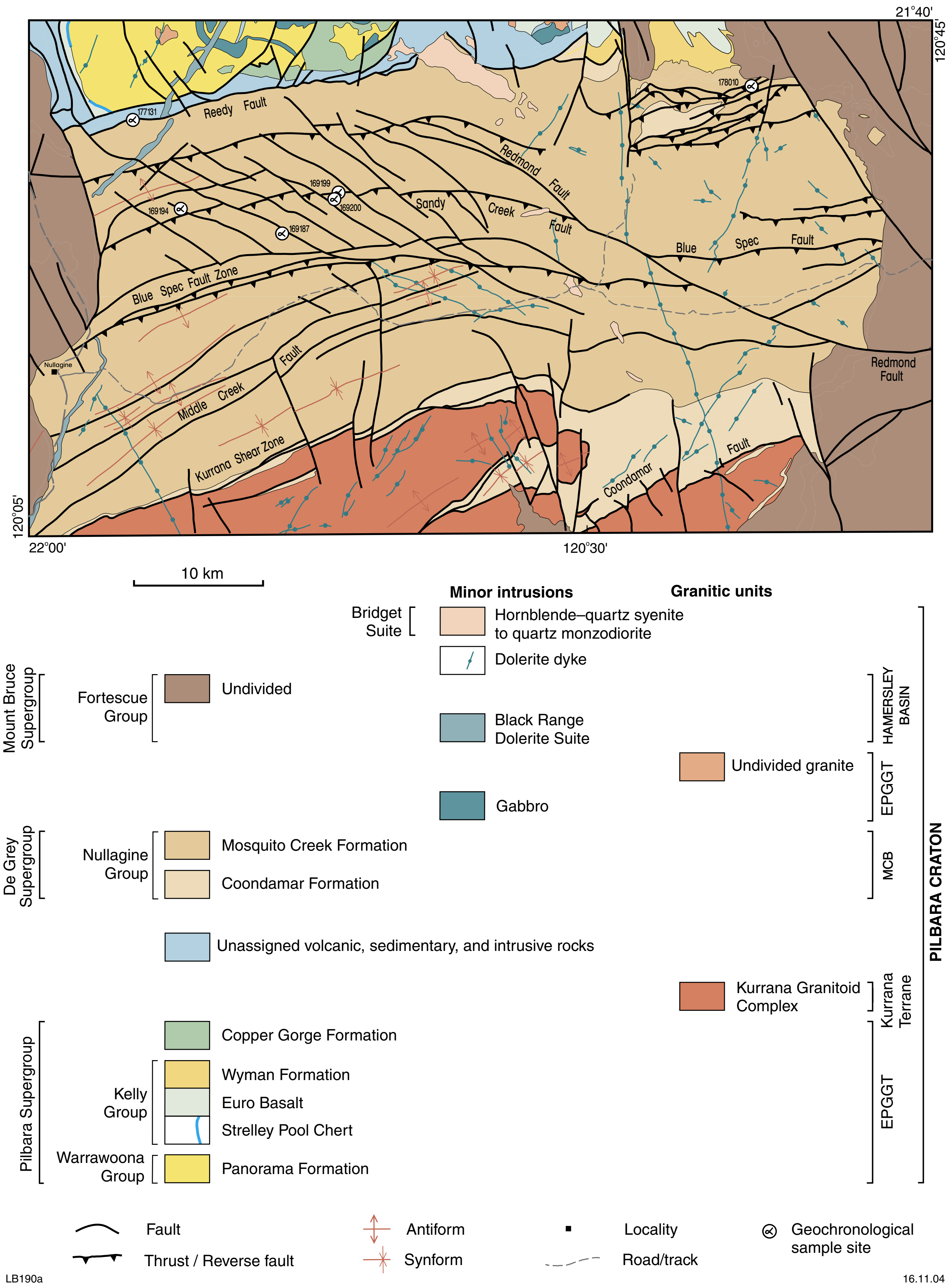

Figure 2. Generalized geological map of the exposed part of the Mosquito Creek Basin, showing the location of geochronological sample sites

Table 1. Deformational events recognized in the Mosquito Creek Basin

Event	*Age (Ma)*	*Structures*	*Tectonics*	*Comments*
D_1	<2950	S_1 fabric, steeply plunging mineral lineation	West-over-east ?thrusting (MCF[a] over ?CF[b])	Metamorphic peak between D_1 and D_2
D_2	c. 2900	Major ENE–WSW folds, S_2 penetrative slaty cleavage, NNW–SSE thrusting, crenulation lineation, weak NNW-plunging mineral lineation	SSE-over-NNW thrusting	Steepening of faults in centre and south (back ?rotation). Probably correlates with the main fabric in the Mallina Basin. Faults associated with this event host Au and base metal mineralization in MCB[c] (Blewett et al., 2002)
		Thrust and reverse faults late in D_2		Disruption of isograds late in D_2
D_3	< c. 2860	S–C fabrics in shear zones, asymmetric boudins	Dextral shearing (MCF and CF)	Possible reactivation of late-D_2 thrust faults. Post-dates BDG[d] in KT[e]
D_4	< 2860	North–south kink folds and kink bands, upright local crenulation cleavage (S_4)	East–west shortening	Last widespread event. Conjugate crenulation cleavages (trending 000–020° and 040°)
D_5	< 2690	Folds adjacent to steeply dipping faults: 5a. North to northwest 5b. West to northwest	 5a. Step down to east (oblique slip) 5b. Sinistral (north side up)	Probably in response to NE–SW compression

NOTES: (a) Mosquito Creek Formation
(b) Coondamar Formation
(c) Mosquito Creek Basin
(d) Bonney Downs Granite
(e) Kurrana Terrane

SOURCE: Farrell and Bagas (in prep.)

prep.), and is conformably overlain by the Mosquito Creek Formation (Fig. 2). These rocks are intruded by Archaean and Palaeoproterozoic igneous rocks, and have been subjected to five deformation events (Table 1).

In the northeastern part of the Mosquito Creek Basin (Fig. 2), the Coondamar Formation consists of lithic sandstone containing subangular to subrounded basaltic clasts. In the southern part of the basin, the formation consists of chloritic metasedimentary rocks, metachert, metagabbro, and amphibolite.

The Mosquito Creek Formation forms the remainder of the Mosquito Creek Basin succession (Figs 1 and 2). The total thickness of the formation cannot be accurately determined owing to the lack of suitable marker units, and because its top is not exposed. Hickman (1983) proposed that it is about 5 km thick, but this is probably an overestimation due to tight folding and structural repetition.

Along the northern edge of the basin, the basal 100 m of the Mosquito Creek Formation consists of a succession of interbedded conglomerate, massive coarse-grained sandstone, siltstone, and shale that unconformably overlies, or is in faulted contact with, the EPGGT. Individual conglomerate beds are channel deposits up to about 10 m thick, and contain rounded green-stone clasts of vein quartz, chert, and basalt, and rare felsic volcanic rocks up to about 200 mm across, in a poorly sorted sandstone matrix. The conglomerate beds are poorly sorted, coarse grained, and are sometimes interbedded with cross-bedded pebbly sandstone. The sandstone is moderately sorted, containing subrounded chert and quartz pebbles, and well-rounded to subrounded grains of quartz, chert, white mica, feldspar, and rare biotite. Eriksson et al. (1994) suggested that the succession was probably deposited in a submarine fan system.

The upper part of the Mosquito Creek Formation consists of thinly bedded sandstone interbedded with siltstone and shale, and has been metamorphosed at sub-greenschist to lower greenschist facies. The sandstone beds are typically fine to medium grained, well graded, and the only tractional structures observed are a weak horizontal lamination and rare ripple marks. Sandstone beds typically have a sharp base, with localized scour structures, and the lack of hummocky cross-bedding suggests a deep-water depositional environment. The contact with overlying siltstone and shale is commonly gradational, and full Bouma cycles are locally present. The sandstone contains a variety of angular to subrounded clasts of quartz, feldspar, chert, intraformation sandstone and shale, and rare felsic igneous rocks and quartz–sericite schist, in a finer grained pelitic matrix. The matrix characteristically consists of metamorphic white mica, chlorite, carbonate, rutile, very fine grained disseminated pyrite, and quartz, with detrital grains of quartz, white mica, and feldspar. The sandstone beds have been classified by Eriksson et al. (1994) as lithic wacke and lithic arenite, and interpreted as turbidites by Hickman (1983).

Age constraints for the Mosquito Creek Basin

A single Pb–Pb model age of 2905 ± 9 Ma records a lode gold mineralizing event in the Mosquito Creek Formation (Thorpe et al., 1992; Table 2), and constrains the minimum age of the host formation. This event appears to be synchronous with 2905 ± 9 Ma base metal mineralization in the Coondamar Formation (Huston et al., 2002; Table 2), which suggests that there was a widespread mineralizing event at c. 2905 Ma in the Mosquito Creek Basin. This event was also broadly synchronous with the emplacement of 2897 ± 6 Ma monzogranite and granodiorite in the Cooninia Inlier (Geological Survey of Western Australia, 2004), about 100 km to the south of the basin (Fig. 1).

U–Pb detrital zircon age constraint for the Mosquito Creek Formation

To better constrain the maximum age for the Mosquito Creek Formation, 195 detrital zircons were dated by D. R. Nelson (Geological Survey of Western Australia, 2004, in prep.) from six samples of medium- to coarse-grained sandstone collected from the northern and eastern outcrops of the formation (Fig. 2). Due to structural complexities it is not possible to place the samples on a single stratigraphic column. The procedures used in rock sampling, and concentrating and selecting detrital zircons for dating, are described in detail by Nelson (1997, 1999).

The youngest group of detrital zircons has an age of 2926 ± 29 Ma, and was obtained from sandstone interbedded with conglomerate near the base of the formation (GSWA sample 177131, Fig. 2). It indicates a maximum depositional age of about 2926 Ma. If the two Pb–Pb model ages of 2905 ± 9 Ma obtained from the Mosquito Creek and Coondamar Creek deposits are regarded as being accurate (Table 2), the depositional age of the formation is probably between 2905 and 2926 Ma.

Provenance

Relative cumulative-probability plots are commonly used to visually assess the statistical similarities or differences between samples and potential source regions (e.g. Camacho et al., 2002). The plots present summed probability density curves for concordant analyses (i.e. those analyses for which there is a 95% confidence level that the $^{206}Pb/^{238}U$ age is within the uncertainty of the $^{207}Pb/^{206}Pb$ age), assuming that the probability density of each analysis follows a Gaussian distribution. The horizontal spread in the graphs for each peak relates to the standard deviation, and generally reflects the accuracy of the data. Such plots for the samples from the Mosquito Creek Formation reveal that the Mosquito Creek Basin had a provenance supplying c. 2926 Ma to c. 3730 Ma zircons (Fig. 3). By comparing data against the pooled data for the WPGGT and EPGGT, it becomes apparent that the provenance for the basin was not entirely the north Pilbara Craton (Fig. 4).

A significant proportion of the detrital zircons dated from the Mosquito Creek Formation are appreciably older than the pooled zircon data for the WPGGT (Fig. 4), and the detrital zircon age distribution data do not correlate well with the pooled zircon data for the EPGGT. For example, prominent peaks at c. 3540, 3360 and 3090 Ma in the profile for the Mosquito Creek Formation are not represented in the plot for the EPGGT (Fig. 4). The implication is that the main hinterland for the Mosquito Creek Basin was an area other than the exposed north Pilbara Craton and one that contains zircons with ages of c. 3540, 3360, and 3090 Ma.

When the detrital zircon data for the samples from the Mosquito Creek Formation are considered individually (Fig. 3), two groups emerge. One group comprises two samples (GSWA samples 177131 and 178010) from the submarine fan deposits at the base of the formation, and the other group includes the remaining samples (GSWA samples 169200, 169199, 169194, and 169187). Samples 177131 and 178010 have distribution peaks at c. 3470 and 3425 Ma and a trough at c. 3370 Ma, similar to the age profile for the EPGGT. A

Table 2. Pb–Pb model ages on galena from mineral deposits in the Mosquito Creek Basin

Deposit	*Location MGA, Zone 51K*	*Description*	*Analytical technique*	*Age (Ma)*	*Reference*
Mosquito Creek in the Mosquito Creek Formation	237565E 7586430N	Galena from gold-bearing quartz veins hosted by D_2 structures in pelitic schist	Conventional	2905 ± 9	I. R. Fletcher, quoted in Thorpe et al. (1992)
Coondamar Creek in the Coondamar Formation	258931E 7572090N	Sulfide deposit (containing sphalerite, chalcopyrite, pyrite, and minor galena) interbedded with black shale	Conventional	2905 ± 9	Huston et al. (2002)

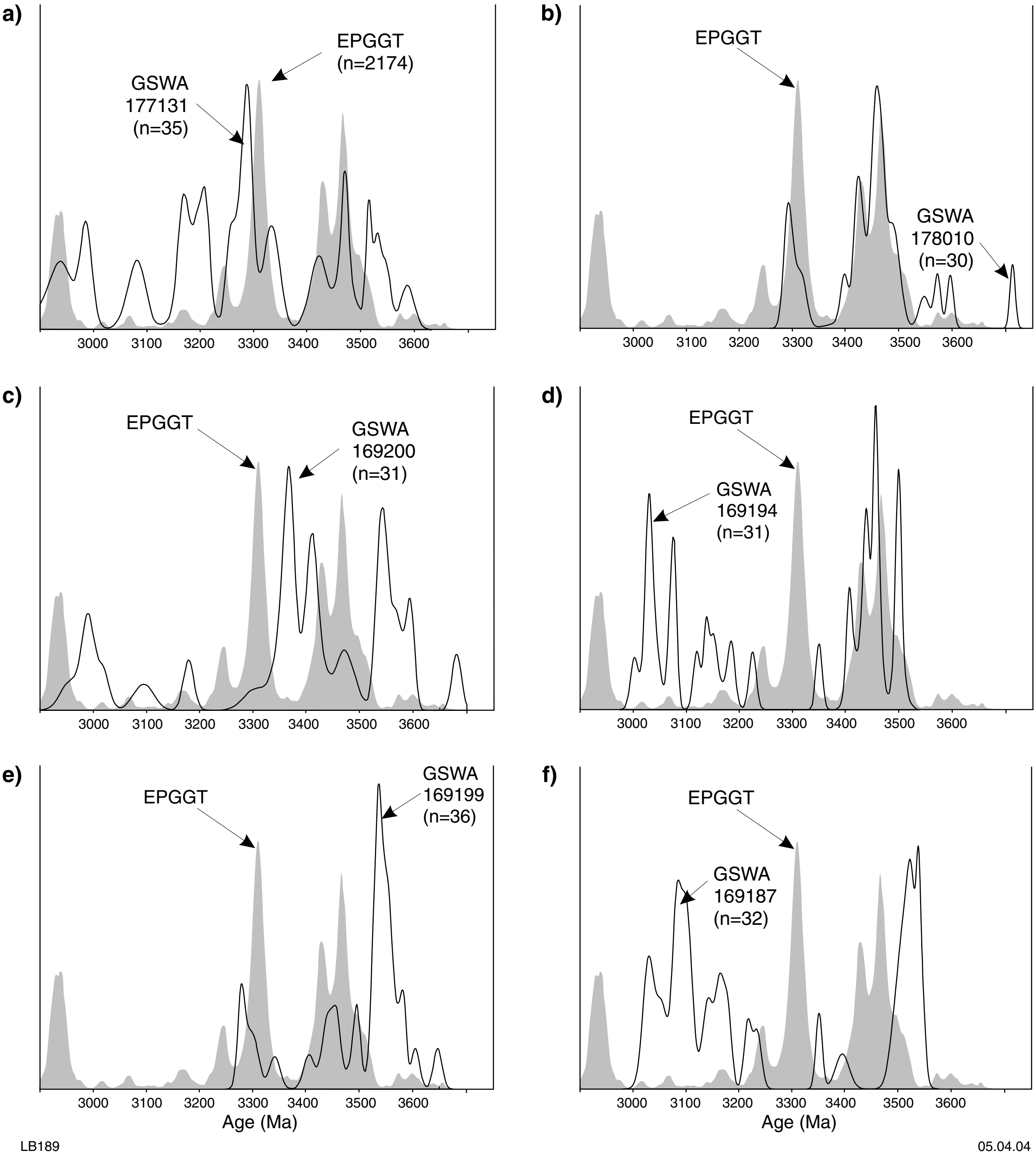

Figure 3. Relative cumulative-probability diagrams of SHRIMP U–Pb zircon ages from the Mosquito Creek Formation (Geological Survey of Western Australia, 2004) and the East Pilbara Granite–Greenstone Terrane (EPGGT) (Nelson, 1996, 1997, 1998, 1999, 2000, 2001, 2002; Geological Survey of Western Australia, 2004) for: a) GSWA sample 177131; b) GSWA sample 178010; c) GSWA sample 169200; d) GSWA sample 169194; e) GSWA sample 169199; and f) GSWA sample 169187. Samples a) and b) are from the basal conglomerate, and the other samples are from the upper part of the formation. The age uncertainties are at the 95% confidence level for the concordant populations of zircons used in the construction of these graphs, and the internal precision for single analyses is 1σ (n = number of analyses)

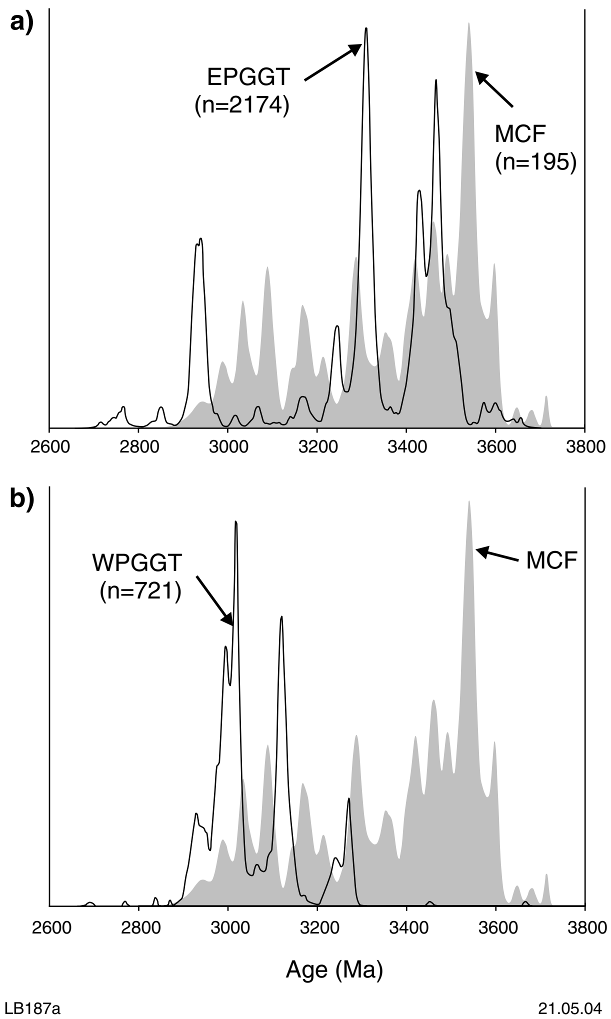

Figure 4. Relative cumulative-probability diagrams of pooled SHRIMP U–Pb zircon ages from the Mosquito Creek Formation (MCF) compared to a) East Pilbara Granite–Greenstone Terrane (EPGGT) and b) West Pilbara Granite–Greenstone Terrane (WPGGT). The age uncertainties are at the 95% confidence level for the concordant populations of zircons used in the construction of these graphs, and the internal precision for single analyses is 1σ (n = number of analyses)

peak in both samples at c. 3290 Ma is consistent with new data for the Yilgalong Granitoid Complex in the EPGGT (Geological Survey of Western Australia, in prep.; Fig. 1). However, the samples also have peaks at c. 3540 and 3200 Ma that are not represented in the plot for the EPGGT. This suggests that the basal fan deposits had a mixed provenance that did not include the EPGGT alone.

The second group contains samples from the upper turbiditic part of the Mosquito Creek Formation. The samples have slightly differing zircon age profiles (Fig. 3), but there are common peaks at c. 3540, 3490, 3360, 3280, 3220, 3140, 3040, and 3000 Ma in some or all of the samples, none of which are common in the plot for the EPGGT. Conversely, peaks at c. 3470 and 3430 Ma in the samples from the base of the formation are not represented in the zircon distributions for the upper part of the formation. These observations suggest that the EPGGT contributed detritus to the stratigraphically lower part of the Mosquito Creek Formation, but did not form a significant source of detritus for the upper part of the formation.

Discussion

The combination of the large volume of the sediment now forming the bulk of the Mosquito Creek Formation (less than 5 km thick), the immaturity of the sediment, and the fine-grained nature of the sandstone in the formation indicate derivation from a tectonically active but distal source (e.g. Haines et al., 2001). From the observations made above it is clear that the EPGGT did not form a significant source of detritus for the upper part of the formation.

Various studies have observed that turbidity currents typically flow parallel to the long axis of elongate confined basins, such as the Mosquito Creek Basin, parallel to basin-controlling normal faults (e.g. Kneller et al., 1991; Flöttmann et al., 1998; Haines et al., 2001). The long axis of the Mosquito Creek Basin trends in a northeasterly to easterly direction; thus, the source of the material in the basin is likely to be an unknown terrane to the east (Fig. 1), or under the Hamersley Basin to the southwest, west of the Sylvania Inlier, which is the largest granite–greenstone terrane exposed in the southeastern Pilbara Craton (Tyler, 1990, 1991).

Conclusions

Geochronology and detailed mapping have identified the following characteristics of the Mosquito Creek Basin:

- the Mosquito Creek Formation is likely to have an age between 2926 and 2905 Ma;
- the basal part of the Mosquito Creek Formation has a provenance that includes the EPGGT;
- the WPGGT and EPGGT are not the main provenances for the upper part of the Mosquito Creek Formation; and

- the provenance for the turbiditic upper part of the Mosquito Creek Formation is either to the southwest towards the Sylvania Inlier, or the east under the Hamersley Basin (Fig. 1).

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The tectonic history of the Waigen area, western Officer Basin, interpreted from geophysical data

by C. D'Ercole and A. M. Lockwood

Abstract

A new filtering technique, using the wavelet transform to downward-continue magnetic data onto a variable surface, was used to enhance the data over the under-explored Waigen area of the western Officer Basin. The enhanced data show that the underlying basement is predominantly Mesoproterozoic Albany–Fraser Orogen extending to the northeast, where it is truncated by the Mesoproterozoic Musgrave Complex. Deep-seated, elliptical magnetic features are possible mantle material emplaced during a rifting event, or deep magma chambers related to an underplating event associated with a large mantle plume. These intrusions are likely to be related to either c. 1075 Ma or c. 510 Ma events.

KEYWORDS: geological interpretation, magnetic data, gravity data, Officer Basin, Albany–Fraser Orogen.

Introduction

The Waigen area is centred on COOPER, WAIGEN, and WANNA* in the eastern part of the western Officer Basin, Western Australia (Fig. 1), and appears to be continuous with the Birksgate Sub-basin in the eastern Officer Basin, South Australia. Gravity modelling shows there is a sedimentary section up to 11 km thick in the Waigen area (D'Ercole et al., in prep.), representing a Neoproterozoic – Lower Cambrian depocentre and possible underlying Mesoproterozoic basin (Apak and Tyler, 2002), covered in part by a thin Phanerozoic succession. Depth-to-basement calculations from isostatic residual gravity data show that basement generally shallows abruptly towards the north (Musgrave Complex) and west (Yilgarn Craton), although the thickness of the sedimentary section in the Cooper Graben, a northerly trending trough near the margin of the Musgrave Complex, is estimated to be up to 10 km (D'Ercole et al., in prep.).

Although there has been sporadic exploration in the Officer Basin since the 1950s, there is only one seismic line and one deep stratigraphic drillhole, Vines 1, in the Waigen area, and the ?Lower Cambrian section in this drillhole may be unrepresentative. BMR Wanna 1, the only other stratigraphic hole in the area, was completed in the Upper Carboniferous – Lower Permian Paterson Formation. There are several shallow mineral coreholes in the area, some of which have been useful for constraining gravity modelling. The closest petroleum exploration wells are Lennis 1, over 200 km to the west in the adjacent Lennis area, and Birksgate 1, 206 km to the east in the Birksgate Sub-basin. Regional potential-field data acquired in the early 1970s, and semi-regional gravity data acquired in 1998, are the only publicly available geophysical datasets covering the area.

