

**ANNUAL
REVIEW**



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 1993-94

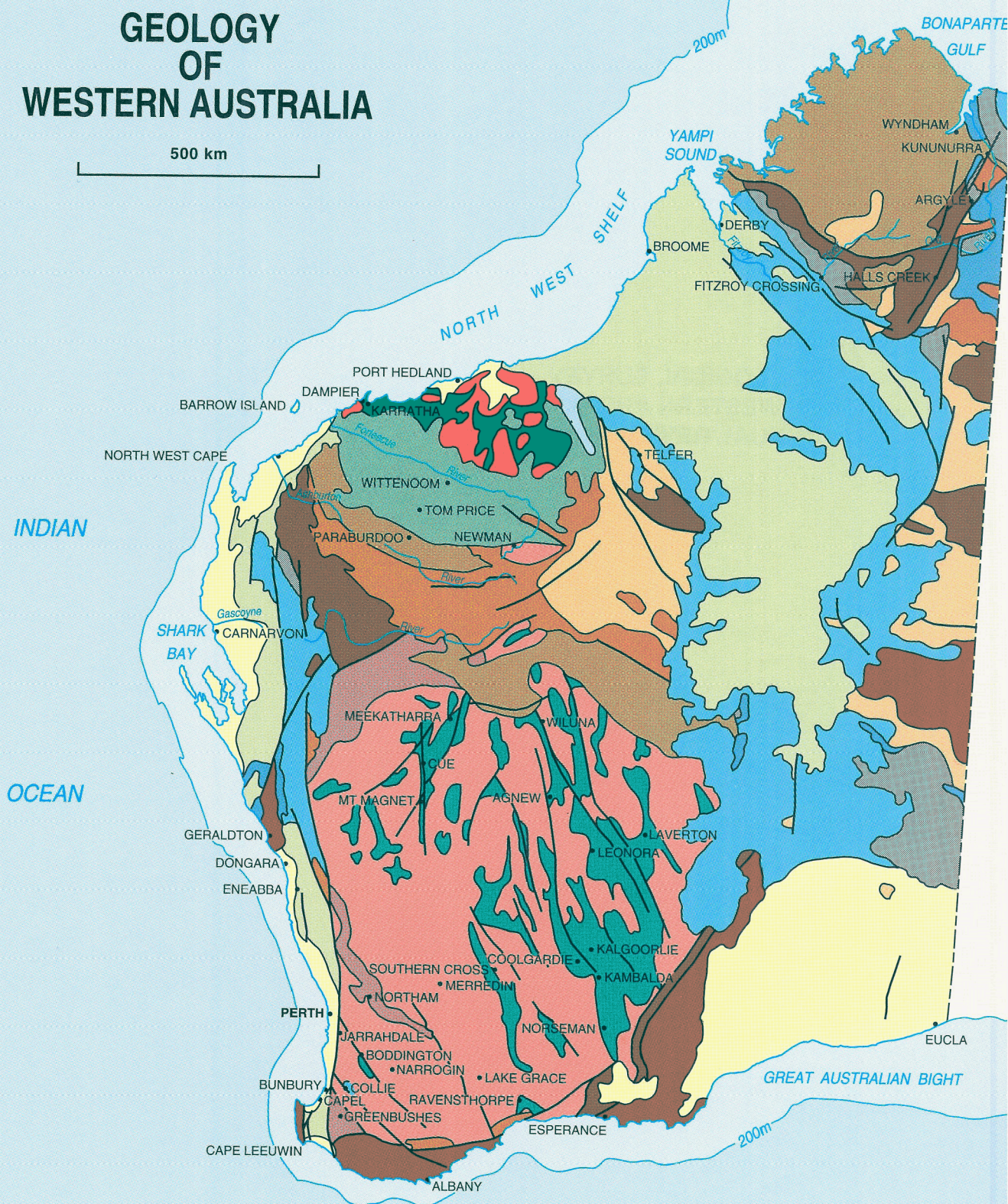


DEPARTMENT OF MINERALS AND ENERGY

**GEOLOGICAL SURVEY
OF WESTERN AUSTRALIA
ANNUAL REVIEW 1993–94**

GEOLOGY OF WESTERN AUSTRALIA

500 km



PHANEROZOIC

CAINOZOIC

Sedimentary

MESOZOIC

Sedimentary, minor volcanic

PERMIAN

Sedimentary

CARBONIFEROUS TO DEVONIAN

Sedimentary

SILURIAN TO CAMBRIAN

Sedimentary and volcanic

PROTEROZOIC

LATE
540-1 000 Ma

Sedimentary, minor volcanic

MIDDLE
1 000-1 600 Ma

Sedimentary and volcanic
Metamorphic and intrusive

EARLY
1 600-2 400 Ma

Sedimentary and volcanic
Metamorphic and intrusive

ARCHEAN

LATE
2 400-3 000 Ma

Sedimentary and volcanic
Granite
Greenstone

EARLY
3 000-3 700 Ma

Granite
Greenstone
Gneiss



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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OF WESTERN AUSTRALIA
ANNUAL REVIEW 1993–94**

Perth 1995

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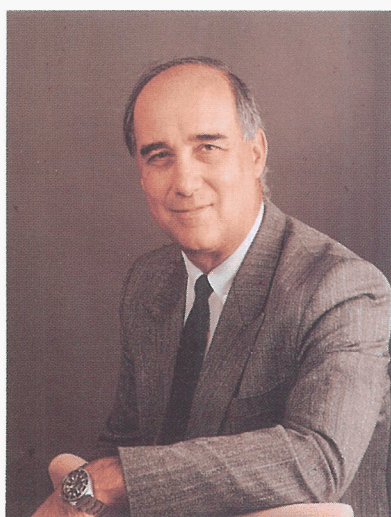
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Foreword



This Annual Review is the first produced by the Geological Survey of Western Australia and will in future years provide an annual record of the work carried out by the Survey. Its broad aim is to inform our customers of what has been achieved in the past financial year. Progress towards the objectives of the annual work program is documented in the form of status reports on the individual projects that make up the total Geological Survey program. Technical summary papers are included to document important preliminary findings of ongoing research. These results will, of course, be more comprehensively presented in relevant publications to be released at the conclusion of each project. Feature articles are also used to present discussions of issues and events that have been of importance or interest during the year under