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

Regional setting and stratigraphy

The Waigen area is flanked by four main areas of crystalline basement: the Mesoproterozoic Musgrave Complex, the Archaean Yilgarn Craton, and the Mesoproterozoic Albany–Fraser Orogen in Western Australia, and the Archaean–Mesoproterozoic Coompana Block in South Australia. The Musgrave Complex consists of igneous rocks (volcanic rocks, granites, and layered mafic–ultramafic intrusions) emplaced into granulite- and amphibolite-facies Mesoproterozoic orthogneisses and paragneisses, which may be migmatitic (Myers, 1990b; Glikson et al., 1996). The Albany–Fraser Orogen, which is longitudinally divided into the Biranup and Nornalup Complexes (Myers, 1990a), comprises stacked thrust sheets of metasedimentary rocks, orthogneiss, and granite, and includes mafic–ultramafic intrusions and remnants of basaltic dykes (Myers, 1990a; Fitzsimons, 2003). The Coompana Block comprises

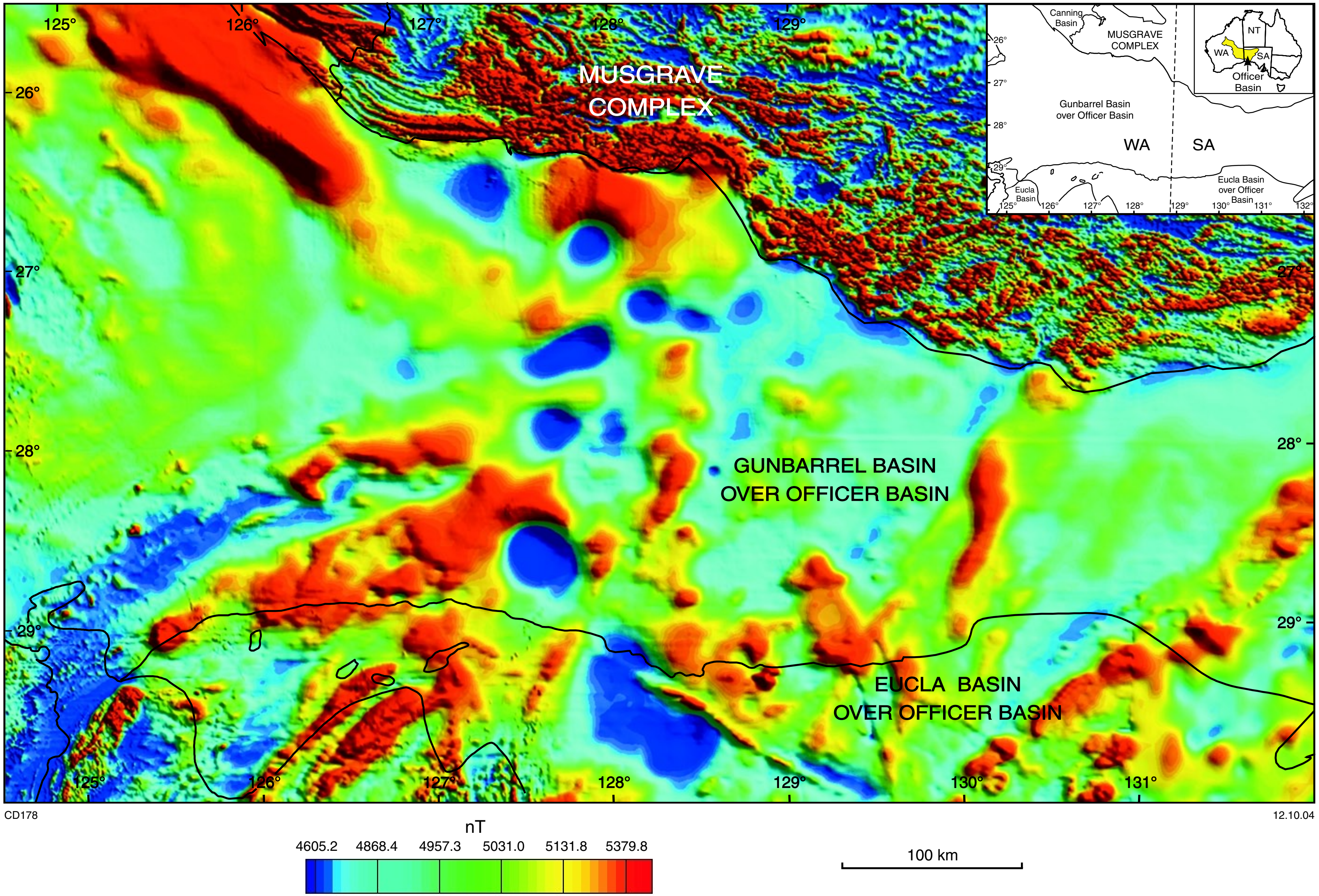

Figure 1. Total magnetic intensity, reduced to pole, of the Waigen area and surrounds. The location of the Waigen area and adjacent eastern Officer Basin are shown in the inset

Archaean to Mesoproterozoic gneiss and granite intruded by dolerite–gabbro plugs and dykes (Flint and Daly, 1993).

The stratigraphy of the western Officer Basin has been reviewed by Apak and Moors (2000) and Grey et al. (in prep.). Only the lower part of Neoproterozoic Supersequence 1 outcrops within the Waigen area. Isolated sandstone outcrops within the area may be the upper part of Supersequence 1, but cannot be assigned unequivocally. Neoproterozoic – Lower Cambrian Supersequence 4 strata are present in Vines 1, and there are outcrops of Supersequence 4 and Supersequence 3 strata in the area. Outcropping rocks of the overlying Gunbarrel Basin include Palaeozoic volcanic and sedimentary rocks.

Potential-field data

Conventional filtering of total magnetic intensity (TMI) images, such as the first vertical derivative of reduced-to-pole images, are useful for enhancing magnetic anomalies associated with shallow structures, but are limited when it comes to better defining anomalies associated with deep structures. The Fourier-transform-based downward continuation filter can be a useful tool for delineating deep structures because it applies the same enhancement over all areas of a dataset. However, this filter is only effective for regions covered by a relatively constant thickness of non-magnetic sedimentary rocks, and any attempt to downward continue data using Fourier-based methods is unstable over areas of shallow basement. Over the Waigen area, the use of a Fourier-based downward-continuation filter to delineate structures in basement beneath the Officer Basin is problematic because of outcropping, highly magnetic Musgrave Complex in the north (Fig. 1).

The wavelet transform is an alternative to the Fourier transform for potential-field data processing, which can be made to vary spatially (Ridsdill-Smith and Dentith, 2000). This is the basis of a new filtering technique called variable downward continuation. A depth-to-basement model, derived from gravity data, is used to determine the optimal downward continuation distance for each datum in the TMI image. The wavelet transform is then used to vary the level of enhancement of the TMI data according to the corresponding thickness of the sedimentary section.

For this study, an isostatic correction (Simpson et al., 1983) was applied to the Bouguer gravity data to remove the effect of large-scale crustal structure consistent with the topography, although there is some evidence that the crust is not in a state of isostatic equilibrium (Haddad et al., 2001). The resulting corrected Bouguer gravity was used to estimate the depth to basement over the Waigen area. The wavelet transform was then used to simulate the magnetic field observed at 200 m above basement, producing the variably downward continued image (Fig. 2).

The variably downward continued image highlights subtle features not seen in the TMI image, particularly over the Officer Basin, where the magnetic response of basement structures is attenuated by the overlying sedimentary rocks. This new image, together with first vertical derivative images, was used to refine the tectonic subdivisions and interpret the tectonic history of this part of the Officer Basin (D'Ercole et al., in prep.).

Interpretation of geophysical data

The gravity (D'Ercole et al., in prep., fig. 9) and magnetic data highlight complex basement structures within the Waigen area. Nine domains of distinct magnetic character (Figs 2 and 3) are evident on the variably downward continued image of the Waigen and surrounding region. A detailed interpretation of the domains, their geophysical signatures, and associated tectonic history is given in D'Ercole et al. (in prep.). A similar tectonic framework of this area was included in an Australia-wide, crustal-scale study by Shaw et al. (1996), but the tectonic evolution of the region was not included in their study.

Domain 1

The complex, mainly west-northwesterly to northwesterly trending structures and narrow, well-defined, high-amplitude anomalies in domain 1 are due to lithological variations and intense deformation within the Musgrave Complex (Fig. 2). The sharp boundary of domain 1 with the Officer Basin is marked by a northerly dipping thrust fault.

Domain 2

Domain 2 consists of basement (?Musgrave Complex or possibly Palaeoproterozoic Rudall or Gascoyne Complex) below a thin cover of Officer Basin strata. The anomalies are slightly deeper and broader compared with outcropping Musgrave Complex in domain 1, but this domain displays similar northwesterly trending lineaments (Fig. 2). Some of the lineaments represented by magnetic lows appear to correlate with either salt walls or salt-related features noted in the western Officer Basin by Japan National Oil Corporation (1997) and Apak and Moors (2000, 2001); for example, the Browne Diapir in the Yowalga area corresponds to a magnetic low flanked by magnetic highs (Fig. 2). The salt has probably migrated up a corresponding structural feature to form the salt wall.

A small, triangular zone of low magnetic response lies between domains 1, 2, and 4 (Figs 2 and 3). A corresponding gravity low in this zone represents the Cooper Graben (Figs 3 and 4), which contains a sedimentary section up to 10 km thick (D'Ercole et al., in prep.). Other magnetic features within this zone indicate areas of shallow, fault-controlled Musgrave Complex basement and the presence of a deep, circular intrusive body.

Domain 3

Domain 3 represents the Yilgarn Craton, with the eastern corner covering the junction between the Yilgarn Craton, Musgrave Complex,

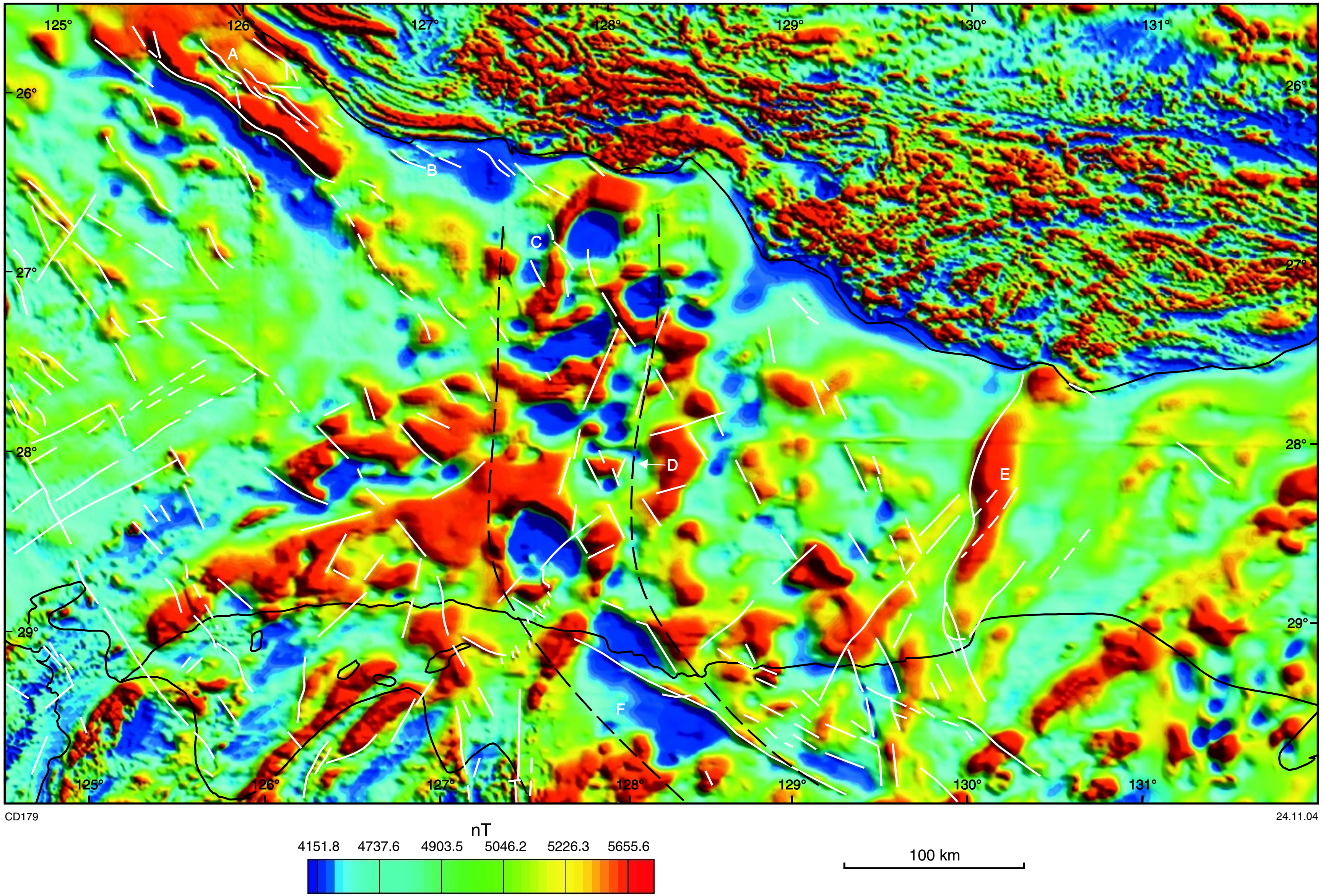

Figure 2. Variably downward-continued image of the total magnetic intensity, showing interpreted magnetic lineaments (white lines). A = Browne Diapir (low related to salt wall); B = triangular zone of low response; C = Cooper Graben; D = northerly trending feature of circular intrusive bodies; E = Nurrai Ridge; and F = circular intrusive body in domain 7

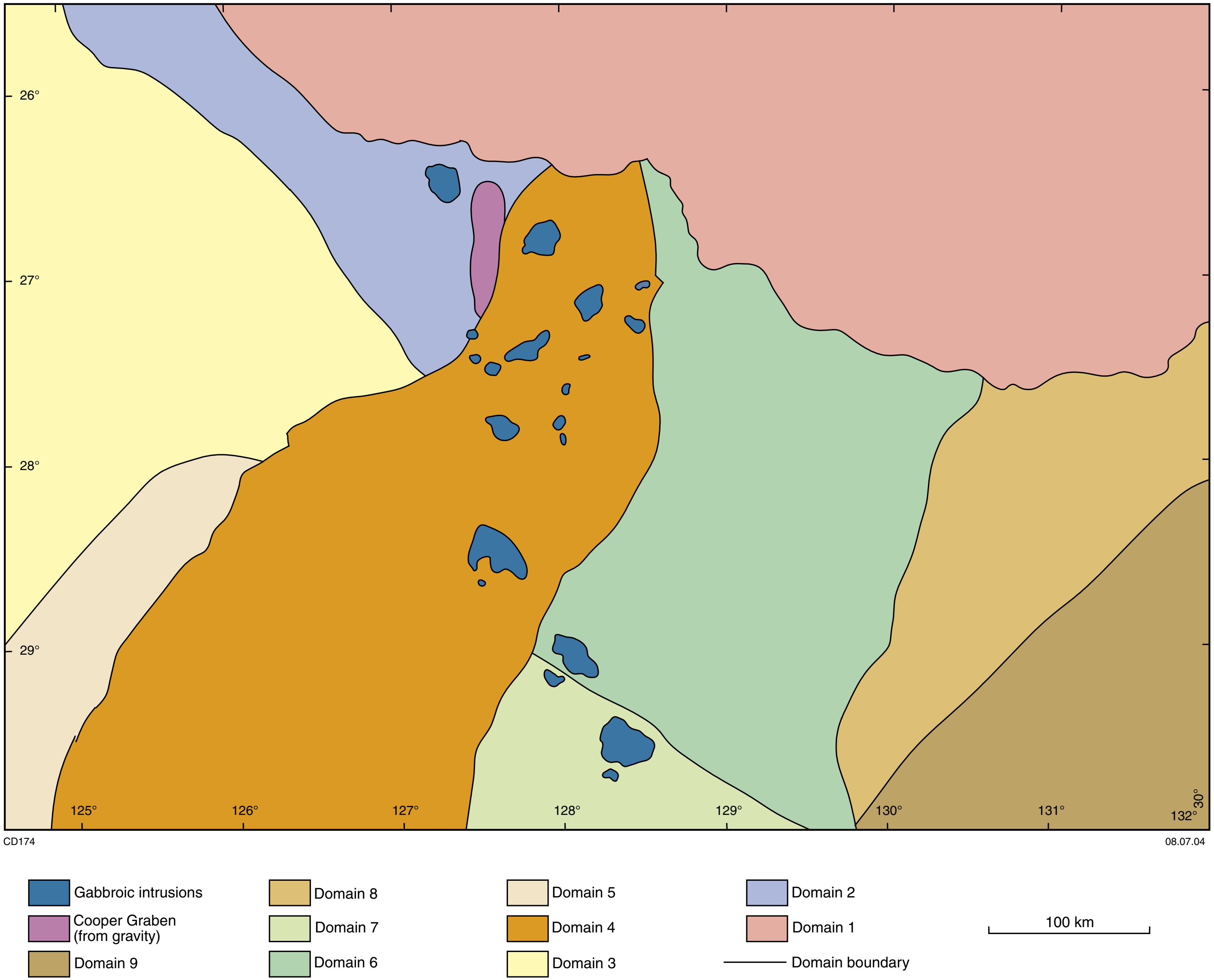

Figure 3. Synthesis domain map of the Waigen area and surrounds interpreted from geophysical (magnetic and gravity) and drillhole data

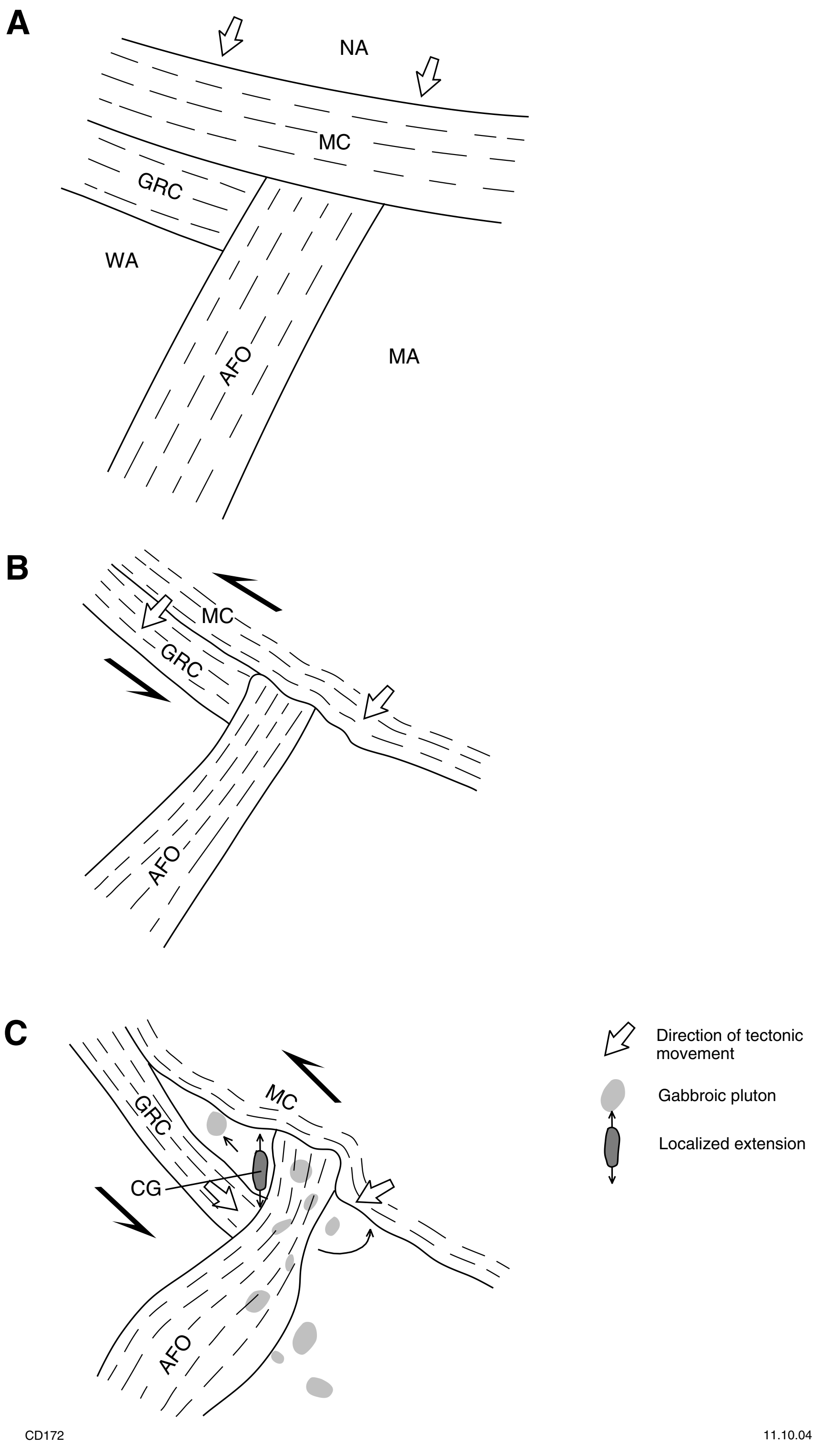

Figure 4. Schematic diagram of the Mesoproterozoic tectonic history of the Waigen area: a) formation of the Albany–Fraser Orogen (AFO) and Musgrave Complex (MC). Initiation of thrusting of MC and rotation around pre-existing Gascoyne or Rudall Complex (GRC); b) continuation of uplift and thrusting of MC, and initiation of AFO rotation and sinistral transpression of GRC; and c) completion of thrusting of MC and rotation of AFO, initiation of local extension (Cooper Graben; CG). Impact of mantle plume (~c. 1075 Ma) and emplacement of mafic–ultramafic intrusions. WA = West Australian Craton, MA = Mawson Craton, and NA = North Australian Craton

and Albany–Fraser Orogen. The domain is characterized by subdued, narrow, northwesterly trending magnetic anomalies truncated or displaced by minor northeasterly trending lineaments (Fig. 2). Some of these anomalies roughly coincide with northwesterly trending salt-related features noted by Apak and Moors (2000, 2001) in the northwestern portion of the area, near the boundary between domains 2 and 3. These anomalies may represent structures related to salt migration.

Drillhole and seismic data confirm that depth to basement is very shallow to the west of this area (~40–100 m), and seismic and gravity data show that this depth increases to the east (~2–5 km; D'Ercole et al., in prep.), consistent with the thickening of the Officer Basin (Apak and Moors, 2000) and a ?Mesoproterozoic basin (Apak and Tyler, 2002) towards the Musgrave Complex. Thus some of the underlying anomalies may represent crystalline basement within the Yilgarn Craton.

Domain 4

Domain 4 has the most complex magnetic pattern within the region, and apart from a few northerly trending major crustal lineaments, it has no dominant structural trend (Fig. 3). The lineaments range in orientation from northwest to northeast (Fig. 2). The area contains broad, high-amplitude anomalies and low-amplitude circular features, ranging from 2 to 21 km in diameter, with sharp, curvilinear, discordant contact zones (Figs 2 and 3). Magnetic modelling indicates depths of between 8 and 19 km for some of these circular magnetic sources, implying that they are mid-crustal features (D'Ercole et al., in prep.). Typically the presence of large intrusive bodies within the crust is expected to influence sedimentary thickness estimates derived from the gravity data, due to a density contrast between crystalline basement and the deep intrusive bodies (Lockwood and D'Ercole, 2003). However, the depth-to-basement model (D'Ercole et al., in prep., fig. 12) shows no strong perturbations above the modelled sources of these anomalies, suggesting little or no density contrast between the lower crust and these intrusions. Magnetic modelling (D'Ercole et al., in prep., fig. 15) suggests the intrusions are reversely remanently magnetized, with the induced field cancelled by the remanent field (Konigsberger ratio of about 1), and are interpreted here as magma chambers, possibly of mafic–ultramafic composition. These intrusions all possess the same polarity, indicating virtually simultaneous emplacement and rapid crystallization during a period when the Earth's magnetic field was reversed relative to the present field.

These circular anomalies form a broad, northerly trending feature (Fig. 2) that seems to coincide with a set of northerly trending lineaments, which collectively form part of a regional crustal-scale feature termed the Lasseter Shear Zone (Braun et al., 1991), the southern extension of which may correlate with the Mundrabilla Fault (Myers and Hocking, 1998). At the southern end of the domain, this feature bends around to the southeast, seemingly lining up with similar anomalies in the Coompana Block, South Australia, that are sourced from shallower mafic intrusives (Flint and Daly, 1993).

The magnetic data clearly show that the Albany–Fraser Orogen extends farther east than previously implied by Hocking (1994; Neale Arch). It swings around to the northeast within the Waigen area, is truncated by lineaments that relate to the Lasseter Shear Zone on its eastern side, and continues northwards to the Musgrave Complex (Fig. 2). The majority of magnetic highs within domain 4 probably correspond to mafic–ultramafic rocks and mafic granulites of the Fraser Complex (part of the Biranup Complex). Outcropping Fraser Complex rocks southeast of domain 4 appear to be continuous with gravity and magnetic anomalies farther northwest.

Domain 5

Domain 5 covers outcropping and subcropping granitic rocks, gneisses, and minor sedimentary rocks of the Biranup Complex within the Albany–Fraser Orogen. This domain is characterized by low magnetic relief compared to the high-amplitude anomalies of the adjacent mafic–ultramafic rocks of the Fraser Complex in domain 4. The change in magnetic character defines the boundary between these two domains. An arcuate belt of high-amplitude magnetic anomalies on the northwestern edge of domain 5 forms the boundary with domain 3 (Fig. 2). Mineral exploration holes drilled on these anomalies intersected metagabbros and norites (Perincek, 1998, appendix 3).

Domain 6

Domain 6 is characterized by smooth magnetic anomalies, indicating deep sources (Fig. 2). The sedimentary section in domain 6 deepens to the north, ranging from about 5 to 11 km, and onlaps the Coompana Block to the south and Gawler Craton to the east. Magnetic and gravity lineaments in this domain are predominantly northwesterly to north-northwesterly trending. North-northeasterly trending magnetic highs, such as the Nurrai Ridge (Fig. 2), mark the boundary between domains 6 and 8. Rankin (2003) interpreted these ridges as folded belts of mafic intrusives.

Domain 7

Magnetically low, circular to elliptical features in domain 7 (Figs 2 and 3) are similar to those within domain 4 and farther south in the Coompana Block. Several holes targeting these circular anomalies in the Coompana Block intersected mafic–ultramafic intrusions, specifically gabbro and dolerite (Flint and Daly, 1993). The intrusive bodies within the Albany–Fraser Orogen in domain 4 may be compositionally similar and part of the same suite of intrusions, but are at considerably greater depths (8–19 km from modelling in domain 4 compared with ~300 m in the Coompana Block).

Domain 8

Domain 8 is magnetically 'quiet', with only minor anomalies, and represents the thickest part of the Officer Basin. The thickness of the sedimentary section increases dramatically towards the northeast (6–11 km) into the Munyarai Trough. The boundary between domains 8 and 9 is marked by a major northeasterly trending magnetic feature, which could be a major thrust fault (Fig. 2).

Domain 9

Domain 9 contains high-amplitude, elliptical anomalies that correlate with granitoids of the Hughes Subdomain (Rankin, 2003) and Gawler Craton (Fig. 2). This area is covered by a veneer of sedimentary rocks. The coincident gravity high indicates higher density lithologies than in surrounding domains.

Synthesis of geophysical and geological data

The basement beneath the Officer Basin in the Waigen area is predominantly Albany–Fraser Orogen, which is interpreted as a northeasterly trending Mesoproterozoic suture along which oceanic crust was consumed as fragments of continental crust were assembled into the Rodinia supercontinent (Condie and Myers, 1999; Fitzsimons, 2003). The Albany–Fraser Orogen is truncated by the northwesterly trending Musgrave Complex of the Paterson Orogen (Fig. 4a), and was deformed and rotated during uplift and thrusting of the Musgrave Complex during the Neoproterozoic. The magnetic data indicate that the Musgrave Complex was indented by the Albany–Fraser Orogen as it thrust over the Officer Basin to the southwest (Figs 2 and 4b). From the shape of domain 4, the orogen appears to have rotated around the shallow basement in domain 2 during sinistral transpression, creating a zone of local extension between the basement elements underlying the Officer Basin (Fig. 4c). This zone of extension is marked by the small, triangular area of low magnetic response between domain 2, the Musgrave Complex, and the Albany–Fraser Orogen (Figs 2, 3, and 4), and by the deep Cooper Graben (Figs 2 and 3). Of the two Neoproterozoic deformation events recognized in the Officer Basin, the c. 550 Ma Petermann Orogeny is interpreted as a dextral transpressive event (Camacho and McDougall, 2000); therefore, the sinistral event recognized here may represent the c. 750 Ma Areyonga Movement.

The broad, circular to elliptical magnetic features in domains 4 and 7 are interpreted as mafic–ultramafic magma chambers deep within basement. Similar features around the world have been linked to mantle plumes (Pirajno, 2000). Four possible mantle plume events and associated volcanism are documented within continental Australia: c. 1075 (Wingate et al., 2004), c. 800 (Zhao et al., 1994), c. 755 (Wingate and Giddings, 2000), and c. 510 Ma (Hanley and Wingate, 2000); however, the timing of the episodes at c. 800 and c. 755 Ma is only constrained by tentative correlations to large dyke swarms. Wingate et al. (2004) inferred that a large mantle plume beneath central Australia produced the Warakurna large igneous province (LIP) event (c. 1075 Ma) and linked this with plate-boundary forces along the Australian–Antarctic continental margin. The overall arcuate trend of magnetic features in the Waigen area follows the boundary between domains 6 and 7 and the northeastern part of domain 4, possibly outlining a lithospheric break. If a plume were present, the magma would have followed this zone of weakness, and intruded the Albany–Fraser Orogen. Such intrusions would then pre-date the Neoproterozoic deformation event affecting the western Officer Basin. Alternatively, the magnetic features may be related to the c. 510 Ma Kalkarinji LIP, which includes the Antrim Plateau Volcanics and possibly the Table Hill Volcanics, and the intrusions would post-date the deformation event.

Conclusions

The resolution of basement over the deeper parts of the Officer Basin was enhanced, compared to the TMI image, by a new downward-continuation filtering technique based on the wavelet transform. The new image shows that the entire Waigen area and surrounds, excluding the Musgrave Complex and subcropping Gawler Craton, is characterized by northwesterly trending anomalies truncated or displaced by minor northeasterly and northerly trending features. Deformation and local extension may be related to a Neoproterozoic sinistral transpression. Circular magnetic bodies within the Waigen area may be related to either the c. 1075 Ma Warakurna LIP or the c. 510 Ma Kalkarinji LIP.

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Western Australian dimension stones for the 21st century

by J. M. Fetherston

Abstract

Dimension stone is a rock material quarried for the manufacture of blocks and slabs for use in the construction industry. The stone must possess appropriate physical properties for a particular end use as well as having an attractive appearance. Dimension stone's principal application is in the cladding of large buildings as panels, slabs, and tiles. It is also used in the construction of private homes, streetscapes, and retaining walls as blocks, tiles, and pavers. Dimension stone is also widely used for the construction of public and private memorials and stone artworks. Western Australia has numerous deposits of high-quality dimension stone, predominantly granites and gneisses, and the prospectivity for further deposits is excellent. Deposits of black granite, limestone, sandstone, quartzite, and marble also have considerable potential for future development.

In recent years, Western Australian dimension stones have received recognition through their use in many national and international building projects. Granites and gneisses from the west Kimberley region, Esperance, and Fraser Range have been used to clad a number of city buildings in Sydney, Melbourne, and Southeast Asia, as well as providing material for city streetscapes. In 2003, a green granite from Jerramungup was used to construct the Australian War Memorial in London. Currently, a light-coloured granite–gneiss from Bruce Rock is in demand for slabs and tiles. Sandstones from Donnybrook and the west Kimberley continue to be used in the cladding of buildings and in the construction of streetscapes, such as Melbourne's spectacular Federation Square project completed in 2003. In the Perth region, the natural limestone industry is gaining momentum, with increasing demand for limestone blocks and housing bricks for use in the construction of private homes, subdivision and landscaping projects, and retaining walls, both locally and interstate.

Currently, Western Australia has a small but vibrant dimension stone industry. However, much work is required for industry to realize the full potential of the State's dimension stone resources and to further identify new niche markets for this material, both at home and abroad.

KEYWORDS: dimension stone, construction materials, dolerite, granite, gneiss, limestone, marble, ornamental stone, quartzite, sandstone, quarries, mineral processing, Western Australia.

Introduction

Dimension stone is a natural rock material that plays a significant role in today's construction industry. It is commonly used in the construction of buildings such as city offices, hotels, and shopping centres, as well as surrounding streetscapes, and private homes. Dimension stone comprises a subset of construction materials that may be defined as "*…a natural rock material quarried for the purpose of obtaining blocks or slabs that meet specifications as to size (width, length and thickness) and shape*" (Barton, 1968).

In addition to the foregoing definition, the physical properties of potential dimension stone must meet end-use requirements and the stone must be attractive to the customer. Properties such as colour, grain texture, pattern, durability, and strength, as well as ability to take a polish or other surface finish, are all important requirements. Most dimension stones are cut or trimmed to specified shapes with one or more sides having a mechanically dressed or polished surface. Other dimension stones, such as flagstones and slates, are often left in their natural state. Demand for stone is commonly influenced by contemporary architectural tastes and styles, as well as availability and consistency of physical properties, especially colour.

Applications

Dimension stone has a number of important applications. The most common of these is the total or partial cladding of large buildings with precut stone panels, slabs, and tiles. These may be applied on interior or exterior wall and floor areas. Wall panels are generally between 20 and 30 mm thick, and of variable length and breadth, depending on the application and physical properties of the stone. In harsh climates, certain dimension stones, especially limestones and marbles, are suitable only for interior use.

In the construction industry, cut stone blocks are used to build solid stone-walled buildings and free-standing and retaining walls. Today, constructions of this type are usually in the form of architect-designed homes and offices, generally of no more than two stories. The most common materials used in this application are limestone and sandstone blocks. In the past, particularly during Australia's colonial days, more-elaborate buildings were constructed from these materials, and there are many outstanding examples of this form of architecture preserved in Perth city, Fremantle, and a number of towns throughout the State.

Urban communities have been using dimension stone for paving public areas for many thousands of years. Rough cut or sawn stone blocks were laid to form roads, footpaths, and market squares, and rock slabs were shaped for use as kerbstones and gutters. These practices still continue today, particularly in the refurbishment of old, inner city areas.

In many areas of the world, especially Europe, dimension stone in the form of natural slate has been used extensively as a roofing material. In areas such as north Wales and northwest England, large slate quarries supplied a substantial part of this market for hundreds of years. Although this application is somewhat diminished today, both natural and machined slates are used extensively as interior floor tiles. In this application, slate's popularity stems from the vast array of colours and surface textures that are available, together with its pleasant, cool feel underfoot. Although high-quality slate is currently mined in South Australia, most slate is sourced from India, China, and Brazil.

Dimension stone is also much sought after for use in the monument stone industry, which uses it for a vast array of applications and structures. In the mortuary industry, monuments range from simple grave markers and tombstones, to vaults and large mausoleums. In the public arena, stone memorials can be single shaped blocks bearing a commemorative inscription, through to elaborate and vast stone statues or bas-reliefs, intricately carved by artisans, commemorating a person or an event. Non-commemorative works of art carved in stone are often erected in public places such as town squares, parks, universities, and art galleries.

Granite and marble are the preferred dimension stones for monument and artisinal work because of their ability to take a high polish and their high resistance to the weathering processes of most climates. This is illustrated by examples of granite obelisks carved in ancient Egypt about 3500 years ago. To this day, many of these monuments retain their smooth surfaces, and their carved hieroglyphs show little evidence of weathering. Other dimension stones that have been used in monuments, such as sandstone, slate, and limestone, often show evidence of staining, spalling, cracking, and chemical dissolution over comparatively short periods of exposure to the elements (as little as 50 to 100 years).

Dimension stones of Western Australia

The prospectivity for deposits of high-quality dimension stone in Western Australia is excellent. Numerous potential dimension-stone deposits and prospects have been identified, extending from the west Kimberley region in the north of the State to the area around Esperance on the south coast. However, comparatively few deposits have been mined in the past, and only a small number are currently in production. In 2002–03, reported production of dimension stone was only 1303 t. However, this figure does not include an estimated 126 000 t of sawn limestone building blocks, as well as unreported production from quarries operating on private land. In the State, most dimension stone falls into five main categories: granite and gneiss, black granite, limestone, sandstone and quartzite, and marble.

Granite and gneiss

Western Australia has numerous Archaean to Neoproterozoic granitic rocks and gneisses potentially suitable for use as dimension stone. Granitic rocks are found in many areas, and may display a variety of textures combined with numerous colours. Colours range from pink to red and mid-brown, and also from green to grey. Textures vary from fine-grained equigranular granites to very coarse grained and porphyritic forms commonly displaying large and often attractively coloured phenocrysts of potash and/or sodic feldspars. Currently, visually attractive granites are mined at Jerramungup (*Laguna Green*), Esperance (*Desert Brown*), and Watheroo (*Verde Lope* and *Mulroy Green*). Locations for these granites and all other dimension stones mentioned are shown in Figure 1.

Possibly the State's most unusual granitic dimension stone is the Boogardie orbicular granite, located about 300 km north-northeast of Geraldton. This relatively uncommon granitic rock contains large, closely spaced, light- to dark-grey, egg-shaped orbicules measuring about 10 cm along the longest axis (Fig. 2). The orbicules comprise radiating and granular concentric shells of mainly hornblende and plagioclase surrounding coarsely crystalline cores of variable composition in a coarse matrix of granitic composition (Bevan, 2004).

Other suitable gneisses with attractive colours and banding patterns have been identified in the southern part of the State. Granite–gneisses such as *Austral Juperana*, *Austral Waterfall*, and *Austral Coffee* are quarried in the Bruce Rock area about 220 km east of Perth. *Austral Juperana* is a beige to deep-yellow rock featuring prominent narrow, black, swirling irregular bands and larger pale-green, brown, and pink irregular bands and blebs. *Verde Austral* is sourced from Fraser Range

Figure 1. Location of operating quarries and significant deposits of dimension stone in Western Australia

about 200 km northeast of Esperance. It is a deep olive-green granite–gneiss with charnockitic affinities, and is physically very strong.

Black granite

The term 'black granite' cannot be equated to true granitic rocks. Instead, it is a name adopted by the dimension stone industry to describe black, fine-grained intrusive igneous rocks — mainly dolerite and gabbro, and their metamorphosed equivalents metadolerite and metagabbro. In the early 1990s, high-grade black granites were quarried from Proterozoic dolerite dykes at Wombarella Creek in the Kimberley region, about 300 km east-northeast of Broome, and from metagabbro deposits at localities in the Fraser Range. In the Ashburton region, about 225 km southeast of Onslow, Proterozoic dolerite dykes were prospected for potential high-grade black granite at Glen Florrie.

Between 1990–95, the Wombarella Creek operation produced black granite boulders up to 2–3 m in diameter. Slabs cut and polished from this material were mostly jet black in colour and were highly sought after by architects for interior and exterior feature cladding on buildings, and by the monument industry. Significant quantities of cut blocks were also exported to Japan.

Limestone

In the Perth region, from Seabird in the north to Postans in the south, there are a number of deposits of Tamala Limestone, which is a Pleistocene calcarenite. Suitable-quality material, containing a sufficiently high calcium carbonate content (typically 74–86% $CaCO_3$), is used for dimension stone manufacture (Abeysinghe, 1998).

Currently, limestone blocks used in building construction (Fig. 3) are extracted from quarries located in the Carabooda–Nowergup area in the northern Perth Metropolitan Area, and at Moore River about 70 km north of Perth. These quarry-cut limestone blocks are 1.0 or 0.5 m in length, 0.35 m high, and of variable thickness, and have a rough-textured, more natural appearance than diamond-cut blocks, which makes them ideal for the external walls of homes and for landscaping projects such as walls and paving. Smaller quarry blocks, approximately 0.5 m in length, are diamond cut to produce housing bricks with a smoother texture and more-accurate dimensions than quarry-cut blocks.

Apart from standard limestone building bricks, blocks are also diamond sawn and machined into many other shapes, including window sills, corbels, copings, cappings, fireplaces, bullnoses, and other special profiles. In the Carabooda–Nowergup area and at Postans to the south of Perth, softer material unsuitable for block cutting is crushed and mixed with cement in the manufacture of reconstituted limestone blocks, which are mainly used for inner wall courses in building construction and for landscaping projects, especially retaining walls.

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Figure 2. Ornamental water sphere of Boogardie orbicular granite in Forrest Place, central Perth. Sphere is approximately one metre in diameter

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Figure 3. A private residence built from quarry-cut blocks of Tamala Limestone from Moore River (courtesy Limestone Resources Australia Pty Ltd)

Sandstone and quartzite

There are a number of sandstone and quartzite dimension stone sites throughout the State. The best known of these is located close to the town of Donnybrook, about 30 km southeast of Bunbury, where the *Donnybrook Sandstone* is quarried. This unit is an indurated, fine- to medium-grained, feldspathic and kaolinitic Cretaceous sandstone with colour varying from white to beige, and pink. This sandstone has been quarried for over 100 years and has been used in the construction of many historic buildings. In recent years, up to three companies were extracting sandstone blocks from quarries in this area.

In the north of the State at Mount Jowlaenga, about 100 km northeast of Broome, the Early Cretaceous Melligo Sandstone outcrops in a series of low hills. This unit is fine grained, thinly bedded, flat to low-angle cross-bedded, and contains bivalve fossils (Gibson, 1983). The sandstone varies from light beige to multicoloured forms, displaying prominent, concentric Liesegang banding varying from yellow to pink, red, and mauve over a beige-coloured, sandy matrix. In the area, two dimension stones are quarried from the Melligo Sandstone. These stones, known commercially as *Kimberley Sandstone* and *Kimberley Quartzite*, have different physical strengths related to the degree of resilicification of the rock at different sites.

Natural quartzose flagstones are mined in two areas of the State. In the Pilbara region, an indurated red-brown sandstone, known locally as *Karratha Stone*, is quarried from the Archaean Hardey Formation in the Pinderi Hills, about 50 km southeast of Karratha. This material varies in colour from cream to brown, light green, and pink. About 10 km south of Toodyay, in the Perth region, are several quarries from which Archaean quartzite flagstones are extracted. This material, named *Toodyay Stone*, varies from milky white to grey, or from cream- to red-brown, depending on the location. The rock commonly exhibits thin, pale-green bands of fuchsite, a chrome-mica mineral, along cleavage planes (Low, 1960).

Marble

In the Ashburton region, between 75 and 250 km southeast of Onslow, high-grade dolomitic marble has been identified at various sites in eight localities. These deposits are found in both the Palaeoproterozoic Duck Creek Dolomite and the Mesoproterozoic Irregully Formation. Several of these deposits were quarried for brief periods in the past, but currently the State's only marble mining operation is located at Sheela Bore on Maroonah Station. The Maroonah marble, known as *Desert Green*, is an attractive deep-green dimension stone displaying thin, black swirling veins, and small, irregular white blebs. Other marbles in the region range from thinly bedded to massive, and a few deposits are intensely brecciated, especially at Wyloo. Colours range from white to cream, pink, deep red, mauve, green, grey, and black.

Other rock types

Two unusual forms of dimension stone are quarried in the State. In the Ord Ranges, about 60 km east of Port Hedland in the Pilbara region, a jaspilite rock known as *tiger iron* is mined on an intermittent basis. *Tiger iron* contains thin, alternating, parallel bands of red jasper, black hematite, and smaller amounts of golden-yellow tiger eye (a silicified form of crocidolite used as a semi-precious stone). These bands vary from straight to highly contorted folds. As a dimension stone, this material is used as specialty floor and wall tiles.

In the far south of the State, spongolite, a pale-brown, porous rock, is present in the Eocene Pallinup Formation in the Bremer Basin (Gammon et al., 2000). Spongolite has similar properties to the industrial mineral diatomite, but is composed of siliceous, fossil sponge spicules. It has excellent insulating properties, and in recent years this material has been used as a lightweight building material. Building blocks of spongolite have been sawn from material quarried close to Mount Barker, and are used in building construction in the local area, where it is known as *Mount Barker Stone*.

Trends in dimension stone usage

Towards the end of the nineteenth century, dimension stone quarrying and processing were major industries in Australia. At that time, natural stone was a major component in most substantial buildings, bridges, and other public works. It was used in walls, floors, staircases, roofs, paving, embankments, and supporting structures. In Western Australia there are many splendid examples of colonial buildings constructed of natural stone, especially in Perth, Fremantle, and Kalgoorlie. The extensive use of dimension stone continued until the mid- to late 1930s, when production was substantially reduced due to the onset of World War II. The demand for stone remained low for the next 40 years, but during the 1980s architects once again began to incorporate dimension stone in their designs, and substantial quantities were used in large building projects and contemporary homes. This trend has steadily increased over the last 20 years and today the use of dimension stone in the construction industry remains firmly in vogue. Natural stone blocks, cladding, and flooring are now frequently and extensively used in modern, large buildings such as city offices and shopping malls, as well as in private homes. The architect's skilful selection of stone, combined with innovative designs, often results in stunning visual effects.

Although most material is cut into large slabs, tiles, and paving stones, industry now has access to an extensive array of high-technology stone cutting and profiling equipment — in particular, high-pressure water-jet cutting — which makes it possible to create stone objects of virtually any shape or size (Ditria, 2004). Some material is manufactured into ornamental work such as listelli (decorative borders), which display frieze-like patterns for use on floors and feature walls, and granitic stone benchtops remain a firm favourite in private homes. Not all stones are produced with the traditional two-dimensional slab shape, or with matte or polished surfaces. For example, modern processes can produce

JMF185 18.10.04

Figure 4. Applications of Western Australian dimension stone in building construction and monuments: a) world headquarters of the ANZ Bank in Melbourne (centre foreground) clad in Desert Brown granite from Esperance; b) detail from the Australian War Memorial, Hyde Park Corner in London, featuring Laguna Green granite from Jerramungup; c) polished benchtop made from a slab of Austral Juperana granite–gneiss from Bruce Rock; d) contemporary building design in Perth employing pale-beige Donnybrook Sandstone cladding; e) a spectacular streetscape created in Melbourne's Federation Square using multicoloured Kimberley Sandstone pavers and blocks. Photo (b) courtesy H. Pronk, Tonkin Zulaikha Greer; photo (c) courtesy Melocco Pty Ltd and Discovering Stone (© Discovering Stone 2004); photos (d)–(e) courtesy Meteor Stone

tumbled marble stones, and perfectly shaped granite spheres at least 1.0 m in diameter. A large, ornamental water sphere of Boogardie orbicular granite forms a spectacular focal point in Forrest Place in the centre of Perth city (Fig. 2). A similar-sized water sphere, donated to the Geological Survey by Mark Creasy, is on display at the Perth Core Library in Carlisle (see Frontispiece). Surfaces may also be honed, flamed, etched, split, rough sawn, and bush-hammered to produce a variety of surface textures that are not only visually appealing, but may also impart safety features such as rapid water drainage and non-slip surfaces.

In recent years, Western Australian dimension stones, particularly the granitic stones, have featured prominently and achieved recognition in many national and international building and memorial projects. Most notable examples of this include: the *Desert Brown* granite from Esperance, which was used to clad, in entirety, the exterior walls of the ANZ Bank world headquarters in Melbourne (Fig. 4a); the lustrous, grey *Kimberley Pearl* granite, which was used on some external walls of the Crown Casino in Melbourne; and the *Laguna Green* granite from Jerramungup, which was used to create the recently dedicated Australian War Memorial in London (Fetherston, 2004; Fig. 4b).

Granitic gneisses have also been in demand in recent years. *Verde Austral* continues to find architectural approval and was used in the run up to the 2000 Olympic Games to refurbish streetscapes in central Sydney, as well as providing cladding for several city towers. *Austral Juperana* (as featured on the cover of this Review) has achieved considerable popularity for feature paving in and around large buildings, polished slabs for interior wall cladding, and as elegant bench tops in private homes (Fig. 4c). Recently, the stone has been specified for use in the prestigious Bovis Lend Lease development in Phillip Street, Sydney, designed by renowned international architect Sir Norman Foster.

Donnybrook Sandstone retains its popularity as a dimension stone due to its consistency of discrete colours and its ability to be cut into precisely shaped blocks. An example of the use of *Donnybrook Sandstone* in a contemporary building design is shown in Figure 4d. The *Kimberley Sandstone*, because of its visually attractive banding, has found popularity in the creation of streetscapes, and recently large quantities of this material were used in the paving and cladding of substantial areas of Melbourne's Federation Square (Fig. 4e). In 2003, a non-banded, beige-coloured variant of the *Kimberley Sandstone* was used to clad the exterior walls of the Motorola Building at the University of Western Australia.

In recent years the popularity of private homes constructed from Tamala Limestone blocks or bricks has been on the increase. Also on the increase is the demand pavers for light traffic areas and limestone blocks for use in free-standing and retaining walls.

There is a continual demand for black granite, especially for the cladding of the interior of buildings. Recently, non-polished, tile-sized black granite pavers have been used for roads in contemporary city streetscapes. As a result of this continuing demand, studies are underway to re-establish the black granite industry in the west Kimberley region.

Summary

Dimension stone has continued to play an important role in construction for many thousands of years. Over the last 20 years there has been a resurgence in demand by architects and engineers for attractive dimension stones for use in the construction of large buildings, private homes, monuments, and landscaped areas. Currently, Western Australia has a small but vibrant dimension stone industry, specializing in limestone, granite, gneiss, sandstone, quartzite, and marble. Prospectivity for attractive dimension stones in the State is excellent, especially for granite, gneiss, and black granite. However, much work is needed to identify vital niche markets for Western Australia's dimension stones, both at home and abroad, in order to attract companies with the capacity to expand the industry in the face of competition from suppliers from overseas and other states.

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The revised GSWA rock classification scheme

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Abstract

A four-tier, hierarchical rock classification scheme provides a consistent approach to lithological nomenclature within the Geological Survey of Western Australia (GSWA). Sedimentary, igneous, and metamorphic rocks are classified using objective criteria observable in all rocks, at outcrop, hand-specimen, or thin-section scale. The scheme conforms mostly to internationally recognized classification schemes, apart from the approach to classification of some volcanic rocks.

Introduction

Revision of GSWA's rock classification scheme is a response to the increasing number of digital products extracted from corporate databases, and the requirement that such products employ consistent terminology. The revision provides the opportunity to clarify the usage of certain terminology within GSWA. As GSWA is a field-based organization, the scheme relies on features observable in all rocks at outcrop scale, in hand specimen, and in thin section. This paper provides an overview of the scheme, together with examples of how it is applied. Further details are available on request.

A successful rock classification scheme has to be applicable within all tectonic units and geological settings, and throughout the geological column, which in Western Australia extends back to the Eoarchaean (3.73 Ga). Such a classification scheme also acts as a guide for creating map unit codes for display on map products, and forms the basis for the entry into, and the searching of, all information on lithologies and rock types within GSWA databases. Throughout the revision process, every attempt has been made to develop a set of map unit codes that closely follows those used on GSWA map products in the past to ensure a degree of continuity. The new scheme has been tested on GSWA's East Yilgarn Geoscience Database (Riganti and Groenewald, 2004).

A revised approach to the classification of regolith in GSWA (Hocking et al., 2001) aimed to be 'uniform, comprehensive, flexible, and reasonably intuitive'. It employed a hierarchical approach, from the highest-level landform setting and process, down to regolith composition, and then parent rock type or cement. The scheme allowed the creation of detailed map unit codes that could be 'rolled up' to a higher level for use at progressively smaller map scales. The same aims and principles have been applied to the revised rock classification scheme; the highest-level divisions (sedimentary, igneous, and metamorphic) are further divided following the principles of established or proposed international schemes where available, or follow well-established principles where such schemes are unavailable.

Sedimentary, igneous, and metamorphic rocks are classified using different criteria, although all use a four-fold hierarchical approach. As an example, a coarse-grained rock with a porphyritic 'igneous' texture consisting of quartz (>20%), equal proportions of plagioclase and K-feldspar, and biotite is defined as a monzogranite. From the rock name, a higher level, more genetic classification is implied: that it is igneous, intrusive, and has a broad granitic composition. When translated into a map unit code, the starting point is its granitic composition and texture (granitic – g), followed by subdivision based on its mineral content and mode (monzogranite – m), and then by its specific mineralogy (biotite – b) and particular texture (porphyritic – p). The resulting code is 'gmbp'. These levels can also be used as searchable fields in attribute tables for use with Geographic Information System (GIS) software. Further examples of this approach are given in Table 1.

Sedimentary rocks

Sedimentary rocks are initially classified as 'siliciclastic', 'carbonate', or 'other chemical or biochemical'. Siliciclastic rocks (s) are subdivided by a secondary code according to grain size (e.g. sandstone – st), and further qualified by a tertiary qualifier according to composition (e.g. quartzose – stq). Subdivision of carbonate rocks (k) is initially based on composition (e.g. limestone – kl), then on grain size or texture, based in part on the schemes of Dunham (1962) and Tucker (1991), which are suited to field mapping (e.g. calcarenite – kla). Other chemical and biochemical rocks (c) are treated in a similar way to carbonate rocks, and are classified according to composition (e.g. iron formation – ci), which can then be further qualified according to grain size, texture (e.g. granular – cig), or further compositional criteria (e.g. jaspilitic – cij). All three divisions of sedimentary rocks make use of the same set of environmental quaternary qualifiers (e.g. alluvial – stqa).

In the scheme, the terms 'arenite' and 'wacke' are only used where petrography has established the amount of matrix present; otherwise the rock is classified as sandstone. Arenite refers to sandstone with less than 10% matrix, and wacke to sandstone with more than 10% matrix (Dott, 1964). The preferred terms for a fine-grained sedimentary rock are mudstone or siltstone. Shale is restricted to a fine-grained sedimentary rock with a shaly parting. Rudite and argillite are not used, as they are synonymous with conglomerate, and mudstone or siltstone, respectively. Quartz sandstone is preferred to quartzite or orthoquartzite, as quartzite is defined here as a metamorphic rock, not as an intensely silicified sandstone.

In some cases, there is textural and compositional overlap between sedimentary rocks that contain volcanic clasts and those that are true volcaniclastic deposits. A sedimentary rock is not classified as volcaniclastic simply because it contains some volcanic material. The sedimentary rock classification scheme should be used for clastic rocks in which: the overall stratigraphic context of the rock unit is dominantly non-volcanic; the rock comprises a mixture of non-volcanic clasts and subordinate volcanic clasts; the volcanic clasts are of different composition and type; or the volcanic clasts are rounded and well sorted.

Igneous rocks

Volcanic rocks

A volcanic rock is defined as an igneous rock that has formed on or near the Earth's surface (Jackson, 1997, p. 704). Therefore, the revised GSWA classification scheme uses volcanic terminology for hypabyssal or sub-volcanic rocks (such as dykes, sills, and cryptodomes) that are both spatially and temporally associated with extrusive volcanic rocks. Intrusive rock nomenclature can be used for rocks that may be coarse-grained parts of an extrusive succession, such as dolerite or gabbro, found amongst demonstrable flow successions.

The GSWA classification scheme has adopted a descriptive rather than a genetic approach to the classification of volcanic rocks, which is appropriate for the poorly exposed, altered, weathered and/or metamorphosed successions (Cas and Wright, 1987; McPhie et al., 1993) common in Western Australia. This is in contrast to the more genetic approach adopted by the International Union of Geological Sciences (IUGS; Le Maitre, 2002).

The Geological Survey of Western Australia adopts a more restricted definition for pyroclastic rocks than the IUGS. The IUGS definition of 'pyroclastic deposits' includes all material with more than 75% by volume of pyroclasts, irrespective of the history of transportation, deposition, and resedimentation. In the GSWA scheme, the use of 'pyroclastic' is reserved for primary volcaniclastic deposits, composed of fragments (pyroclasts) generated by explosive eruptions, which have undergone single-phase transport and have been deposited directly by volcanic processes (i.e. pyroclastic fall, surge, or flow; Fisher, 1966).

Consistent with emphasizing the importance of field observations in classification, the revised GSWA classification scheme uses the term 'komatiite' for ultramafic rocks with olivine spinifex texture, or rocks spatially associated with such rocks (e.g. mesocumulates or orthocumulates). Rocks with MgO contents between those of tholeiitic basalts and komatiites (roughly 6–18% MgO) — termed 'high-Mg basalts' in many GSWA publications — are common in Western Australia. In the revised GSWA scheme, the term high-Mg basalt has been abandoned because: not all rocks thus classified have a high MgO content; textural criteria taken as indicative of high MgO contents (e.g. varioles or ocelli) are not confined to rocks with high MgO contents; and some high MgO rocks do not have ocelli or varioles. However, in most cases, rocks with randomly oriented acicular pyroxene (usually replaced by amphibole) have elevated MgO contents of about 10 to 18%. Because these rocks are usually spatially associated with komatiites, and the texture is similar to olivine spinifex texture found in komatiites, such rocks are termed pyroxene spinifex-textured basalts. The term 'komatiitic basalt' is used for rocks which, when analysed, have elevated MgO contents (usually 10–18%) but no textural information to indicate such elevated MgO levels. Units with varioles or ocelli are named accordingly (e.g. 'ocellar basalt' or 'variolitic basalt').

Examples of the revised GSWA classification scheme (Table 1) illustrate the use of the four-letter hierarchical coding system for volcanic rocks. The mandatory primary code provides a broad compositional subdivision (felsic volcanic – f; mafic volcanic – b; ultramafic volcanic – u; feldspathoid-bearing volcanic – l; undivided – n). The secondary code is a more detailed compositional breakdown into lithology (e.g. basalt – bb), whereas the tertiary code contains textural features for coherent units (e.g. pillowed – bbo) and a grain-size breakdown for volcaniclastic units (e.g. volcanic breccia – bbx). The quaternary code includes options for indicating alteration (e.g. carbonate-altered – bbxk), or textural features more strongly aligned with a genetic classification (e.g. lithic-rich – bbxt). In one example (pillowed basalt with radiating pipe vesicles), the scheme does not accommodate the coding of both 'pillowed' and 'vesicular'. In this

Table 1. Examples of the revised GSWA rock classification scheme

Description	*Primary*	*Secondary*	*Tertiary*	*Quaternary*	*Comment*	*Code*
Ferruginous chert	c – other chemical or biochemical	c – chert	i – ferruginous			cci
Polymictic conglomerate interbedded with sandstone; of glacial origin	s – siliciclastic	g – conglomerate and sandstone (conglomerate>sandstone)	p – polymictic	g – glacial		sgpg
Stromatolitic carbonate, with subordinate siliclastic component; back reef	k – carbonate	t – carbonate with minor siliciclastic component	s – stromatolitic	b – back reef		ktsb
Pillow basalt with radiating pipe vesicles	b – mafic volcanic	b – basalt	o –pillowed g – vesicular/amygdaloidal	–	Scheme does not allow for coding of both pillowed and vesicular (both are tertiary codes). Code for one that is most prominent or significant, and put the omitted term in the legend	bbo or bbg
Fragmental komatiite (possible near-vent deposit)	u – ultramafic volcanic	k – komatiite	x – volcanic breccia	–	Could further qualify using a quaternary code for monomictic (u) or vitriclastic (v)	ukx
Komatiitic peperite	u – ultramafic volcanic	k – komatiite	x – breccia	x – sediment-matrix rich		ukxx
Rhyolitic ignimbrite	f – felsic volcanic	r – rhyolite	s – volcanic breccia-sandstone	g – pumice-lithic		frsg
Dacite accretionary lapilli-bearing tuff	f – felsic volcanic	d – dacite	t – volcanic sandstone (grain size equivalent to tuff)	h – accretionary lapilli-bearing		fdth
Monzogranite with muscovite and tourmaline	g – granitic	m – monzogranite	v – muscovite	t – tourmaline		gmvt
Banded olivine norite	o – mafic intrusive	r – olivine norite	y – layered/banded	–	Part of a layered mafic intrusion	ory
Brecciated, goethite-bearing vein quartz	z – hydrothermal	q – vein quartz	i – goethite/hematite	x – brecciated		zqix
Amphibolite after basaltic volcanic and volcaniclastic rocks	m – metamorphic b – mafic	v – metavolcanic and metavolcaniclastic b – basaltic	w – mafic a – aphanitic	a – amphibole/ hornblende	Metamorphic code emphasizes metamorphic features; igneous code emphasizes protolith	mvwa or bba
Schistose, sillimanite-bearing, interlayered pelite and psammite	m – metamorphic	h – psammite and pelite, interlayered	s – schistose	l – sillimanite	Structural code (s) precedes mineralogical code (l)	mhsl
Orthopyroxene-bearing quartzofeldspathic gneiss (protolith unknown)	m – metamorphic	n – gneiss	f – felsic/feldspathic/ K-metasomatized	o – orthopyroxene	–	mnfo

Table 1. (continued)

Description	*Primary*	*Secondary*	*Tertiary*	*Quaternary*	*Comment*	*Code*
Schistose, muscovite-bearing metagranite	m – metamorphic	g – metagranitic	s – schistose	m – muscovite	–	mgsm
Metabasalt interleaved with foliated granitic rock	x – mixed rock types	mbb – metamorphosed basalt	mg – metagranitic	–	–	xmbb-mg
Interleaved mafic and ultramafic schist	x – mixed rock types	mus – ultramafic schist volcanic	mbs – schistose metamafic	–	–	xmus-mbs
Granitic rock with mafic volcanic xenoliths	j – xenolith bearing	g – granitic (predominant) (subordinate; xenolith phase)	b – mafic volcanic	–	–	jg-b

case, the dominant or most significant feature should be included in the code, and any other features described in the legend.

Intrusive and other igneous rocks

The GSWA approach to the classification of plutonic rocks (i.e. coarse-grained, intrusive rocks, indicating crystallization at considerable depth) largely follows that of the IUGS (Le Maitre, 2002), which is based on modal mineralogy, rather than chemistry. The IUGS recommend a grain size of greater than 3 mm for a rock to be classified as coarse grained, and this scheme is adopted here with the exception of the 'igneous other' category, which is reserved for lithologies where the rock name is not dependent on the rock's grain size or mode of occurrence.

All intrusive igneous rocks with a grain size of less than 3 mm contain the prefix 'micro', in accord with IUGS recommendations. For two discrete mappable rock units that differ only in grain size (e.g. fine grained versus medium grained), grain size is incorporated into the codes with a textural and mineralogical qualifier.

Recent practice in GSWA has been to give layered mafic–ultramafic intrusions a primary compositional code of 'a', in order to distinguish them from massive mafic and ultramafic intrusions ('o' and 'u', respectively). This practice is contrary to the IUGS scheme, which classifies rocks according to their mineral content or mode, and not according to the form of the intrusion that hosts the rocks. Therefore, rocks within layered mafic–ultramafic intrusions are now coded according to their composition only (mafic or ultramafic).

There are a number of terms in widespread usage that convey useful information, or are very entrenched in the literature, yet do not conform to the IUGS scheme. For example, the terms 'dolerite', 'pegmatite', and 'granophyre' are in wide use, and have therefore been retained in the new GSWA scheme. However, the terms 'aplite' and 'porphyry' have been abandoned, as they do not convey any useful information about the rock, and suitable compositions (e.g. microsyenogranite) can be used instead.

In the classification of intrusive rocks, the primary code identifies the general compositional type of intrusive igneous rock (granitic – g, mafic intrusive – o, ultramafic intrusive – a, foid-bearing intrusive – d), whereas the secondary codes allow classification of common lithologies (e.g. 'm' for monzogranite). The tertiary codes mainly deal with grain size (e.g. very coarse grained – gmd), although other tertiary and quaternary codes deal with both texture (e.g. equigranular – gme) and mineralogy (e.g. hornblende – gmeh). For 'other igneous rocks', the primary code identifies the general compositional type of igneous rock (lamproite – i, lamprophyre – y, kimberlite – p, carbonatite – r, melilitic rock – e, and kalsilitic rock – w), and the secondary codes offer a means of subdividing these broad groupings into common lithologies (e.g. the lamprophyre vogesite is coded – lv). Grain-size terms (e.g. fine, medium, very coarse) are restricted to the tertiary codes only, and other textural and mineralogical criteria can be specified by tertiary or quaternary codes.

Hydrothermal rocks

Hydrothermal rocks (z) include veins, and massive and bedded material. Gossan is regarded as a regolith unit, not a product of hydrothermal activity.

Metamorphic rocks

The GSWA scheme for metamorphic rocks is based on the recommendations of the IUGS Subcommission on the Systematics of Metamorphic Rocks (SCMR; Schmid et al., 2002), with structural terms following Brodie et al. (2002). Any scheme for classifying and coding metamorphic rocks will be complex, as it must be consistent with the classification of the igneous or sedimentary protolith of the metamorphic rock, and must also cater for classification according to the processes associated with metamorphism.

Under the revised GSWA scheme, metamorphic rocks can be classified in two ways:

- A rock can be named by prefixing the appropriate protolith rock name with 'meta' (e.g. metabasalt, metasandstone) where the protolith is known. A protolith rock name that requires the recognition of a specific primary texture, primary mineralogy, or chemical composition should not be used with a 'meta' prefix if the primary feature has been destroyed or altered by metamorphic processes. Where primary structures are no longer obvious, an approved specific metamorphic rock name can be applied to the unit (usually implying the protolith). This name is based on metamorphic mineralogy, and reflects composition and metamorphic grade or process (e.g. amphibolite, marble, and skarn). The scheme also provides codes for metamorphic rocks where some general inference can be made on the origin of the rock (e.g. mafic igneous rock, whether intrusive or volcanic).
- Where the protolith is unknown, metamorphic rocks can be either classified by applying the IUGS SCMR recommended structural root terms (schist, gneiss, and granofels), or classified as the product of a specific metamorphic process (impactite, fault rock, and metasomatic rock).

In both cases the meta(protolith) name, the specific name, or the structural root or process terms can be combined with composition or mineral qualifiers to complete the metamorphic rock name.

Where characteristic compositions, lithological features, original layering, and stratigraphic relationships are readily distinguishable, lower grade metamorphic rocks (usually up to and including greenschist facies) can be treated as unmetamorphosed sedimentary and igneous rocks. Where the degree of deformation and recrystallization varies within a sequence of lower grade rocks (e.g. in Archaean greenstone belts), units coded according to preserved sedimentary and igneous features (e.g. pillowed basalt – bbo) can exist alongside those coded for metamorphic features (e.g. mafic schist derived from a basalt – mbbs).

The primary code (m – metamorphic) is mandatory. A combined secondary and tertiary code is applied to protolith rock names with 'meta' prefixes and to specific rock names, and generally follows the igneous or sedimentary protolith code (e.g. metabasalt – mbb, metamonzogranite – mgm, and metasandstone – mt). Where the protolith in unknown, the structural root or metamorphic process terms are used (schist – s, gneiss – n, granofels – e, impactite – p, fault rock – y, and metasomatic rock – z). Tertiary and quaternary qualifiers include structural and textural terminology, composition, mineralogy, and alteration. The same tertiary or quaternary code letter can be used for more than one qualifier, as the context, denoted by the secondary or tertiary code letter, can be different (e.g. metagranodiorite – mgg; garnet-bearing pelite – mlg).

The scheme allows for coding of compositionally similar rocks in a number of ways, depending on what feature is to be emphasized. For example, a metamorphic rock derived from a monzogranite could be classified as a felsic meta-igneous rock (mr), a metagranite (mg), a schistose granitic rock (mgs), a felsic schist (mrs), a mylonitic granite (mgy), or a cataclastic fault rock (myxf).

Mixed lithologies, and inclusion- or xenolith-bearing lithologies

Many mappable units contain more than one lithology or rock type. When applying a rock classification scheme in the construction of lithological map unit codes for a mappable unit at any scale, emphasis should be placed initially on the predominant lithology or rock type, or a diagnostic or significant lithology or rock type within the unit (i.e. the feature that makes the unit distinguishable from adjacent mappable units). The principles are those discussed for lithostratigraphic units in the International Stratigraphic Guide (Salvado, 1994, p. 31–43). Mixtures of lithologies within rock types where no one lithology is predominant are best dealt with within each classification scheme by creating an appropriate code if necessary. For example, within the 'sedimentary siliciclastic' classification, siltstone/mudstone would appear as 'sl', and interbedded sandstone and siltstone as 'ss'.

There are mappable units that at the highest level of division represent mixtures of sedimentary, igneous, and metamorphic rocks, and units at a lower level of division that are mixtures of rock type. In these cases an 'x' is used in place of a primary rock type code and is followed by two bedrock codes, in order of predominance, separated by a hyphen (e.g. *lit-par-lit* intrusion of granitic rocks into igneous mafic volcanic rocks at a greenstone belt margin – xg-b; interbedded carbonate and ultramafic rocks – xk-u).

In some cases it is necessary to code a mappable unit that has abundant inclusions or xenoliths, such as in granite–greenstone terranes where the margins of granite bodies have abundant greenstone xenoliths. In this case, the code 'j' is used in a similar way as 'x' for mixed rock types as a primary code. Thus, 'jg-b' is granitic rock with mafic volcanic xenoliths, whereas 'jo-g' is gabbro with granitic xenoliths.

Conclusions

The revised GSWA rock classification scheme aims to be flexible and intuitive. Consistent with GSWA being a field-based organization, classification is based on the objective observation of features at the outcrop, hand-specimen, and thin-section scale. Attempts have been made to follow accepted international recommendations for lithological classification and nomenclature, and this has been largely achieved. Most notable exceptions are in the classification of volcanic rocks: the GSWA and IUGS schemes diverge when it comes to identifying pyroclastic rocks, the IUGS scheme uses chemistry in classification, and there are differences between the GSWA and IUGS approaches to nomenclature and classification of volcanic rocks with elevated MgO contents.

Revision of the nomenclature of rocks in GSWA has also provided the opportunity to clarify the organization's usage of common terms that do not strictly conform to the classification and nomenclature guidelines. Some terms have been retained, whereas others have been abandoned.

Although sedimentary, igneous, and metamorphic rocks form by different geological processes, the revised classification scheme attempts to provide a common approach to classification of all rock types by adopting a four-tier hierarchical coding scheme. Although map unit codes are largely based on objective criteria, quaternary codes allow more-genetic criteria to be included in the classification.

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GeoVIEWER.WA — adding value to geological mapping

by S. G. Bandy

Introduction

For more than 100 years the Geological Survey of Western Australia (GSWA) has acquired, enhanced, archived, and disseminated regional geological, geophysical, geochemical, mineral, and petroleum data as a fundamental component of its work program.

GeoVIEWER.WA signifies a new direction in GSWA's approach to managing and distributing these geoscientific data on digital video disc (DVD) and compact disc (CD). *GeoVIEWER.WA* will be the foundation for delivering several very distinct DVD/CD products including the 1:100 000 Geological Information Series, mines and mineral deposits data, geochronology, and a catalogue of products.

The primary objectives of *GeoVIEWER.WA* are to:

- enable GSWA customers to access spatial and associated textual data distributed on our data DVD/CDs;
- allow more control over the display and analysis of geoscience data distributed on our data DVD/CDs;
- position GSWA to take advantage of evolving technologies in its operations and in design and delivery of products.

GSWA recently released a number of much-enhanced geological 'maps' that include not only the interpreted geology, but all the underlying data that went into constructing the map: lithological and structural data, petrographic reports with photomicrographs, site photos, and geochemical data, as well as other datasets such as aeromagnetic, gravity, radiometric, and satellite images and orthophotography.

As an easy-to-use interface, *GeoVIEWER.WA* (Fig. 1) improves access through visualization, query, and integration of raster, vector, and point data using common tools that do not require specialized GIS skills. Each point or polygon can be interrogated on the virtual map, and the relevant summary, full description, or report, including photographs, are displayed in seconds. The displayed maps and reports can be printed or pasted directly into any Microsoft Windows-based program. Full Explanatory Notes to accompany the map will also be included on the DVD/CD rather than being published separately, giving GSWA the opportunity to include many more colour photographs than would otherwise be possible.

GeoVIEWER.WA also provides complete flexibility to the user in the presentation of the data including labelling, ordering, and rendering of all data, which can be any combination of ESRI shp, MapInfo tab, geoTiFF or ECW. The viewer also supports transparency in the presentation of layers.

Technical overview

GeoVIEWER.WA was developed to have standard 'Windows' look and feel. This makes the application intuitive to customers and requires minimal learning to be able to get the most from any data package.

GeoVIEWER.WA was built using a modular approach and following object-oriented development guidelines. This concept enables a more robust framework and a scalable architecture that provide additional functionality and the potential for future customizing to better service customers' needs.

The viewing tool was developed using AspMap by VDS Technologies. The software is supplied as a collection of Dynamic Link Libraries (dll) on a royalty free distribution license, thus ensuring the cost of distributing the software need not be passed on to the customer.

The properties and methods of the dlls are accessed through the Visual Basic 6.0 (VB) development environment. Through the use of these dlls in conjunction with Windows system functionality, controlled through customized VB code, *GeoVIEWER.WA* has been built to allow not only the display and query of the supplied spatial data but also the linking to non-spatial data. This non-spatial data is held as Microsoft Access Databases and Adobe's Portable Document Format (PDF). Figure 2 shows the process flow.

Data connection

In addition to *GeoVIEWER.WA*, the key element in providing data in this format is the increasing sophistication of GSWA's databases that house the spatial, numeric, and textual data. These databases fit within GSWA's corporate schema and are related through a SITES table. These databases include:

- WACHEM — geochemical data
- WAMIN — mineral occurrence data
- WAPIMS — petroleum administrative and exploration data

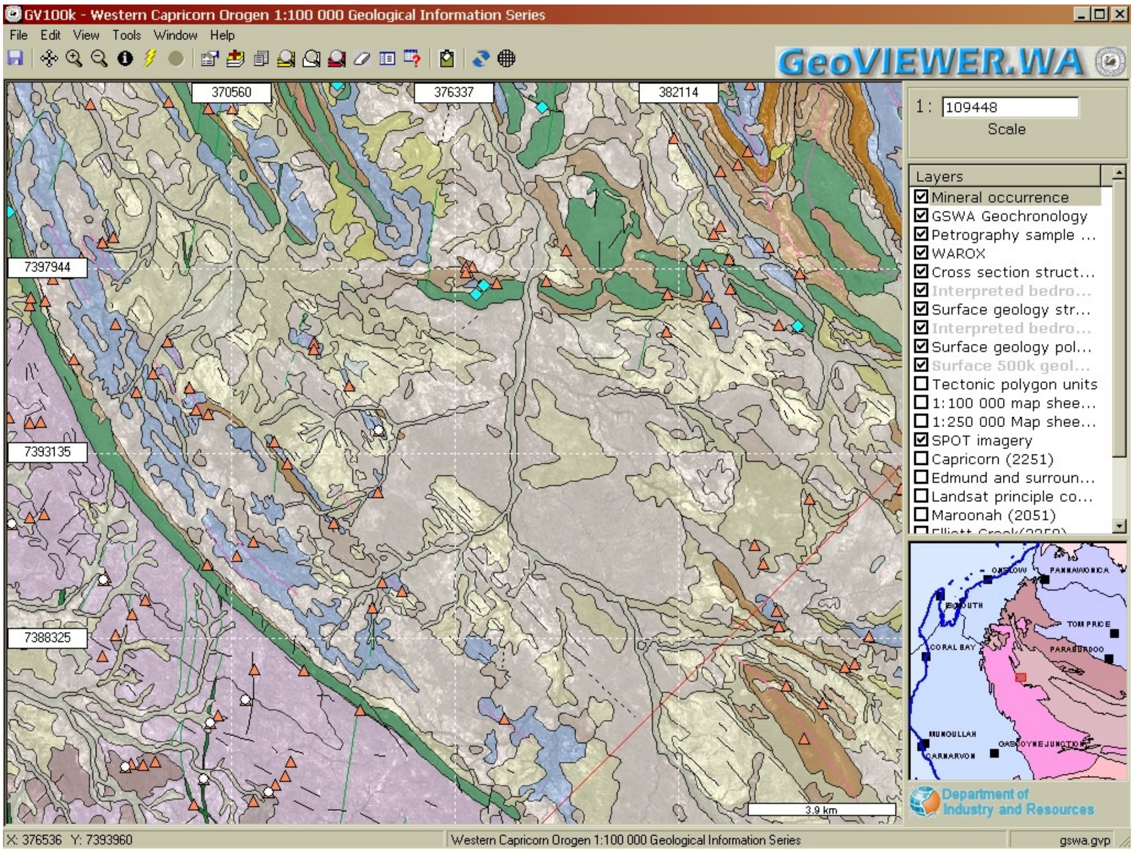

Figure 1.** GeoVIEWER.WA **interface

- GEOCHRON — geochronology data
- WAROX — sample details, field observations, photos, and related reports
- EXACT — exploration activity summaries.

All new data are now entered into these databases. In addition to the new data, a substantial quantity of legacy data spanning the last 100 years of GSWA activities throughout the State is being added on a project by project basis. It is hoped to incorporate much of this legacy data into the new 1:100 000 Geological Information Series as they are produced, but clearly that will not always be possible in the short term.

GeoVIEWER.WA allows the linking of spatial and associated textual data through one easy-to-use tool, which controls the display and reporting of data. Through the advanced query functions, customers can construct and link complex database queries to the supplied GSWA data, or through a primary/foreign key link to their own databases (Fig. 3).

Tool box

You can interact with the data through a set of tools provided in the interface (see Fig. 4):

Save Project
Save changes made to *GeoVIEWER.WA* GVP file.

Recentre Mode
Use the recentre tool by pointing to a location on the map. The Map Display will recentre on the point you selected.

Zoom In Mode
To zoom in on a particular position on the Map Display, click that position once with this tool. To zoom to a particular area on the Map Display, drag a box over the area with this tool.

Zoom Out Mode
Same as the zoom-in tool but zooms out from the position you click or the area you drag over.

Identify Mode
Click on a layer in the Layer Manager to make it active. Click on the Identify button, and then select a feature in the Map Display to return information about that feature. This button will be 'greyed' out if the active layer is an image or raster dataset.

Hyperlink Mode
Click on the Hyperlink button, and then select a feature to see any information linked to the active layer. If there is no linked information then this button will do the same as the Identify button.

Textual Search
This option is specific to the GSWA Catalogue products and will be 'greyed' if the product layer does not exist on the CD/DVD.

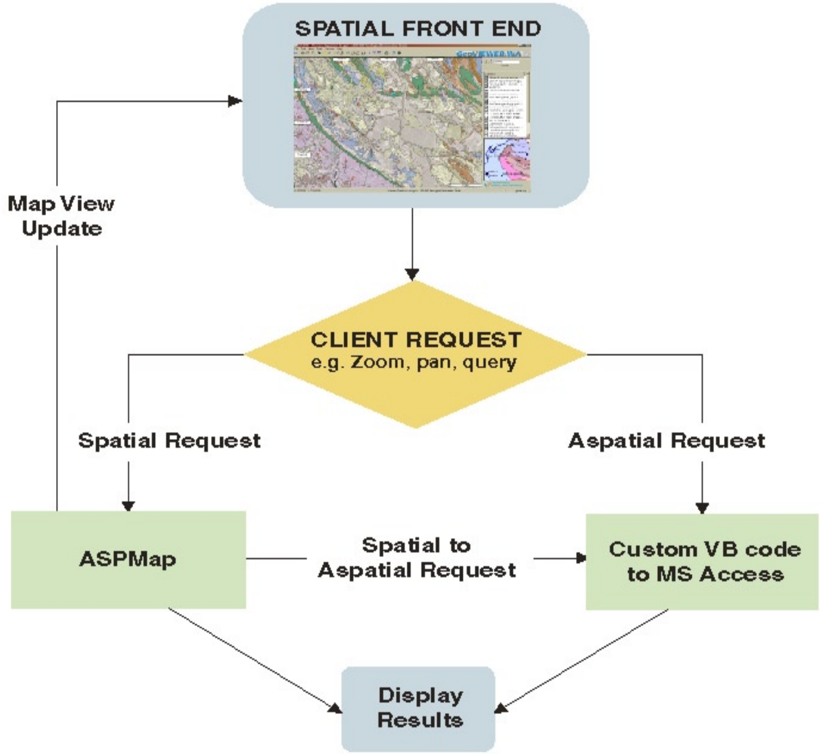

Figure 2. Process flow diagram

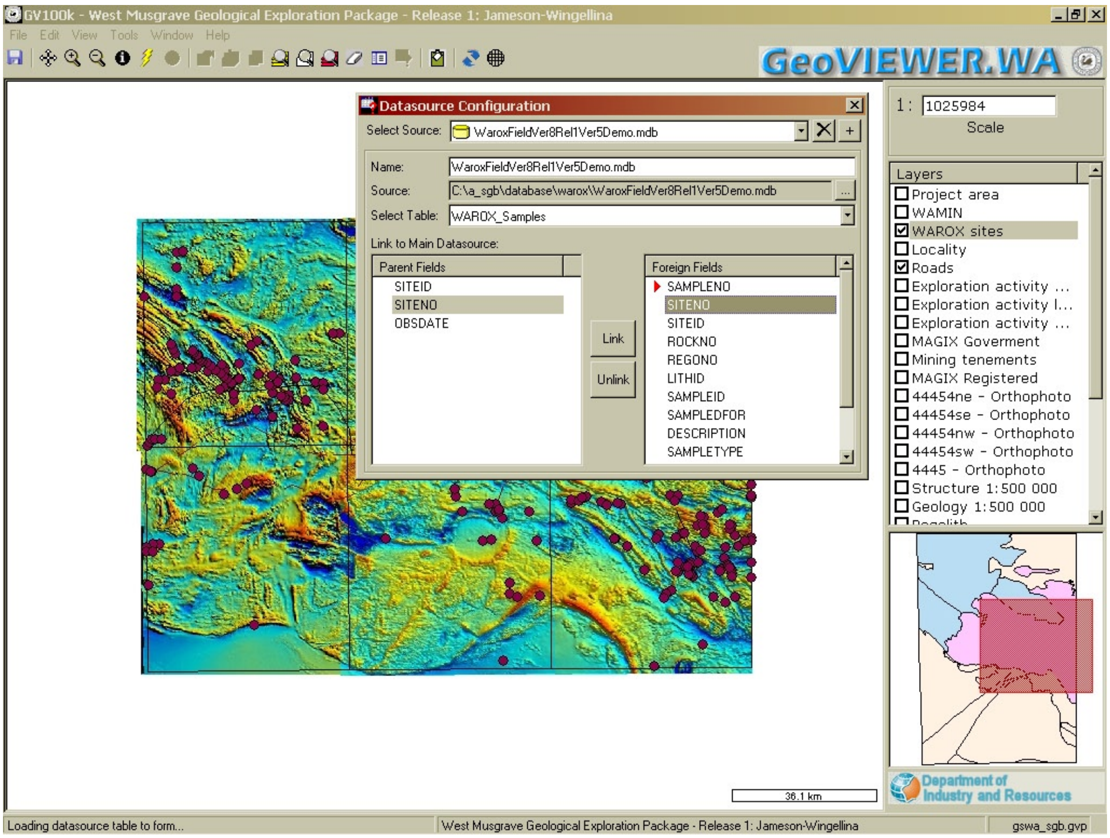

Figure 3. Linking to an external database

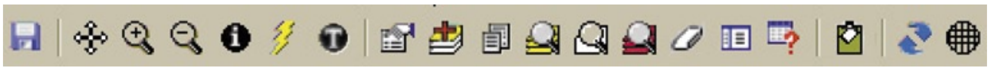

Figure 4. Tool bar

Click on the Textual Search button, and then specify your search criteria.

Edit Layer Properties
Click to view or modify the way the active layer is drawn in the Map Display.

Add Layers
Click to select the layers you want to add to the Layer Manager.

You can also add local datasets to the data menu. GSWA's strategy is to provide updated geoscience data via the Internet from GSWA's Data and Software Download Centre (www.doir.wa.gov.au/gswa). Customers can download updated data at no cost and store these data on their hard drive. Using *GeoVIEWER.WA* these data can be loaded into the viewing tool.

View Report
Click on this button to view the associated report. This button is greyed out if there are no associated reports.

Zoom to Full Extent
Zooms to the full spatial extent of all the layers in your Map Display. For example, if you have zoomed in a couple of times on your view, click on this button to zoom to the extent of all layers.

Zoom to Layer Extent
Click to zoom to the extent of the active layer.

Zoom to Selected
Click to zoom to the extent of the selected features.

Clear Selection
Click on this button to remove any selected features that are highlighted.

Display Legend
View a legend for features displayed in your Map Display.

Query Layer
Create and run query expressions. You can add new and delete existing data sources used by the Layer Query Builder.

Copy Map Image to Clipboard
Click on this button to copy your Map Display to the clipboard. To copy the overview map to the clipboard, place your cursor over the overview map, then press the right mouse button. To copy the map legend to the clipboard, place your cursor over the map legend, then press the right mouse button.

Refresh Current Map
Refresh your Map Display by clicking this button.

Add Grids to Map
Add map coordinate grid lines to your map by clicking on this button.

Conclusion

GeoVIEWER.WA, as a state-of-the-art geoscientific data product, provides the most up-to-date data from GSWA's continuously updated databases, delivered in a timely manner and at no cost via a user-friendly DVD/CD interface.

GeoVIEWER.WA is changing the concept of the traditional geological map. GSWA is moving away from the standard map-centric structure, to a data-centric approach in the delivery of geoscience and associated data. By making the geoscientific data readily accessible, these DVD/CD data can be integrated with local data and incorporated into decision-making processes, thereby promoting mineral and petroleum exploration in Western Australia.

Program review

PETROLEUM SYSTEMS STUDIES AND PETROLEUM EXPLORATION DATA

Basin studies

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

Highlights and activities 2003–04

Activities during 2003–04 focused on the Officer Basin, as work on the western margin basins approached completion and preparatory studies of the Canning Basin commenced. Some of the highlights are:

- A 1501-m stratigraphic drillhole, Lancer 1, was successfully drilled in the Gibson area in November 2003. The basic well completion report was completed in March 2004. Preliminary analyses indicate that sandstone facies typically have excellent reservoir characteristics (with porosities up to 29% and permeabilities up to 10 Darcies), and that there are potential regional seals at the base of the Hussar and Kanpa Formations. Organic richness, however, is low with only two samples yielding total organic carbon over 0.5%. Remaining work to be completed on Lancer 1 core includes palaeontological (stromatolite and acritarch), palaeomagnetic, isotopic, petrographic, and seal property analyses.
- Approximately 4300 line kilometres of seismic data from the Officer Basin reprocessed by GSWA in 2002–03, and 2165 line kilometres reprocessed by JNOC in 1996, were interpreted for a report on the geophysics of the basin.
- Reports on the lithostratigraphic framework of the basin, and a report on the Waigen area, south of the Musgrave Complex, were completed. For the latter, subsurface information is limited to a single drillhole, Vines 1, and potential field data.

Other projects during 2003–04 included: a geophysical review of the southern Perth Basin; the generation of a new isostatic gravity image of the State incorporating offshore satellite data and based on improved modelling techniques; GSWA participation in a Geoscience Australia dredging cruise along the southern margin of Western Australia to investigate the petroleum potential of the western Bight Basin; sampling and analysis of mineral holes in the Southern Bonaparte Basin for their source rock potential (with Geoscience Australia and the Northern Territory Geological Survey); and participation with SRK Consulting in the construction of open-file Oz SEEBASE (Structurally Enhanced view of Economic Basement) modules for onshore Western Australia based on the interpretation of magnetic and gravity data, and calibrated with many other datasets including mapped geology, topography, event histories, wells or drillholes, and seismic data. This participation is to continue into 2004–05.

2003–04 publications and products

- Report 89: *Geophysical investigation of the Bernier Ridge and surrounding area, Southern Carnarvon Basin, Western Australia*;
- Report 91: *Hydrocarbon migration and entrapment in potential Lower Cambrian reservoirs, Vines 1, Officer Basin*;
- Record 2004/4: *GSWA Boologooro 1 well completion*

report (interpretive data), Gascoyne Platform, Western Australia (includes digital dataset);

- Record 2004/7: *Depositional facies and regional correlations of the Ordovician Goldwyer and Nita Formations, Canning Basin, Western Australia, with implications for petroleum exploration*;
- Record 2004/8: *Gravity and magnetic interpretation of the southern Perth Basin, Western Australia*;
- Record 2004/10: *GSWA Lancer 1 well completion report (basic data), Officer and Gunbarrel Basins, Western Australia* (includes digital dataset);
- Record 2004/4: *Western Australia: isostatic residual gravity anomaly and depth to basement model*;
- *Summary of petroleum prospectivity, onshore Western Australia 2004: Bonaparte, Canning, Officer, Perth, Southern Carnarvon, and Northern Carnarvon Basins*;
- State Specific Area Gazettal data package (in conjunction with Petroleum Division and Petroleum Exploration Data Group);
- external papers on the Bernier Ridge in the APPEA Journal, and on Silurian carbonates of the Gascoyne Platform in Sedimentary Geology.

Future work

As a consequence of a joint GSWA and industry workshop held in late 2002, the basin studies group will increasingly focus on framework studies of the onshore Canning Basin, and maintain a monitoring role of other onshore basins. Initial products for the Canning Basin will consist of data packages, assembled to assist later interpretive work, with an emphasis on trial seismic reprocessing and logging of available core from the pre-Permian section.

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Petroleum exploration reports and data

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

Highlights and activities 2003–04

The program of scanning of well completion reports from hardcopy to PDF and TIFF file formats continued with a total of 271 wells focusing on the Canning Basin being scanned and loaded into the WAPIMS system for online web viewing.

As part of the WAPIMS database program, well-log curves for a further 166 wells — giving a total of 692 wells — were loaded into the system, enabling the public to view the data via the web.

Transcription of seismic field and processed data from the Canning Basin from nine-track reels to 3590 cartridges (4875 tapes from ten surveys) continued to reduce the number of 'old' tapes in the archive and move these valuable data to new and more reliable media.

Upgrades to the WAPIMS public interface were completed.

WAPIMS database

During 2003–04 a total of 72 476 new data items received from industry were loaded into the system and core data for both the Kalgoorlie and new Perth core libraries have been entered into WAPIMS.

Data release

During 2003–04, 313 edited and unedited reports were released. Ninety-five industry requests for loans of seismic and well, digital field, and processed data for 212 seismic surveys and 329 wells were met. In addition, 84 requests for sample drillcore or cuttings from 247 wells were processed. A further 193 ad hoc requests for data were also processed.

Future work

Continue scanning of well completion reports for upload in to WAPIMS to complete all of the onshore Canning, Officer, and Carnarvon Basins.

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MINERAL RESOURCES ASSESSMENT AND MINERAL EXPLORATION DATA

Mineralization and exploration assessment

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

Highlights and activities 2003–04

Two mineral prospectivity data packages on the west Kimberley and Canning areas were released during the year. Two data packages were nearing completion for the Earaheedy and Paterson areas. Compilation of databases and digitizing of spatial data for mineral occurrences and mineral-exploration activities continued for the Gascoyne area and commenced for the west Hamersley and Mid-west coast projects. An updated CD-ROM with data from the latest WAMEX releases since 2000 was completed for the east Kimberley and one CD-ROM update is in progress for the east Pilbara (Fig. 1).

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

The CD-ROM for each package contains the following datasets available in shapefile format: WAMIN (spatial and attribute database of mineral occurrences); EXACT (spatial and attribute database of mineral-exploration activities); MINEDEX (extract of Departmental database with mine sites and mineral resources); WAMEX (extract of Departmental database with index of open-file mineral exploration reports); TENGRAPH (extract of Departmental database with mining tenements and holders); geology (solid and regolith); LANDSAT; aeromagnetics; radiometrics; gravity; and topographic and cultural features.

A further enhancement was introduced to GeoVIEW.WA to provide links between the EXACT database and WAMEX on the web, whereby exploration activities from WAMEX open-file reports are displayed as points, lines, and polygons. Clicking on an activity activates an attribute box containing information on the activity type and the 'A' number of the open-file report; a hyperlink from the report 'A' number provides access to WAMEX reports on the web.

2003–04 publications and products

Report 88: *Mineral occurrences and exploration potential of the west Kimberley*;

Record 2004/3: *Mineral occurrences and exploration activities in the central and south Canning area*;

CD-ROM update: 2004 update of Report 74, east Kimberley.

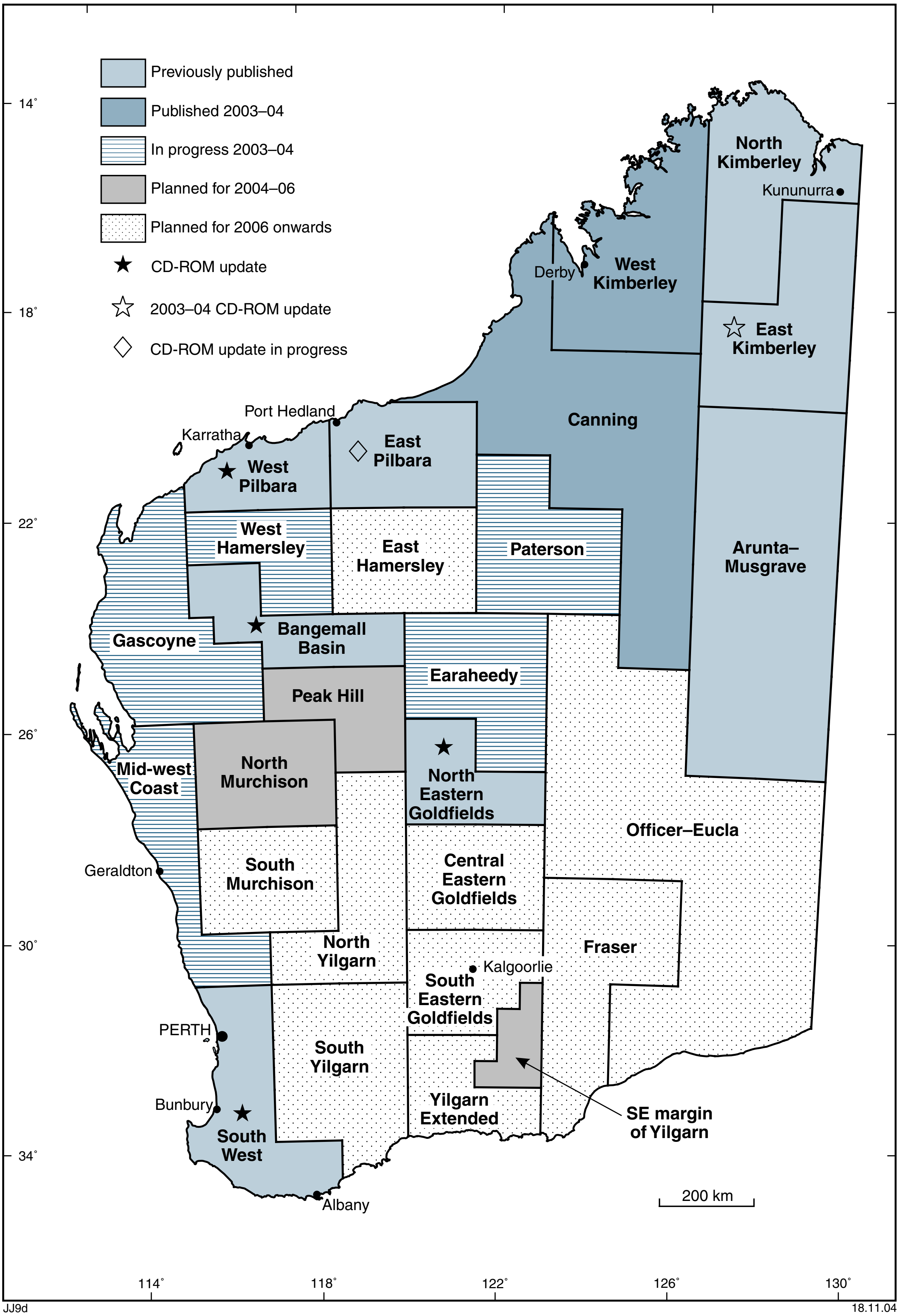

Figure 1. Progress of regional mineralization mapping projects

Future work

Four data packages for the Earaheedy area (Report 96), the Paterson area (Report 97), the Mid-west coast area, and the west Hamersley area are in preparation for release in 2005. Database compilation and digitizing will continue for the Gascoyne area, and will commence for the north Murchison and Peak Hill areas (Fig. 1).

An updated CD-ROM of mineral occurrences and mineral-exploration activities for the east Pilbara is planned.

Database compilation and digitizing of mineral occurrences and mineral-exploration activities will also be completed for an area of eight 1:100 000 map sheets over the southeastern margin of the Yilgarn Craton (Fig. 1).

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Commodity and industry analysis

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

2003–04 highlights, activities, and publications

- The ongoing data capture into DoIR's mines and mineral deposits database (MINEDEX) formed an important part of the function of this section. A total of about 350 ad hoc inquiries seeking information on mines, deposits, mineral resources, and mineral production were received from industry, the public, other Government agencies, and staff of DoIR.
- Publication of: *Tantalum in Western Australia* (Mineral Resources Bulletin 22); *Iron ore deposits of the Pilbara* (June 2004 edition) map and CD; a new map *West Australian mines — operating and under development, April 2004*; the November 2003 edition of the popular *Major Resource Projects* map; and annual overviews on mineral exploration and development in Western Australia.
- A draft GSWA Record *Industrial minerals in Western Australia: the situation in 2004* was prepared.
- Preliminary compilation and fieldwork started on a project covering dimension stone in Western Australia, with publication intended as a two-part Mineral Resources Bulletin.

2004–05 activities and planned publications

Updates and new editions for a suite of publications and maps covering the mineral deposits of Western Australia, the iron ore industry, mineral exploration, and industrial minerals will be published.

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Inventory of abandoned mine sites

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

Highlights and activities 2003–04

The inventory, which commenced in 1999–2000, has the objective of locating mining-related features within historic mine sites in the State and documenting factors relevant to their safety and environmental impact. This information can be used to provide advice on rehabilitation or conservation of historic mine sites.

Data entry in the field is via a hand-held computer that is linked to satellite navigation equipment capable of locating mine site features such as shafts to an accuracy of around 10 m. More than 27 000 mine site features were added to the inventory during 2003–04, resulting in a total of 121 376 features at 30 June 2004 (Fig. 2).

Priority for field inspection is being given to those sites within 10 km of major towns, and within 1 km of important access roads. About 35% of all historic mine sites are in this high-priority category. At 30 June 2004, approximately 82% of known high-priority production sites had been inspected during the program. Priority is now also being given to sites within 5 km of smaller towns and communities, and less than 1 km from selected tourist routes.

Fieldwork during 2003 was conducted in the Southern Cross region, extending from Marvel Loch to Bullfinch, and including Westonia. Fieldwork commenced in the Norseman area in 2004.

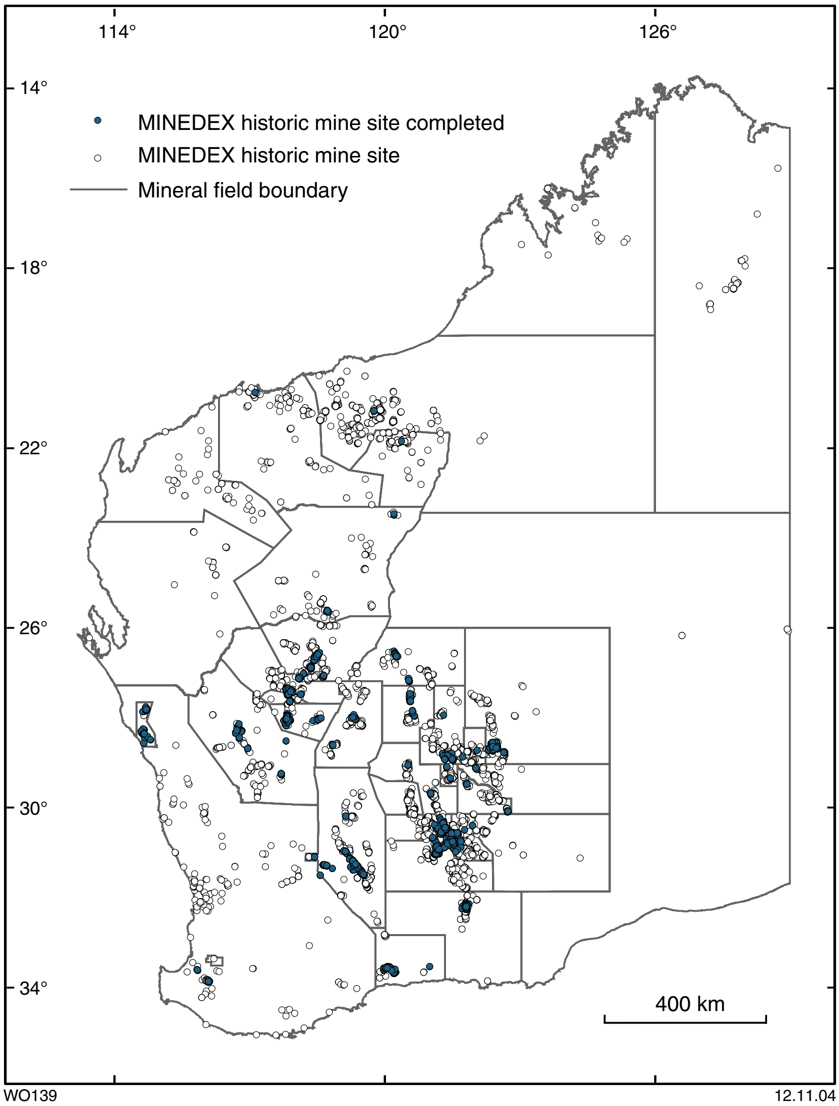

Figure 2.** **Status of the inventory of abandoned mine sites — MINEDEX sites completed as at 30 June 2004

2003–04 publications and products

- Digital datasets on DVD: *Inventory of abandoned mine sites: progress 1999–2003.*

Future work

The team will continue work in the Norseman, Widgiemooltha, and Kambalda areas.

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Land access and resource assessment

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

2003–04 highlights and activities

The primary function of the group is to provide geological advice with respect to changes to the tenure and purpose of Crown land and Private land. During 2003–04, advice was given on 912 requests for land title or land use changes. These included advice on land subdivision proposals, pastoral lease acquisitions for conservation purposes, and the creation of terrestrial and marine conservation reserves to ensure future resource access.

Detailed resource assessment studies, including preparation of land use maps, were carried out on:

- the Hope Downs railway project. This involved the assessment of the mineral potential of the underlying railway corridor, negotiating appropriate deviations, and discussions with tenement holders;
- the Dampier Archipelago. A *Resource potential for land use planning* map was completed and used to support the Department's position on retaining strategic resources of limestone and limesand for future industry requirements;
- local government town planning schemes and local planning strategies for the Shires of Gingin, Toodyay, Dowerin, and Bruce Rock;
- CALM pastoral leases that are being considered for conversion to conservation reserves.

2003–04 publications and products

Resource potential for land use planning maps of the:

- Cape Range region (1:100 000);
- Cape Range – Ningaloo area (1:500 000);
- Dampier Archipelago (1:100 000);
- Gingin area (1:200 000);
- Lake MacLeod area (1:500 000);
- Ravensthorpe district (1:15 000);
- Toodyay area (1:200 000);

Future work

The group will continue to examine land title and land use changes for potential conflict with land access for exploration or the sterilization of known and potential mineral resources. Some ongoing projects are:

- the Hope Downs railway project;
- assessment of sand and gravel resources in the Kalgoorlie region for the Department of Planning and Infrastructure;
- proposed expansion to the Kalgoorlie–Boulder townsite for the City of Kalgoorlie–Boulder;
- proposed expansion of the town of Ravensthorpe;
- proposed nature reserves at Corinthia, Yarloop, Yalgorup, and Dundas.

A review and update of the Memorandum of Understanding between the WA Planning Commission, the Department of Planning and Infrastructure, and DoIR is programmed to improve efficiencies in referrals.

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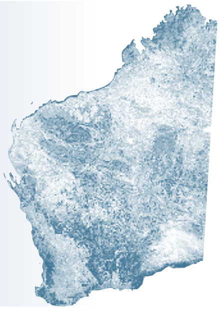
Industry and community liaison

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



2003–04 highlights and activities

Conservation issues

- As identified in the Government's 'Protecting Our Old Growth Forest Policy', the Southwest Forest Management Plan proposes 30 new national parks and a large number of other new conservation reserves. Advice was provided to the Minister for State Development, and presentations were made to the Department of Conservation and Land Management (CALM) with the goal to minimize the impacts on future resource access in the State. Areas within State Agreement mining leases were protected through these negotiations with CALM and industry.

- Proposed extensions to the Mount Manning Nature Reserve, north of Southern Cross, were initiated by CALM. Presentations were made outlining the impacts of the proposed reserve on future resource access and the regional community, including the fact that the reserve directly impacts on known mineralization with a gross in-ground value of more than $2.5 billion.

- World Heritage nomination of the Ningaloo – Cape Range region and Ramsar nomination of the Lake MacLeod areas have been initiated by CALM. Concerns were expressed to appropriate authorities about the implication of these proposals on resource tenement holders' rights and future resource access.

- Advice was provided on the implications of converting 42 pastoral leases owned by CALM to conservation reserves, many cover areas prospective for minerals or petroleum.

Community liaison

- The group had input of geological and resource information to a broad range of planning initiatives related to urban, rural, and community developments — such as supplies of basic raw materials, including gravel around the proposed Walpole Wilderness Area, and for the Shires of Nannup, Broome, and Roebourne, limestone mining at Cape Range, and implications of the town expansion at Ravensthorpe. Advice was provided to a number of local Government authorities regarding extractive industry policies and projects.

- Watching briefs were maintained on the Perth Metropolitan, Peel, and the Greater Bunbury Regional Plans in relation to protection of access to titanium mineral deposits and construction materials. Information and advice was provided for the Central Coast Regional Planning study.

- Work continued on the definition of a buffer surrounding the Bunbury Basalt quarries at Gelorup. If accepted, the principles used in the buffer definition will be a very significant outcome for the future protection of these quarries from conflicting land uses, and are likely to be applied widely on a generic basis.

- A talk was presented at the AIG Regulatory Seminar on 'Access to the conservation estate and other environmentally sensitive lands'.

Planning initiatives

- Mapping of the titanium mineral deposits in the northern Swan Coastal Plain has continued to ensure resources are protected from conflicting land uses until mining and rehabilitation is completed. Similar mapping of the southern Swan Coastal Plain has been particularly effective in protecting deposits.

- Advice was provided on the Ord Stage 2 proposal, the proposed radio telescope site for Western Australia, a replacement area for the Lancelin defence training area, the Bush Forever Bushplan, and Fauna Habitat Zones.

Geological initiatives

- As part of GSWA's responsibility to manage sites of geological significance, work has commenced on the development of a comprehensive database of geoheritage sites. GSWA is part of an interdepartmental committee considering protection of important fossils from inappropriate collection.
- GSWA is finalizing the creation in the Pilbara region of small Crown reserves over internationally important stromatolite fossil sites — these are the oldest fossils known on Earth.

Future work

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

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

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Geoscientific advice relating to exploration

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

Highlights and activities 2003–04

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 2868 mineral tenements (Table 1) was reviewed during 2003–04 as part of the assessment of applications for exemption from expenditure conditions, applications for extension of term of Exploration Licences, applications for Retention Licences, applications for Special Prospecting Licences, applications for iron ore authorization under Section 111, and applications for Ministerial consent to dealings in Exploration Licences during their first year of tenure.

Due to the strength of the world iron ore market, there has been a steep increase in the number of applications under Section 111 of the Act to authorize the holder to explore for iron ore (from 30 applications in 2002–03 to 90 in 2003–4). Exploration activity has increased, not only in the Pilbara, but also in other regions (Murchison, Southern Cross, Ravensthorpe, and Kimberley).

The number of applications for exemption from exploration expenditure determined by the Department during 2003–04 has decreased by about 9% to 5211.

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

Exemption applications recommended for refusal are referred to GSWA if they require the assessment of work programs that have been lodged as part of a company's submission. Before an exemption application is finally recommended for refusal, a Departmental committee (Exemption Committee) reviews the recommendation. The Geological Survey is represented on this committee to ensure that geoscientific issues are considered in any decision. The committee also considers whether a fine should be imposed in lieu of forfeiture where

Table 1. Tenement reviews

Geological advice provided	*Number of tenement actions*					
	1998–99	*1999–2000*	*2000–01*	*2001–02*	*2002–03*	*2003–04*
Expenditure exemption	580	1 287	1 569	1 962	2 362	2 406
Extension of term of Exploration Licences	48	82	394	411	369	323
Dealings in first-year Exploration Licences	27	7	75	42	43	30
Iron ore authorization (Exploration Licences)	9	22	16	32	30	90
Iron ore drop offs (Exploration Licences)	27	22	2	0	0	8
Retention Licence applications	3	3	6	6	5	5
Special Prospecting Licence applications	14	1	4	4	4	6
Total	**708**	**1 424**	**2 066**	**2 457**	**2 813**	**2 868**

an expenditure exemption has been refused. The number of exemption applications refused constituted about 13% of total applications in 2003–04. This figure of 13% includes lapsed applications where tenements have been surrendered before the intent to refuse could be carried through.

The number of granted exemptions seems high but most are for partial amounts. It should be noted that overall expenditure by industry (exploration and production) is currently close to fifteen times the expenditure commitment under the Act.

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Mineral exploration reports and data

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

Highlights for 2003–04

- Development and implementation of the core library database.
- Development of a link to the WAMEX database through GeoVIEW.WA.

Mineral exploration reports

During the year, 2081 mineral exploration reports (3594 volumes) were received, representing industry activity on 9208 tenements. The total number of volumes held is now 83 753. Gold is still the most commonly sought-after commodity, with over 75% of reports submitted relating to exploration programs for gold. Submission of data in digital form continues to increase, with some 71% of all reports submitted during the year containing some digital data.

Reporting standards

This year has been the eighth full year of required compliance with the 'Guidelines for mineral exploration reports on mining tenements' and the third year in which companies could submit data in digital format following the Department's requirements. The quality-control checking by Departmental staff found that the content of the hardcopy reporting has been improving with only 11% of reports not complying with the reporting guidelines. The submission of digital data is voluntary; however, about 71% of reports contain some digital data and about 66% of all reports

submitted are totally digital. About 17% of reports submitted in digital form required some amendments or additional
data.

The 'Requirements for the submission of mineral exploration data in digital format', which were developed in consultation with industry groups, have been adopted by the Government Geologists' Information Policy Advisory Committee (GGIPAC) as the basis of national reporting requirements for the mineral exploration industry.

WAMEX database development

During the development of processes and data management systems for the core library, it was recognized that a review of the management and delivery of mineral exploration data was needed. Significant progress has been made in developing a new database.

Data release

During the year 799 volumes were released to open file bringing the total number of open-file mineral reports to 32 422.

Future work

Redevelopment of the WAMEX database will continue. Scanning to PDF of mineral exploration reports for release to open file, particularly via the web-based WAMEX interface, will continue.

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REGIONAL GEOSCIENCE MAPPING

Regolith and resource mapping and geochemistry

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

Highlights and activities 2003–04

Existing datasets were collated over four 1:50 000-scale map sheets in the Kalgoorlie–Boulder area, as part of a regolith–landform project (Fig. 3). The datasets comprise high-resolution orthophotography, digital elevation data, geological maps, geophysical images, and point observations. The compilation is available on DVD with GSWA's *GeoVIEWER.WA* GIS viewing program.

A report on the Warakurna Large Igneous Province (LIP) was completed. Detailed geochemistry of sills intruding the Bangemall Supergroup shows that 1070 Ma sills of the Warakurna LIP can be separated in terms of composition from 1465 Ma sills in the western part of the succession. Trace element data show that some 1070 Ma sills are crustally contaminated, and have potential for magmatic-hosted Ni–Cu–PGE sulfide mineralization. An external paper was published on the extent and age of the Warakurna LIP, and the sill geochemistry can be viewed on GEOVIEW.WA.

Implementation of DataShed software as the database to house geochemical data was continued, including migration of the system to an Oracle platform, and ongoing importation of various geochemical datasets. Development of the related WAROX database for importation of company data has been successfully trialled. Additional company datasets (rock pulps and analytical data) were acquired.

A collaborative venture with CRC–LEME and CSIRO was commenced to compile a geochemical map of the Yilgarn Craton (the Yilgarn Geochemical Map (YGM) project), based on laterite chemistry of samples at a nominal spacing of 9 km. This project extends the CSIRO-AGE database from the southwest of the State. Approximately 500 samples have been collected from the southwest quadrant of the Yilgarn Craton (i.e. west of 120°E and south of 30°S).

Approximately 20 samples, including in-house reference materials, were analysed at a Canadian laboratory that offers analysis of platinum group element (PGE) and Au at low detection levels. The purpose of this project is to gradually compile low-level Au and PGE data for a variety of rock types in the State.

2003–04 publications and products

- GSWA Record 2004/12: *Regolith–landform resources of the Kalgoorlie–Kanowna Region*, 1:50 000 (DVD)
- external paper on the Warakurna LIP (Wingate et al., 2004; *in* Geology, v. 32, p. 105–108).

Future work

GSWA has embarked upon a collaborative study with CSIRO on the use of Hymap hyperspectral mapping in the Kalgoorlie area, which involves the use of remotely sensed data to identify mineralization-related alteration.

During 2004–05, GSWA will continue to populate the corporate geochemical database using the DataShed software. Interpretive regolith maps will be compiled for areas of future 1:100 000-scale mapping in the Musgrave area. Sample collection in the southwest quadrant for the YGM program will be completed, and multi-element analysis commenced.

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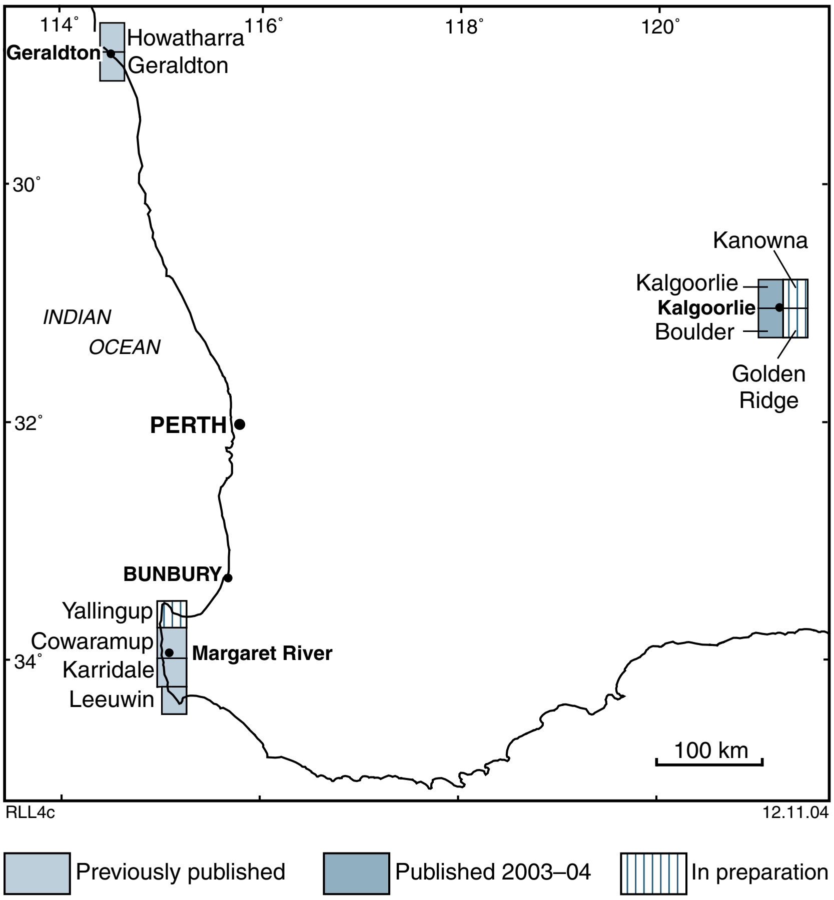
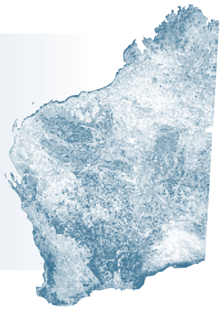


Figure 3. Progress of regolith–landform resources project

King Leopold and Halls Creek Orogens project



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

Highlights and activities 2003–04

During 2003–04 Explanatory Notes for the DIXON 1:100 000 map sheet were released. Writing continued for Bulletin 143 on the geology of the King Leopold and Halls Creek Orogens.

Future work

Bulletin 143 will be completed ready for release in the following year. Writing of Explanatory Notes for TURKEY CREEK and MCINTOSH will commence.

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Lennard Shelf project

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

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

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

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

Highlights and activities 2003–04

Compilation of Bulletin 145 on Devonian reef complexes of the Canning Basin has continued. The text of most chapters has been completed in draft form and the remaining sections are anticipated to be complete by the end of 2004.

An excursion to the Lennard Shelf in June–July 2004 was organized to introduce two PhD candidates from the University of Texas to projects in the area and obtain precise GPS coordinates on key localities to be described in the bulletin.

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Pilbara Craton project

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

All field mapping required for the new 1:100 000 and 1:250 000 Geological Series maps of the Pilbara granite–greenstone terranes was completed by October 2003. By 30 June 2004 all but five of the 31 new 1:100 000 maps within the project area had been released (Fig. 4). Commencing in 1995, this has been one of GSWA's largest mapping projects, and has been undertaken collaboratively with AGSO (now Geoscience Australia). By 2006 the project will have resulted in the detailed remapping of a 70 000 km^2 area, publication of 31 new 1:100 000-scale maps, new editions of seven 1:250 000-scale maps, and various non-series maps at 1:50 000 and 1:250 000 scales. An additional four 1:100 000-scale maps (ROCKLEA, ISABELLA, BRAESIDE, and PEARANA) and two 1:250 000-scale maps (MOUNT BRUCE and ROY HILL) were mapped as parts of earlier projects immediately prior to commencement of the Pilbara Craton project. Explanatory Notes describing all aspects of the geology of individual sheets accompany all published maps. GSWA Reports, papers in international journals, and contributions to a number of geological conferences have presented both regional syntheses and the results of specialized research.

Highlights and activities 2003–04

Geological mapping was completed on YILGALONG and MARBLE BAR, and on the PORT HEDLAND 1:250 000 map sheet. New mapping, and geochemical and geochronological data from the entire 1:100 000 mapping program were used to substantially revise the lithostratigraphy of the northern part of the Pilbara Craton, and for the first time to express the area's crustal evolution in terms of discrete thermotectonic events. The resulting event stratigraphy correlates intrusion of major suites and supersuites, and accompanying tectonism, with the deposition of volcanic and sedimentary formations, subgroups, groups, and supergroups within the supracrustal succession.

This new interpretation was first summarized at GSWA's Open Day in February 2004, and is described in more detail in the Technical Papers of this Annual Review.

Members of the Pilbara mapping team made major contributions to three international geoscientific drilling projects: the Archaean Biosphere Drilling Project (ABDP) in 2003, and the Deep Time Drilling Project (DTDP) and the Pilbara Drilling Project (PDP) in 2004. The ABDP is an international collaborative project between GSWA, NASA (through Pennsylvania State University), Kagoshima University (Japan), and the University of Western Australia. The DTDP is a collaborative project between all members of the ABDP and the University of Washington, Arizona State University, and the NASA Astrobiology Institute (NAI). The PDP is a collaborative project between GSWA and the Institute de Physique du Globe de Paris (IPGP). Half of all diamond drill core from the three projects, totalling about 3000 metres, is to be stored at the Perth Core Library, whereas the remaining core will be exported for advanced research overseas. The main objective of the drilling is to obtain samples of Archaean rock (mainly carbonaceous black shale, carbonate rock, and several varieties of chert) that remain unaltered and uncontaminated by the modern environment. These can be analyzed and otherwise investigated to increase our understanding of the early Earth, particularly its evolving biosphere, and the composition of its atmosphere between 3500 and 2700 Ma. The Pilbara Craton is widely regarded as providing Earth's best-preserved ancient rocks for such investigations.

2003–04 publications and products

- SPLIT ROCK 1:100 000 Explanatory Notes;
- HOOLEY 1:100 000 Explanatory Notes;
- CARLINDIE 1:00 000 Explanatory Notes;
- DE GREY – PARDOO 1:100 000 Explanatory Notes;
- WHITE SPRINGS 1:100 000 Explanatory Notes;
- COOYA POOYA 1:100 000 Explanatory Notes;
- DAMPIER – BARROW ISLAND 1:250 000 Explanatory Notes;

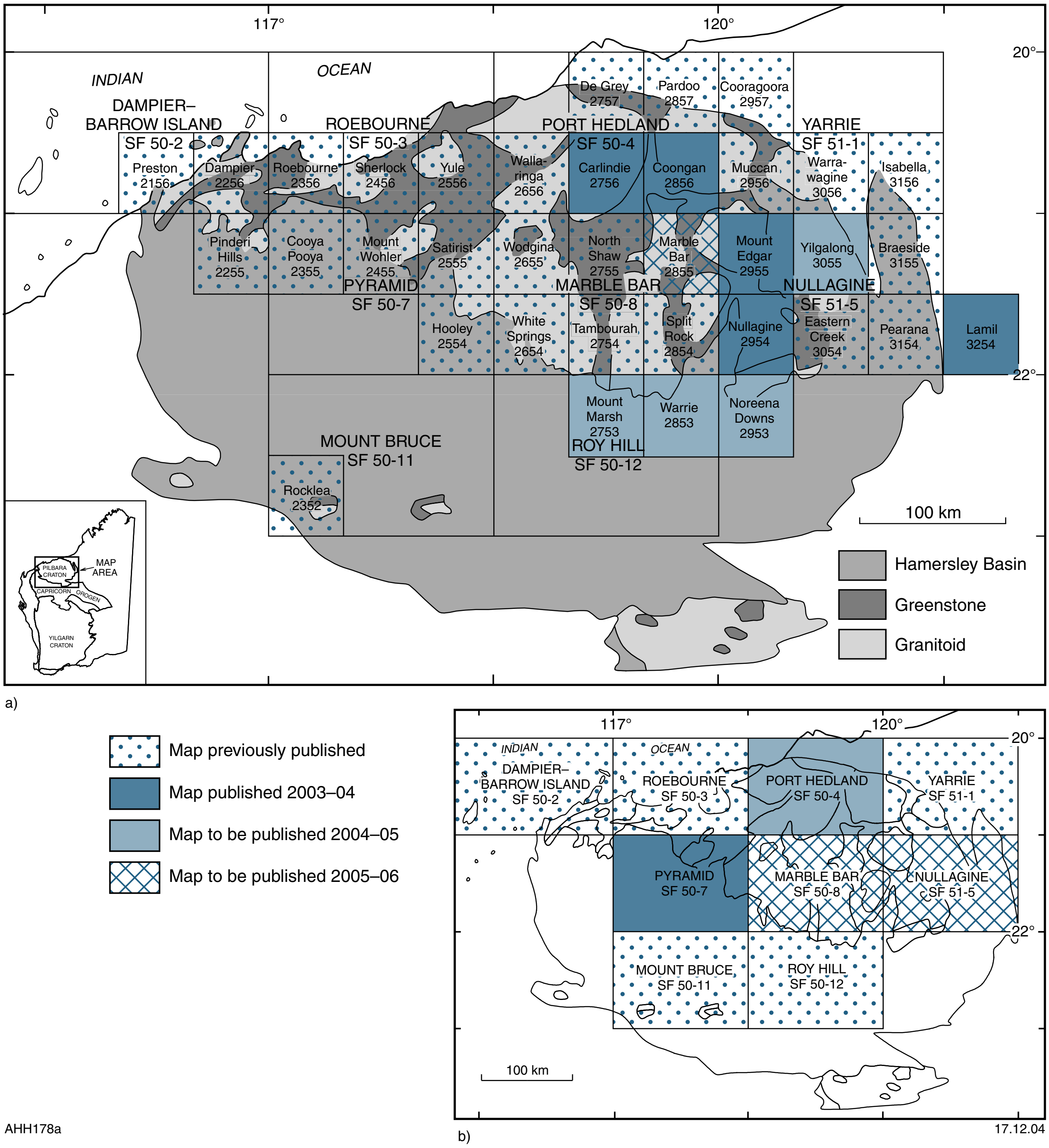

Figure 4. Progress of recent regional mapping in the Pilbara Craton: a) 1:100 000 sheet areas; b) 1:250 000 sheet areas

- YARRIE 1:250 000 Explanatory Notes;
- CARLINDIE 1:100 000 map sheet;
- MOUNT EDGAR 1:100 000 map sheet;
- NULLAGINE 1:100 000 map sheet;
- LAMIL 1:100 000 map sheet;
- PYRAMID 1:250 000 map sheet;
- Record 2004/15: *The Neoproterozoic Throssell Range and Lamil Groups, northwest Paterson Orogen, Western Australia — a field guide.*

Future work

The 2004–05 year will see the publication of several maps in the 1:100 000 Geological Series (YILGALONG, NOREENA DOWNS, WARRIE, and MOUNT MARSH) and the 1:250 000 Geological Series

(PORT HEDLAND), and project maps for NORTH SHAW – TAMBOURAH (1:50 000), West Pilbara Granite–Greenstone Terrane (1:250 000), and the Whim Creek greenstone belt (1:10 000). Explanatory Notes for EASTERN CREEK, PRESTON, WODGINA, MOUNT EDGAR, NULLAGINE, and LAMIL, as well as PYRAMID (1:250 000 Series) will be released. Compilation of several maps will be continued and their Explanatory Notes commenced.

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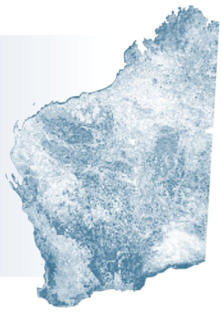
Earaheedy Basin project

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



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

The Earaheedy Basin contains the Earaheedy Group and lies at the easternmost end of the Capricorn Orogen. Basement to the exposed Earaheedy Basin is the Archaean Yilgarn Craton and, to the west, the Yerrida Basin. The regional structure is an asymmetric east-plunging syncline with a vertical to locally overturned northern limb, due to compressive movements from the northeast that created a zone of intense deformation along the exposed northern margin of the Earaheedy Basin. This zone of deformation — named the Stanley Fold Belt — is characterized by reverse faults and shear zones that consistently dip steeply to the north, the development of slaty cleavage and phyllitic rocks, and the presence of metamorphic minerals (e.g. muscovite, sericite, and chlorite). The intensity of deformation gradually decreases southward, but abruptly decreases to the north.

The Palaeoproterozoic Earaheedy Basin contains the Earaheedy Group, a 5 km-thick succession of shallow-marine clastic and chemical sedimentary rocks that is divided into two subgroups — the Tooloo Subgroup and the overlying Miningarra Subgroup. The age of the Earaheedy Group is stratigraphically constrained by the age of the underlying Mooloogool Group (Maraloou Formation, c. 1.84 Ga), and by the Malmac (2.6 Ga) and Imbin (1.99 Ga) Inliers. Given these age constraints on the Earaheedy Group, deposition of the group was essentially synchronous with the Capricorn Orogeny.

Highlights and activities 2003–04

During the year, mapping was completed on COLLURABBIE, CARNEGIE, WINDIDDA, and VON TREUER. This mapping encompassed tectonic units such as the Glenayle and Prenti Dolerites, which intrude c. 1200 Ma sedimentary rocks of the Collier Basin and correlative units, as well as the Earaheedy Group. This work led to the recognition that these mafic rocks belong to a much wider unit, in which coeval and compositionally similar rocks can be traced as far as the western parts of the Edmund Basin and the Musgrave Complex, along a strike length of more than 1000 km, thereby constituting a large igneous province (LIP). Recent dating by SHRIMP (U–Pb; baddelyite) indicates that the LIP was emplaced at c. 1070 Ma. This discovery may have important economic implications, and the LIP is still under investigation in cooperation with researchers from UWA and Curtin University.

Three papers were published in an international journal.

2003–04 publications and products

- Explanatory Notes for NABBERU – GRANITE PEAK and WONGAWOL;
- LEE STEERE 1:100 000 geological map.

Future work

Work planned for 2004–05 includes new compilations for VON TREUER

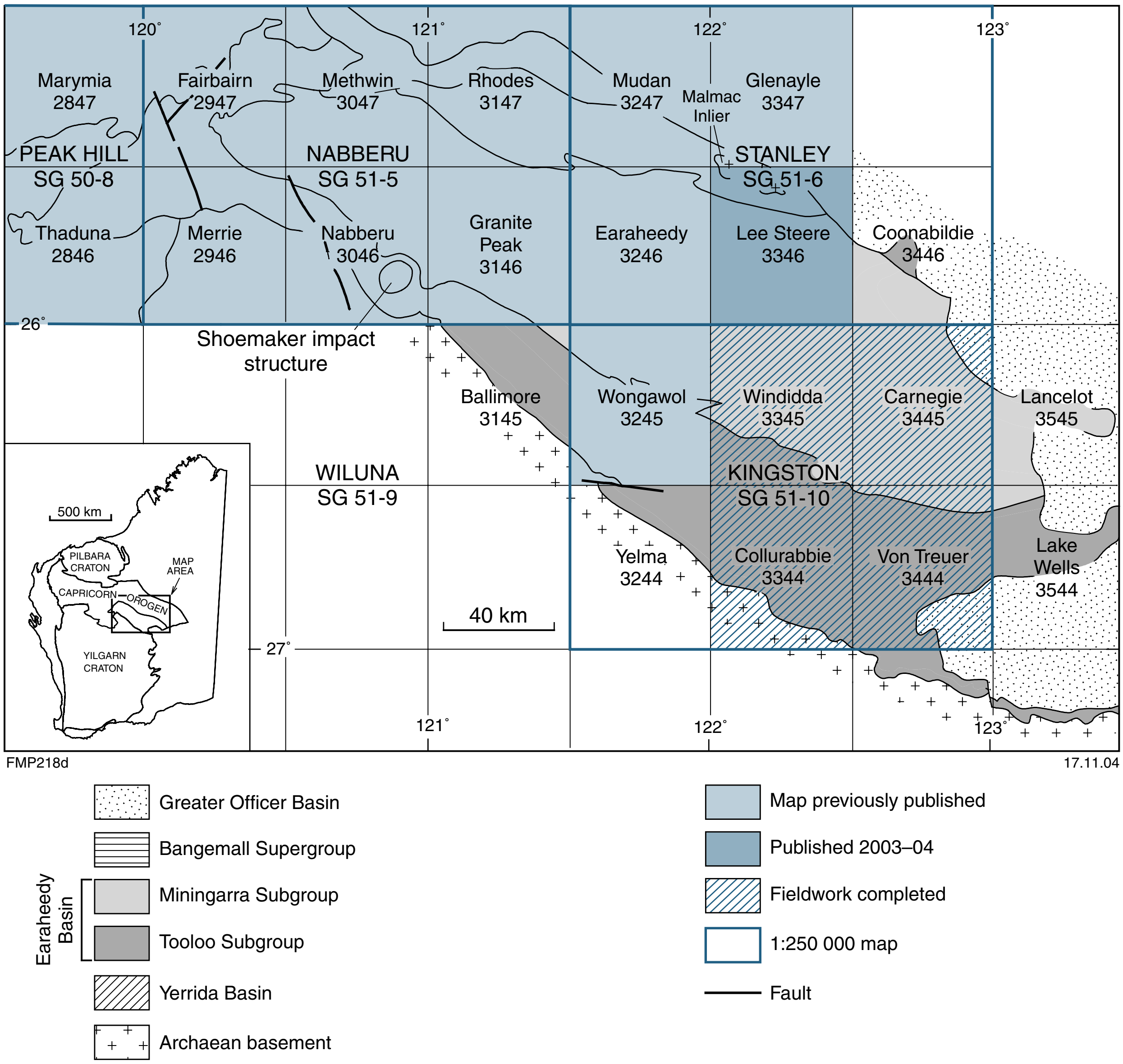


Figure 5. Progress of 1:100 000-scale geological mapping for the Earaheedy Basin project

and WINDIDDA. A final GSWA Report on the geology and mineralization of the Earaheedy Basin will be prepared.

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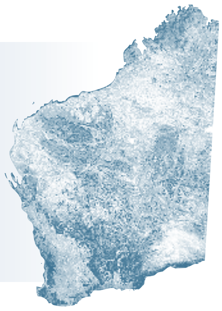
Capricorn Orogen

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



Highlights and activities 2003–04

Fieldwork carried out in the northwestern part of the Capricorn Orogen during 2003–04 has involved detailed mapping of the Bangemall Supergroup rocks on MOUNT AUGUSTUS and Gascoyne Complex rocks on EUDAMULLAH and MOUNT PHILLIPS (Fig. 6). In addition, there has been collaboration with university and Geoscience Australia staff engaged in detailed geoscientific studies within the Capricorn Orogen.

On MOUNT AUGUSTUS, the northwest-trending Lyons River Fault has had a significant influence on lower Edmund Group sedimentation and subsequent deformation. The basal unit of the Edmund Group, the Yilgatherra Formation is dominated by coarse-grained fluvial sandstone and conglomerate. North of the Lyons River Fault the succession is relatively thin and dominated by southwesterly flowing palaeocurrents. South of this structure, the Yilgatherra Formation is at least 1 km thick and is characterized by palaeocurrents that flowed to the southeast, parallel to the fault trace. During the Neoproterozoic Edmundian Orogeny strong transpressional movement along the fault was responsible for juxtaposing Edmund Group rocks to the south with Gascoyne Complex rocks of the Mangaroon zone to the north.

On EUDAMULLAH and MOUNT PHILLIPS, mapping concentrated on the Minnie Creek batholith.

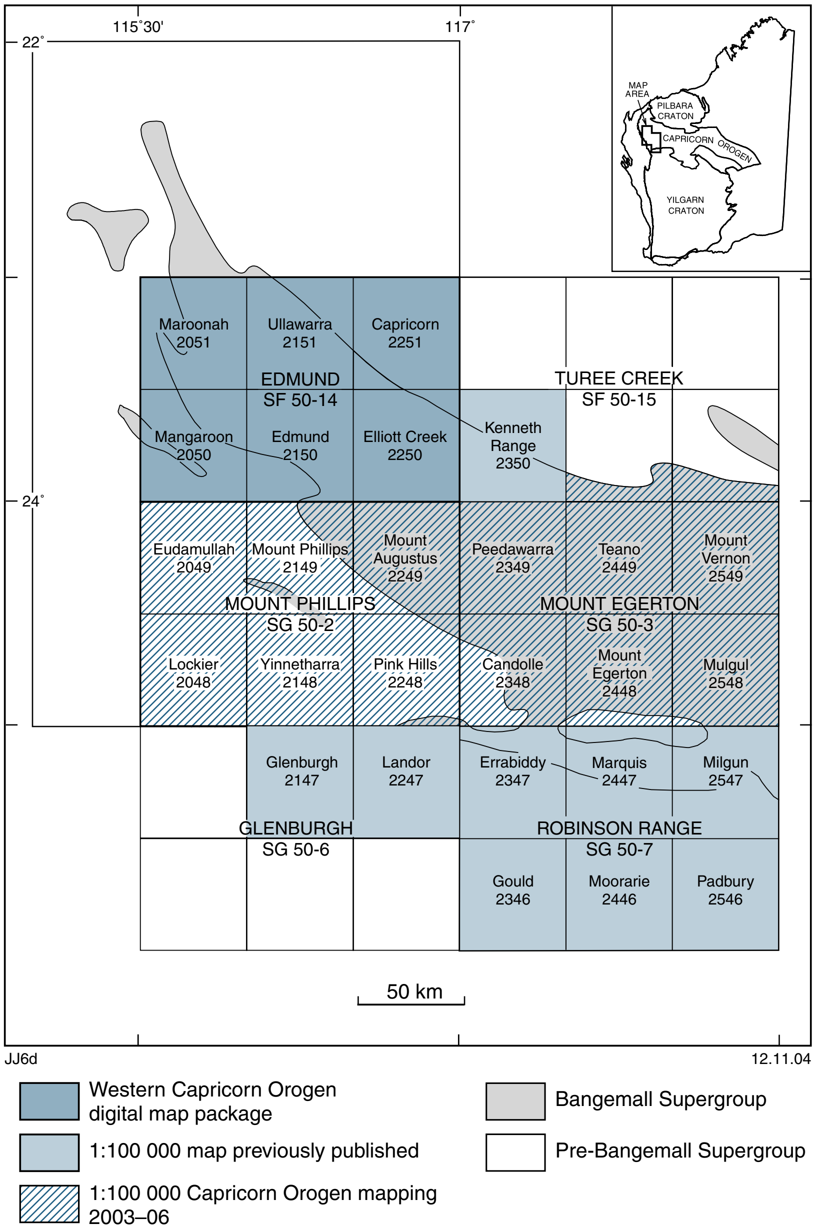


Figure 6. Progress of recent mapping for the Capricorn Orogen project

Initial SHRIMP U–Pb zircon results for these granites suggest that they crystallized at between 1795 and 1783 Ma. The batholith appears to be part of an episode of felsic magmatism (Moorarie Supersuite) that is recognized across the width of the Capricorn Orogen. In contrast with most parts of the supersuite, granites in the Minnie Creek batholith contain rafts of gabbroic rock and widespread small mafic inclusions. Preliminary Sm–Nd isotope data suggest a higher proportion of juvenile crust, or a mantle component, in the source of these granites, relative to the bulk of the Moorarie Supersuite.

A major focus of activity during 2003–04 has been the preparation of the Western Capricorn Orogen 1:100 000 Geological Information Series digital package. This has involved updating the six 1:100 000-scale map sheets covering the EDMUND 1:250 000 map sheet and presenting the data in a digital format that can be accessed either through the Survey's free *GeoVIEWER.WA* software, or through commercial GIS packages. Geological linework and structures have been updated to take into account the results of recent mapping of Gascoyne Complex rocks on MAROONAH and MANGAROON as well as minor revisions to the Bangemall Supergroup stratigraphy that have resulted from recent mapping on adjacent areas. In addition to the geological linework, the package also includes a wealth of well-located supporting data that includes geologists' field notes, field photographs, structural data, rock-sample information, petrographic descriptions, and a wide range of georeferenced remotely sensed imagery. Other data layers within the package include mineral exploration activity (from the EXACT database), mineral deposit and occurrence information (from WAMIN and MINEDEX databases), tenement details, and indexes of aeromagnetic data.

A GSWA-supported PhD study by S. A. Occhipinti at Curtin University of Technology examining the tectonothermal evolution of the southern Capricorn Orogen is nearing completion. A paper describing some of this work was published in a special issue of Precambrian Research on the Capricorn Orogen, and an abstract was published at the SGTSG Field Meeting in September 2003. During the year, analytical work for an MSc project by D. Shewfelt (nee Bray) at the University of Saskatchewan on the origin and possible economic significance of tourmaline nodules in c. 1800 Ma granites on GLENBURGH (1:250 000 sheet) was completed. Other collaborative work has involved Dr Keith Sircombe, of Geoscience Australia, who is carrying out a joint geochronological and provenance study of Edmund and Collier Group rocks with GSWA staff.

GSWA staff prepared several papers that were published in a special issue of Precambrian Research on the Capricorn Orogen.

2003–04 publications and products

- KENNETH RANGE 1:100 000 (preliminary) map sheet;
- Western Capricorn Orogen 1:100 000 Geological Information Series comprising data from MANGAROON and MAROONAH;
- MANGAROON, MAROONAH, ULLAWARRA, EDMUND, CAPRICORN, and ELLIOTT CREEK 1:100 000 map sheets;
- GSWA Record 2003/16: *Proterozoic geology of the Capricorn Orogen, Western Australia — a field guide*.

Future work

Work to be carried out during 2004–05 includes mapping and compilation of the Bangemall Supergroup on MOUNT AUGUSTUS and PEEDAWARRA; updating the Western Capricorn Orogen Geological Information Series to include explanatory notes for ULLAWARRA, EDMUND, CAPRICORN, and ELLIOTT CREEK, and geological linework and data for EUDAMULLAH, KENNETH RANGE, MOUNT AUGUSTUS, and MOUNT PHILLIPS. Explanatory Notes for the second edition ROBINSON RANGE 1:250 000 map sheet will also be published.

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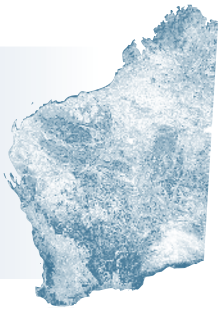
West Musgrave Complex project

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



Highlights and activities 2003–04

The 2003–04 period saw the first release of the West Musgrave Geological Exploration Package (GSWA Record 2004/9), which incorporates a range of new and pre-existing geoscientific datasets that cover the eastern part of the project area including FINLAYSON, HOLT, BATES, COOPER, BLACKSTONE, and BELL ROCK 1:100 000 sheet areas. A significant component of this package was a geological interpretation of the recently acquired aeromagnetic data.

An agreement was reached in late 2003 between GSWA and the traditional owners of the region (represented by the Ngaanyatjarra Council) for routine regional mapping of the West Musgrave region. Mapping of BATES is well advanced.

Work released during 2003–04

- Record 2004/9: *West Musgrave Geological Exploration Package — release 1: Jameson–Wingellina*;
- Record 2004/11: *West Musgrave Geological Exploration Package — release 2: digital elevation model data*;
- *Catalogue of geoscience products Musgrave Complex*.

Future work

The 2004–05 field season will see the completion of fieldwork on BATES and the commencement of work on BELL ROCK. BATES will be compiled and all legacy data (mainly from GSWA and GA) covering that area will be captured digitally and combined with our newly acquired data for release with BATES.

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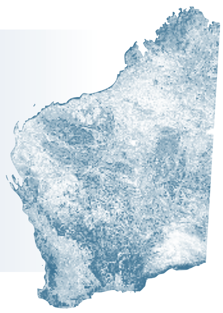
Central Yilgarn (Southern Cross) project

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



The central Yilgarn 1:100 000-scale field mapping program began in the Marda–Diemals area, the geographic centre of the Yilgarn Craton, in late 1997 and twelve 1:100 000 sheets have now been published (Fig. 7).

Highlights and activities 2003–04

In 2003–04, fieldwork on the SANDSTONE 1:100 000 sheet was completed; and fieldwork was undertaken on MONTAGU, YOUNO DOWNS, and YAGANOO.

Papers detailing the stratigraphic correlations in the Marda–Diemals area and results of geochronological

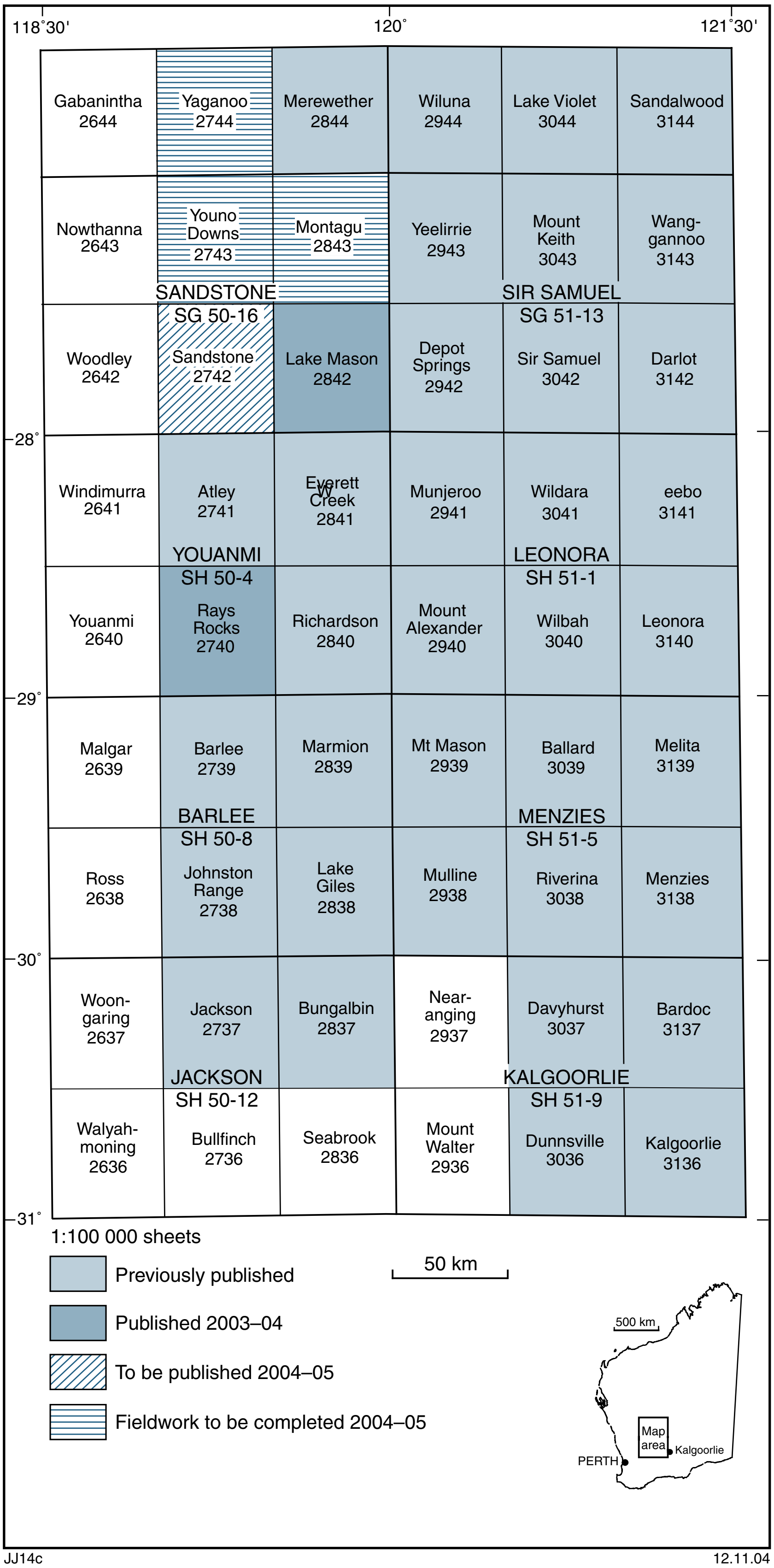


Figure 7. Progress of recent geological mapping for the Central Yilgarn (Southern Cross) project

studies of detrital zircons in quartzites in the central Yilgarn were published externally.

The greater part of the succession in the Sandstone and Gum Creek greenstone belts consists of rocks similar to those that make up the rest of the belts in the region. However, the new mapping in these greenstone belts has delineated the distribution of substantial volumes of siliciclastic metasedimentary rocks within the greenstone succession, possibly associated with felsic volcanic or intrusive rocks. The large extent of metasedimentary rock is unusual in greenstone belts in this region. However, these rocks are poorly exposed, with much of their distribution determined from mineral exploration drillholes. The poor exposure means that it has not yet been possible to determine from field relationships whether they are part of the main mafic-dominated succession, or whether they represent an unconformably overlying succession. However, they are different in character from the felsic and metasedimentary rocks of the Marda Complex and Diemals Formation that unconformably overlie the mafic-dominated succession in the Marda–Diemals greenstone belt to the south. Samples of the felsic rocks have been collected for U–Pb zircon SHRIMP geochronology.

Publications and products 2003–04

- MARMION and RICHARDSON 1:100 000 Explanatory Notes;
- MENZIES 1:250 000 Explanatory Notes;
- LAKE MASON 1:100 000 map sheet;
- RAYS ROCKS 1:100 000 map sheet.

Future work

SANDSTONE will be published in 2004–05; and fieldwork and compilation will be completed on MONTAGU, YOUNO DOWNS, and YAGANOO. The first edition of the Central Yilgarn 1:100 000 Geological Information Series, incorporating twelve 1:100 000-scale map sheets, will be released in 2004–05.

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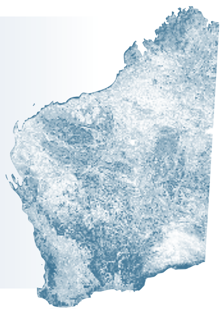
East Yilgarn project

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



The East Yilgarn project covers the highly mineralized Eastern Goldfields Granite–Greenstone Terrane and the southern part of the Southern Cross Granite–Greenstone Terrane that together make up the eastern part of the Archaean Yilgarn Craton (Fig. 8). The project is based in the Kalgoorlie regional office, which includes the Joe Lord Core Library.

Highlights and activities 2003–04

The complete revised and expanded seamless East Yilgarn dataset in the new digital 1:100 000 Geological Information Series was released. This has been refined through application of the new GSWA rock classification and coding scheme, and the inclusion of higher resolution aeromagnetic data and more recent Landsat images. The area covered now includes fifty-seven 1:100 000-scale geological map sheets as a single seamless coverage of most of the Eastern Goldfields. The themes included are 1:100 000 outcrop geology and structures, mineral location (from WAMIN database) and resource data (from MINEDEX database), abandoned minesite localities, regolith geochemistry, tenement and geographic information, Landsat images, aeromagnetic and gravity images, and 1:500 000 interpretative geology. The data are supplied in GIS software-compatible formats, together with *GeoVIEWER.WA*, a free software package developed by GSWA that allows powerful interactive visual access to the database.

Mapping and compilation of YARDINA and ERAYINIA was completed.

The Joe Lord Core Library that is part of the regional office facility in Kalgoorlie–Boulder has continued to assist the mining and exploration

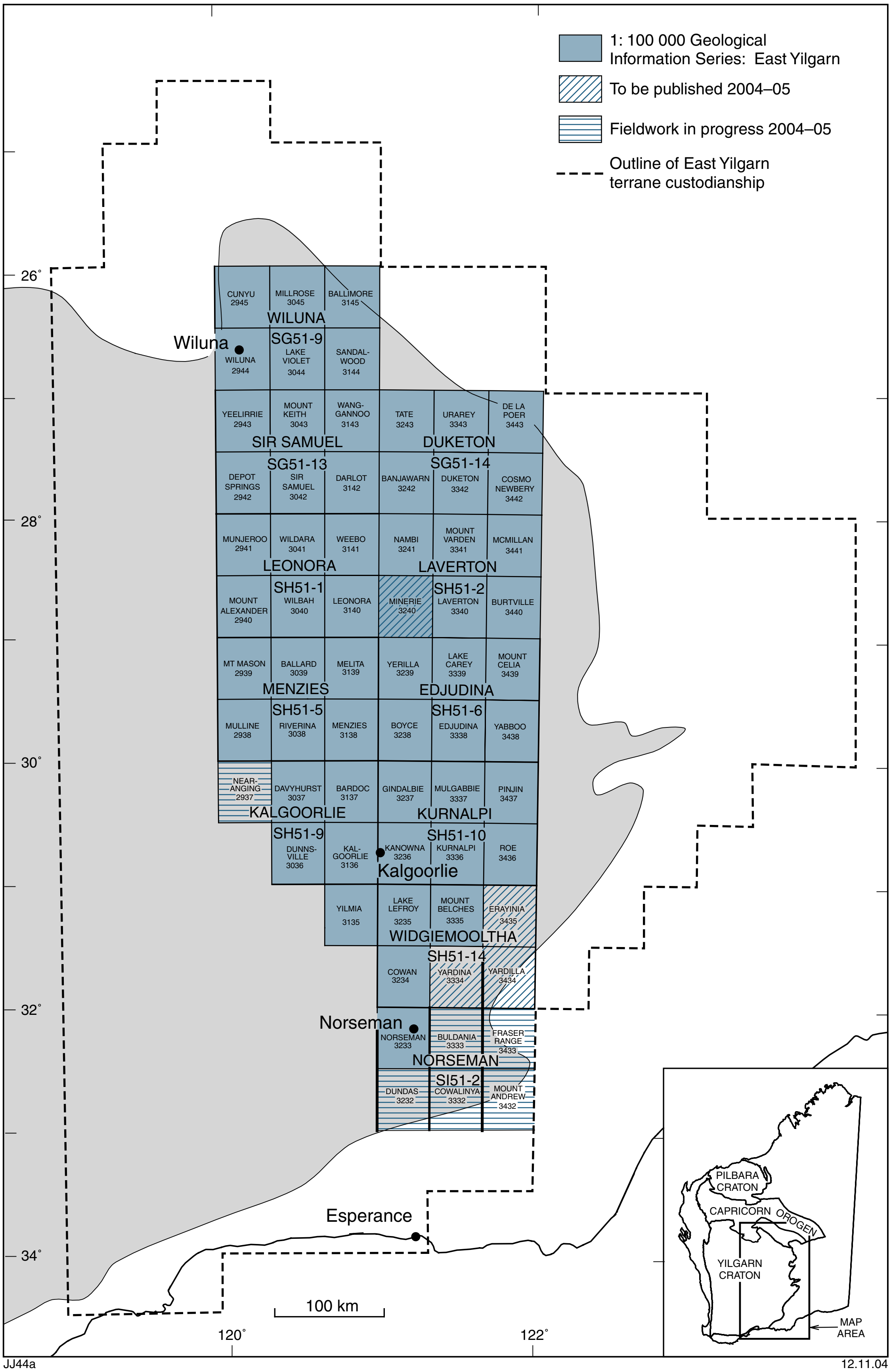


Figure 8. Progress of recent geological mapping in the east Yilgarn region and progress towards the GIS-based seamless digital database

industry through the acquisition, storage, and display of drillcore. Industry and university researchers have made use of the core, and detailed sampling for metallogenic studies has been undertaken. Measurements of specific gravity and magnetic susceptibility of drill core and rock samples from MINERIE have contributed the detailed petrophysics for gravity inversion modelling of the three-dimensional structure of the upper crust, in cooperation with Geoscience Australia for the pmd*CRC project.

The regional mapping geologists at the Kalgoorlie regional office of the Geological Survey provide advice to the general public, mining companies, and others on the geology of the East Yilgarn. In October 2003 the annual GSWA open day was held in Kalgoorlie. Particular focus was given to the corporate databases, with tutoring of applications in Tengraph, WAMEX, and WAMIN. As in previous years, recent activities of GSWA in the Yilgarn Craton were presented in posters, displays, and a series of talks.

Presentations were delivered at the GSA–SGTSG meeting in Kalbarri regarding Archaean and Proterozoic aspects of tectonic activity in the East Yilgarn, and at the GSWA 2004 open day on the use of the new East Yilgarn 1:100 000 Geological Information Series in exploration targeting, and about the application of new regolith interpretations to the Eastern Goldfields.

2003–04 publications and products

- Western Australia 1:100 000 Geological Information Series: *East Yilgarn dataset*;
- Record 2003/12: *Metamorphic petrography of the Kalgoorlie region, Eastern Goldfields Granite–Greenstone Terrane: METPET database*;
- Record 2004/13: *East Yilgarn geoscience database — updated rock codes*;
- Explanatory Notes for the LEONORA 1:250 000 geological sheet;
- GSWA Report 90: *Gold mineralization in the Edjudina–Kurnalpi–Kanowna area*.

Future work

YARDILLA, MINERIE, ERAYINIA, and YARDINA will be published in the new GeoVIEWER.WA digital format that includes field notes, photographs, petrography, and explanatory notes. Mapping and compilation of BULDANIA – FRASER RANGE, COWALINYA – MOUNT ANDREW, and DUNDAS will be completed. Field mapping will continue on NEARANGING.

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SCIENTIFIC, TECHNICAL AND FIELD SUPPORT

Geoscientific specialist support

Chief Geoscientist and Terrane Custodianships

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

Highlights and activities 2003–04

Activities were focused on revising and upgrading the database structures and standards for the State tectonic units, interpreted bedrock geology, and regolith datasets. The review and approval of all manuscripts and map products to ensure the quality of their content and the consistency of their presentation is a major ongoing task.

Working with geologists from the Regional Geoscience Mapping Branch, this team finalized and distributed a uniform rock classification scheme for GSWA. The classification scheme is applicable throughout the state, and is an essential requirement for the further development of fully integrated GSWA field and map databases. The rock classification scheme, and associated new map unit coding scheme, has been applied to the latest release of the East Yilgarn 1:100 000 Geological Information Series datasets and to the first release of the Western Capricorn Orogen 1:100 000 Geological Information Series datasets. It will be applied to all future GSWA products.

WAROX — GSWA's field observation database — is being redeveloped and will be consistent with the uniform rock classification and regolith classification schemes. A WAROX dataset is now provided with each 1:100 000 Geological Information Series product, as well as a GIS viewing-tool on CD or DVD. The structured nature of data entry for the redeveloped WAROX will allow field observations to be more accessible.

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

The Chief Geoscientist coordinated GSWA's significant contribution to the Kalbarri Field Meeting of the Specialist Group on Tectonics and Structural Geology (SGTSG) of the Geological Society of Australia, which involved assistance in organization, the presentation of talks, and leading field excursions. The Chief Geoscientist and Archaean Terrane Custodian coordinated GSWA's contribution to pmd*CRC projects in the east Yilgarn Craton.

Geoscience Australia invited GSWA to participate in a scientific cruise in February–March 2004 to map and sample canyons offshore from the southern coast of Western Australia. Our role was to provide onboard broad-based knowledge of Western Australian geology, as well as sedimentological expertise. The cruise involved broad-ranging surveys to investigate the petroleum potential of the basins along the southern margin of Australia, which have not been explored since the 1970s. Preliminary results are encouraging for maturity of the sedimentary section.

2003–04 publications

The Chief Geoscientist assisted Professor Peter Cawood, of the Tectonics Special Research Centre (TSRC) at the University of Western Australia, in editing a special issue of Precambrian Research on 'Assembling the Palaeoproterozoic Capricorn Orogen' (Issue 3–4, Volume 128, 2004). Eight papers within the volume present the results from GSWA remapping programs, and joint GSWA and TSRC research projects in the southern part of the orogen. To accompany the SGTSG field trip Record 2003/16 *Proterozoic geology of the Capricorn Orogen, Western Australia — a field guide* was published by GSWA. The Survey also published Record 2003/15 *Structure and tectonics of the Leeuwin Complex and Darling Fault Zone, southern Pinjarra Orogen, Western Australia — a field guide* to accompany the pre-SGTSG Kalbarri Field Meeting field trip.

Future work

The Chief Geoscientist and the Terrane Custodians will be involved in the testing and roll out of the redeveloped WAROX database for field use. They will also be involved in the ongoing assessment of computer hardware for field-data entry.

The various GSWA geological datasets will continue to be improved to ensure a genuine seamless coverage is achieved across the state. Future explanatory notes to accompany geological maps will be derived from a continually updated database structured around the tectonic unit and stratigraphic or lithological unit. The explanatory notes will be linked to the maps via a set of unique map unit codes. The database framework will provide the basis for a geological map reference that can be constructed on-demand for customer-defined areas.

Work will begin on revising the State 1:500 000 digital interpreted bedrock geology map using the new map unit coding scheme. The revised map will be used to derive a new 1:2 500 000-scale digital Tectonic Units of Western Australia map and, together with the State 1:500 000 digital regolith map, a new 1:2 500 000 digital Geological Map of Western Australia.

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Geochronology

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

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

Highlights and activities 2003–04

Seventy six samples from throughout Western Australia were dated, with typical precision of ± 6 Ma. Of these, 67 were dated by SHRIMP U–Pb analysis of zircon, two by SHRIMP U–Pb analysis of monazite, and seven by Ar–Ar analysis of amphibole. Samples were collected from the Pilbara, Southern Cross, Eastern Goldfields, and Gascoyne areas, and the Leeuwin Complex.

GSWA Record 2003/2 is a digital compilation on CD of geochronological data acquired from 1994 to 2001, incorporating data from both Geoscience Australia and GSWA. This product represents a significant change to the traditional hardcopy (book) provision of geochronological data. The digital data package is self-contained, in that it incorporates GeoVIEWER.WA software to view, access, and query the geochronology data. Other data layers include geology at 1:500 000 scale, and tectonic units. As well as providing an onscreen summary of age data, each sample is linked to associated metadata in pdf format, including locational, stratigraphic, petrographic, and analytical data, as well as cathodoluminescence imagery, where available. These digital data will be supplemented by new data as they become available; GSWA Record 2004/2 is a compilation of geochronological data acquired between 1994 and 2002. It is planned to eventually release all data via the web, rather than on solid media.

2003–04 publications and products

- Record 2003/2: *Compilation of geochronology data, Western Australia, 1994–2001.*
- The 2004 update CD *Compilation of geochronology data, Western Australia,* was prepared.

Future work

Geochronology work in the Pilbara, Southern Cross, Gascoyne, West Musgrave, Eastern Goldfields, Tanami, Paterson, and Bangemall regions is in progress for 2004–05.

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Biostratigraphy and palaeontological services

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

Highlights and activities 2003–04

In late 2004, the Biostratigraphy and Palaeontological Services section moved from Mineral House to the Department's Carlisle site. Fossil specimens are now housed under a single roof for the first time in 15 years. There is space for visiting scientists to examine specimens, for microscope work, and access to the nearby Core Library, which plays a key role in the work undertaken by the section.

Work continued on western Officer Basin biostratigraphic correlations (part of the Petroleum Systems Studies program). Preliminary palynomorph and stromatolite studies of Lancer 1 indicate that precise correlations with Empress 1 and 1A will be possible once detailed analysis is completed. Initial results confirm correlations with the Amadeus Basin and Adelaide Rift Complex successions. A revision of western Officer Basin stratigraphy will be released as a GSWA report.

Palaeontological and biostratigraphic studies undertaken during the last fifteen years have contributed towards the documentation of the Australian Neoproterozoic succession. The work culminated this year in the ratification by the International Union of Geosciences (IUG) of a global stratotype and section (GSSP) for the latest Neoproterozoic, and in a new geological System and Period, the Ediacaran, based on outcrops in the Flinders Ranges, South Australia. A large monograph, detailing the taxonomy of about 50 Ediacaran acritarch species, discovered during these studies, is now at the final editing stage. A paper about the Acraman impact ejecta horizon was published and other papers on aspects of Neoproterozoic correlation are in preparation.

Interest in the 3.5 Ga (early Archaean) stromatolites in the Pilbara or living stromatolites at Shark Bay and Lake Clifton remains high, and several groups are taking advantage of the GSWA stromatolite collection and the palaeontologist's expertise to advance their studies. The work of developing and documenting recognition criteria for Archaean and other stromatolites continues. Assistance was provided to the Archaean Biosphere Drilling Project. The vulnerability of the Pilbara sites to over-collecting remains a concern, and some key sites are in the process of being declared Ministerial Reserves to allow monitoring. A site suitable for general access has been identified and could be developed as a tourist site to enable visitors from a range of backgrounds to examine the fossil evidence for Archaean life.

A review of stromatolites in the Bangemall Supergroup has begun and a manuscript on the c. 1050 Ma 'string of beads' fossils is nearing completion. GSWA palaeontological studies maintained their usual high profile through several lectures and talks, including a keynote address at the Australian Geological Convention in Hobart. Continuing study of Ediacaran acritarchs supports the earlier interpretation that a major biotic change is associated with a large bolide impact that hit Australia about 580 Ma ago.

2003–04 publications

One external paper was published on new records of the Acraman impact ejecta layer.

Future work

Work on the palaeontological collection and its database continues, with storage documentation a high priority. Palynological and stromatolite biostratigraphy results from Lancer 1 will be published as a GSWA Record, and the broader implications of the biostratigraphy will be presented as an external publication.

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Geophysics

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

Regional airborne geophysics

GSWA and GA contracted Fugro Airborne Surveys to acquire approximately 29 500 line km of new magnetic and radiometric data in the Murchison area as part of a new National Geoscience Agreement project. The new data were merged with previously flown private-company data and existing GSWA–GA data to provide complete coverage of the Robinson Range and Belele 1:250 000 sheet areas at survey line spacings from 200 to 400 m. The located and gridded data were made available for public access, together with hardcopy magnetic and radiometric images.

GA contracted Fugro Airborne Surveys and UTS Geophysics to extend 400-m coverage over Cue, Kirkalocka, and Ninghan.

Airborne geophysical survey register and data repository

During 2003–04, 53 new airborne survey datasets, containing approximately 200 000 line km of magnetic, radiometric, digital elevation, and electromagnetic data, were received for inclusion in the MAGIX data repository. At the end of the year, about 3.1 million line km of private data from 622 surveys were held in the repository.

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

2003–04 publications and products

- Robinson Range – Belele regional airborne geophysical survey digital dataset and images.

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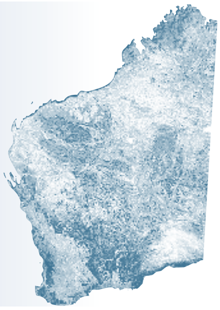
Logistics support and core libraries

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



Perth and Kalgoorlie core libraries

The new core storage facility in Perth has now been commissioned and is fully operational to service the petroleum and mineral exploration industries. This facility at Carlisle, with an 8 640-pallet capacity (equivalent to about 1200 km of core), holds mineral and petroleum core and cuttings, geochemical samples including rock pulps, and GSWA rock collections.

A program to collect valuable historical core is ongoing. Core has been collected from significant mineral deposits from many regions of the state and is available for inspection at Carlisle.

The Kalgoorlie J. H. (Joe) Lord Core Library, with a capacity to warehouse 2880 pallets (equivalent to about 400 km of core), has maintained a mineral core archiving and client viewing service for the exploration industry in the Eastern Goldfields. Kalgoorlie contains core from mineral deposits in the eastern Yilgarn region.

During the year there was a significant increase in client activity of viewing and sampling core and cuttings at both core libraries. This can partly be attributed to the new state of the art core-viewing facility and associated equipment for use by clients, including the digital-imaging unit. A total of 456 clients viewed and/or sampled core or cuttings at the Perth and Kalgoorlie facilities. Clients spent 1818 hours viewing core and cuttings and took 1684 samples for further analysis. Some 20 141 m of core, 1412 boxes of cuttings, and 1620 sidewall cores were accessioned into the collection. A large number of geochemistry samples from company collections were also archived.

Field support

The specialized 4WD fleet has been used most efficiently — measured by all requests being satisfied and a minimum of vehicles remaining at base in the high-season of field activity. The rapid turn-around time for vehicle preparation has continued to service the field program without delay. Three fifths (15 vehicles) of the fleet was disposed of, and replaced with customized 4WD utilities specific to Geological Survey requirements. Refurbishment costs and customization of new vehicles made a significant impact on the vehicle budget. A revised plan has been put in place to provide for regular annual disposal and replacement, taking into account the off-season. This will make further savings and also distribute costs on an annual basis to simplify budgeting.

Base-level field staff requirements have been maintained, and the provision of additional field assistants by an employment agency continues to allow flexibility in meeting short-term needs. An agency employee was contracted for a three-month period in Kalgoorlie to assist the East Yilgarn mapping program.

Continuous improvement of work practices and training remain a high priority for field safety, with the high-frequency radio communications base at the Carlisle depot and a Safety Officer on weekend roster the focus for monitoring safe operations in the field. Modification of field utilities (designed in-house) has improved load capacity, braking, and further lowered the centre of gravity to reduce the chance of rollover. Thirty-two persons were trained in the 4WD Familiarization and Safety Training Course run at Carlisle. There were no significant safety issues during the year.

The publications inventory was transferred to a purpose-built archive-storage facility. The planning and organization was very successfully undertaken in-house by the Publications Officer. His initiative provided an outcome of significantly increased efficiency in the annual stocktake and in the daily issue and receipt of publication material.

Future work

A new continuous core-logging system (Hylogger) developed by CSIRO will operate from the Kalgoorlie Core Library in August and September 2004. A total of 18 000 m of core will be measured during the project, which is funded by Placer Dome, Goldfields Australia, and GSWA. This new technology streamlines the process of examining core and swiftly provides information about potential mineralization.

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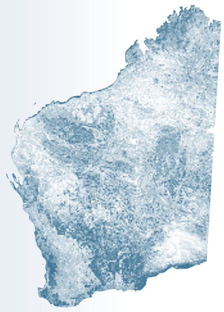
Geoscience information products

Objectives:

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



2003–04 publications and products

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

Geological and geophysical maps

Forty maps and images at various scale were published (see Appendix: Planned achievements and publications released, p. 137), including:

- fourteen 1:100 000 geological series maps
- one 1:250 000 geological series map
- three project maps at various scales
- six geophysical images at various scales
- sixteen miscellaneous plates.

Geoscientific digital data packages

Twenty-four geoscientific digital data packages were released in 2003–04 (Appendix, p. 137), including:

- two 1:100 000 Geological Information Packages (new product)
- two Geological Exploration Package DVDs for the Musgrave region (new product)
- one annual update for the Pilbara iron ore resources package
- one mineral occurrences and exploration potential data package
- update of one mineral occurrences and exploration potential data package
- two well completion report data packages
- two acreage release data packages
- one explorers' guide promotional CD
- one catalogue of publications CD for the Musgrave area
- one geochronology package, including spatial data in *GeoVIEWER.WA*
- one airborne geophysical data package
- nine miscellaneous data packages.

Geoscientific reports

Forty-three manuscripts were edited, illustrated, and published (Appendix, p. 137), including:

- fifteen Explanatory Notes for series maps
- nineteen Records and Reports
- one Mineral Resources Bulletin
- eight miscellaneous publications including the GSWA Annual Review 2002–03

Other activities

Promotional activities

Publication of Fieldnotes (the GSWA quarterly newsletter) continued during 2003–04 and provided a medium for informing our customers about our activities, and promoting newly released maps, publications, and datasets. During the year, advertisements and short articles publicizing the release of GSWA published products were placed in a number of newspapers, industry magazines, and journals. Media releases describing GSWA products, services, and new publications were prepared and issued during the year, in cooperation with the Corporate Communications Branch of DoIR.

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

- annual conference of the Prospectors and Developers Association of Canada (Toronto)
- Offshore Europe (Aberdeen)
- American Association of Petroleum Geologists (Dallas)
- Diggers and Dealers (Kalgoorlie)
- Mining 2003 (Brisbane)
- Australian Petroleum Production and Exploration Association (Canberra)
- Australian Society of Exploration Geophysicists (Adelaide)
- RIU Explorers Conference (Perth)
- New Generation Gold Conference (Perth)
- North American Prospectors' Expo (Houston)
- Good Oil Conference (Perth)

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

- Petroleum Open Day — showcasing recent work by the Department and issues of interest to petroleum explorers (Perth, October)
- Open day and display of recent work in the Eastern Goldfields (Kalgoorlie, October)
- GSWA 2004 (Perth, February)
- Company visits — a number of companies in Perth and Kalgoorlie were visited to promote our latest products and services and to provide an opportunity for feedback.

GSWA 2004 was held a month earlier than usual to hook up with the RIU Explorers Conference conducted at the same venue in Fremantle. The idea of holding the event immediately before a mining conference proved very successful.

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Appendices

Planned achievements and publications released

Major planned achievements for 2003–04

GSWA again proposed an ambitious project-based program of work for 2003–04 that was designed with a major component of promoting Western Australia's exploration potential. The planned achievements for 2003–04 included the release of 32 geoscientific maps at various scales; publication of 52 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers; publication of 22 digital geoscience datasets; and continued and enhanced provision of geoscientific data and exploration information to industry and the public through our library services and the mineral (WAMEX) and petroleum (WAPIMS) exploration databases. During 2003–04, changing priorities resulted in the completion of a slightly different mix of published output for the year than was originally planned.

In 2003–04 GSWA published:

- 40 geological maps, including fourteen 1:100 000 Geological Series Maps
- 43 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers
- 24 digital datasets.

This product mix is similar to that in recent years, reflecting the Survey's continued emphasis on providing a large volume of geoscience data in digital form. In overall terms, GSWA publication milestones for 2003–04 were met. The total combined number of published products released was 107, which exceeded our stated target by one, and represents a continuation in our level of productivity (excluding corporate overheads) compared to 2002–03.

Provision of open-file exploration company reports to industry via the WAMEX and WAPIMS database systems continued through the year. Work continued on enhancements to both systems, which allow the delivery of digital reports and data to customers via the worldwide web.

Maps, books, and datasets released in 2003–04

Geological Series maps

1:100 000 Geological Series

KENNETH RANGE by A. M. Thorne and D. McB. Martin
MAROONAH by D. McB. Martin, S. Sheppard, A. M. Thorne, and I. A. Copp
MANGAROON by S. Sheppard, D. McB. Martin, and A. M. Thorne
ELLIOTT CREEK by D. McB. Martin, A. M. Thorne, and I. A. Copp
CAPRICORN by A. M. Thorne, D. McB. Martin, and I. A. Copp
RAYS ROCKS by S. F. Chen

LAKE MASON by S. Wyche
MOUNT EDGAR by I. R. Williams
CARLINDIE by M. J. Van Kranendonk
LAMIL by L. Bagas
NULLAGINE by L. Bagas
EDMUND (version 2.0) by D. McB. Martin, A. M. Thorne, and S. A. Occhipinti
ULLAWARRA by I. A. Copp, A. M. Thorne, D. McB. Martin, and L. Bagas
LEE STEERE by R. M. Hocking

1:100 000 Geological Information Series (new series)

East Yilgarn
Western Capricorn Orogen

1:250 000 Geological Series

PYRAMID (second edition) by R. H. Smithies and A. H. Hickman

1:500 000 maps

Pilbara iron ore deposits, June 2004
Mineralization and geology of the west Kimberley, by L. Y. Hassan (Report 88)

Resource potential for land use planning (new series)

Cape Range – Ningaloo area — Resource potential for land use planning
Scale 1:500 000; compiled by M. J. Freeman

Cape Range region — Resource potential for land use planning
Scale 1:100 000; compiled by M. J. Freeman

Dampier Archipelago — Resource potential for land use planning
Scale 1:100 000; compiled by C. J. Kojan

Gingin area — Resource potential for land use planning
Scale 1:200 000; compiled by G. Trench

Lake MacLeod area — Resource potential for land use planning
Scale 1:500 000; compiled by F. I. Roberts

Ravensthorpe district — Resource potential for land use planning
Scale 1:15 000; compiled by L. Y. Hassan

Toodyay area — Resource potential for land use planning
Scale 1:200 000; compiled by M. J. Freeman

Geological maps at other scales

Canning Basin prospects and leads, by C. D'Ercole, L. Gibbons, and K. A. R. Ghori (3 plates; Record 2003/14)

Major resource projects map, 2003

Western Australia mines — operating and under development, April 2004

Ordovician Goldwyer and Nita Formations, by P. W. Haines (4 stratigraphic correlations; Record 2004/7)

Tantalum occurrences in Western Australia, by J. M. Fetherston (MRB 22)

Geophysical images

Belele Total Magnetic Intensity image (1:250 000)
Belele Ternary Radiometric image (1:250 000)
Robinson Range Total Magnetic Intensity image (1:250 000)
Robinson Range Ternary Radiometric image (1:250 000)
Isostatic residual gravity anomaly, Western Australia (1:2 500 000; Record 2004/14))
Decompensative gravity anomaly, Western Australia (1:2 500 000; Record 2004/14)

Mineral Resources Bulletin

22. Tantalum in Western Australia, by J. M. Fetherston

Reports

86. **A summary of the geological evolution and petroleum potential of the Southern Carnarvon Basin, Western Australia — May 2004 update,** by A. J. Mory, R. P. Iasky, and K. A. R. Ghori
88. **Mineral occurrences and exploration potential of the west Kimberley,** by L. Y. Hassan
89. **Geophysical investigation of the Bernier Ridge and surrounding area, Southern Carnarvon Basin, Western Australia,** by A. M. Lockwood and C. D'Ercole
90. **Gold mineralization in the Edjudina–Kanowna region, Eastern Goldfields, Western Australia,** by I. Roberts, W. K. Witt, and J. Westaway
91. **Hydrocarbon migration and entrapment in potential Lower Cambrian reservoirs, Vines 1, Officer Basin, Western Australia,** by P. J. Hamilton, P. J. Cope, and M. Lisk
94. **Western Australian mineral exploration and development in 2001 and 2002,** by D. J. Flint and S. M. Searston

Records

2003/1 **Geological Survey work program for 2003–04 and beyond**

2003/2 **Compilation of geochronology data, 1994–2001**

2003/12 **Metamorphic petrography of the Kalgoorlie region, Eastern Goldfields Granite–Greenstone Terrane: METPET database,** by E. J. Mikucki and F. I. Roberts

2003/14 **Prospects and leads, central Canning Basin, Western Australia, 2003,** by C. D'Ercole, L. Gibbons, and K. A. R. Ghori

2003/15 **Structure and tectonics of the Leeuwin Complex and Darling Fault Zone, Southern Pinjarra Orogen, Western Australia — a field guide,** by D. P. Janssen, A. S. Collins, and I. C. W. Fitzsimons

2003/16 **Proterozoic geology of the Capricorn Orogen, Western Australia — a field guide,** by S. A. Occhipinti, S. Sheppard, I. M. Tyler, K. Sircombe, S. Reddy, D. Hollingsworth, D. McB. Martin, and A. M. Thorne

2004/3 **Mineral occurrences and exploration activities in the central and south Canning area,** by E. P. W. Peiris

2004/4 **GSWA Boologooro 1 well completion report (interpretive), Gascoyne Platform, Southern Carnarvon Basin, Western Australia,** by D. W. Haig, A. J. Mory, M. Dixon, J. Backhouse, R. J. Campbell, K. A. R. Ghori, R. Howe, and P. A. Morris

2004/5 **GSWA 2004 extended abstracts: promoting the prospectivity of Western Australia**

2004/7 **Depositional facies and regional correlations of the Ordovician Goldwyer and Nita Formations, Canning Basin, Western Australia, with implications for petroleum exploration,** by P. W. Haines

2004/8 **Gravity and magnetic interpretation of the Southern Perth Basin,** by R. P. Iasky and A. M. Lockwood

2004/9 **West Musgrave geological exploration package — release 1: Jameson–Wingellina**

2004/10 **GSWA Lancer 1 well completion report (basic data), Officer and Gunbarrel Basins, Western Australia,** by P. W. Haines, A. J. Mory, M. K. Stevens, and K. A. R. Ghori

2004/11 **West Musgrave geological exploration package — release 2: DEM data**

2004/12 **Regolith–landform resources of the Kalgoorlie–Kanowna region, 1:50 000**

2004/13 **East Yilgarn Geoscience Database — updated rock codes,** by A. Riganti and P. B. Groenewald

2004/14 **Western Australia: isostatic residual gravity anomaly and depth to basement model,** by A. M. Lockwood

2004/15 **The Neoproterozoic Throssell Range and Lamil Groups, northwest Paterson Orogen, Western Australia — a field guide,** by L. Bagas

Explanatory Notes

1:100 000 Geological Series

Geology of the White Springs 1:100 000 sheet, by R. H. Smithies
Geology of the Dixon 1:100 000 sheet, by I. M. Tyler
Geology of the Nabberu and Granite Peak 1:100 000 sheets, by F. Pirajno, J. A. Jones, and R. M. Hocking
Geology of the Cooya Pooya 1:100 000 sheet, by A. H. Hickman
Geology of the Marmion and Richardson 1:100 000 sheets, by S. F. Chen
Geology of the Everett Creek 1:100 000 sheet, by A. Riganti
Geology of the Wongawol 1:100 000 sheet, by J. A. Jones
Geology of the Carlindie 1:100 000 sheet, by M. J. Van Kranendonk
Geology of the Split Rock 1:100 000 sheet, by L. Bagas and M. J. Van Kranendonk
Geology of the Hooley 1:100 000 sheet, by R. H. Smithies
Geology of the De Grey and Pardoo 1:100 000 sheets, by R. H. Smithies

1:250 000 Geological Series

LEONORA 1:250 000 sheet, Western Australia, by A. J. Stewart
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GSWA Annual Review 2002–03
Overview of mineral exploration in Western Australia for 2002–03, by D. J. Flint
Fieldnotes v. 28
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Fieldnotes v. 30
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Catalogue of geoscience products 1980–2004 (February 2004)

Digital products

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Iron ore deposits of the Pilbara region, June 2004 — 1:500 000 digital data package

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Mineral occurrences and exploration potential of the west Kimberley (Report 88)

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GSWA Boologooro 1 well completion report (interpretive), Gascoyne Platform, Southern Carnarvon Basin, Western Australia: (Record 2004/4)

Compilation of geochronology data, 1994–2001 (new digital product)

Southern Carnarvon Basin geological evolution and petroleum potential, May 2004 update

Metamorphic petrography of the Kalgoorlie region, Eastern Goldfields Granite–Greenstone Terrane: METPET database (Record 2003/12)

1:100 000 Geological Information Series: East Yilgarn (new series)

1:100 000 Geological Information Series: Western Capricorn Orogen (new series)

Murchison airborne data

Isostatic residual gravity anomaly dataset (Record 2004/14)

Mineral and petroleum explorers' guide — CD

'From exploration to rehabilitation: the life of a gold mine' CD

Western Australian Petroleum Acreage Release, March 2004

Inventory of abandoned mine sites: progress 1999–2003 (update)

Mineral occurrences and exploration activities in the central and south Canning area (Record 2004/3)

Regolith–landform resources of the Kalgoorlie–Kanowna region (Record 2004/12)

Major planned achievements for 2004–05

GSWA will continue to pursue a project-based program of work and maintain a vigorous level of output to match funding received. In 2004–05, GSWA's budget will include the first component of $12 million funding over four years from the State Government to double the area of the State covered by high-tech aerial geophysical surveys. The Survey aims to address the decline in WA's market share of world exploration expenditure through collection of this data. The priority areas for the surveys are the Murchison–Gascoyne region and the eastern wheat belt (highly prospective for nickel and gold); the Esperance to Warburton area (potential base metal and nickel deposits); the Musgrave–Arunta region (base metals, nickel and gold); and the Kimberley (nickel, base metals, and diamonds). Expenditure planned for 2004–05 is $3 million.

Planned achievements for 2004–05 include:

- release of 49 geological maps at various scales;
- publication of 45 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of 26 digital data packages.

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

GSWA has also secured a three-year $1.2 million commitment from the State Government to release more than 20 000 geological confidential reports submitted by mineral exploration companies over many years. Expenditure planned for 2004–05 is $400 000, sufficient to release up to 7000 reports.

External publications published by GSWA staff in 2003–04

The following GSWA staff published papers in external journals during the year, and gave talks and seminars at a variety of venues.
Note: GSWA authors are in italics

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List of acronyms and abbreviations

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

SGTSG	Specialist Group on Tectonics and Structural Geology of Geological Society of Australia
SHRIMP	Sensitive high-resolution ion microprobe
TENGRAPH†	DoIR's electronic tenement-graphics system
UWA	University of Western Australia
WACHEM	Western Australian inorganic geochemistry database
WACHRON	Western Australian geochronology database
WAMEX†	Western Australian mineral exploration database
WAMIN	Western Australian mineral occurrence database
WAMPRI	Western Australian Minerals and Petroleum Research Institute, now MERIWA
WAPEX†	Western Australian petroleum exploration database
WAPIMS	Western Australian petroleum information management system database
WAREG	Western Australian regolith observation database
WAROX	Western Australian field observation database
WASM	Western Australian School of Mines

NOTE: † GeoVIEW.WA, WAMEX, WAPEX, and TENGRAPH are registered Trade Marks of DoIR

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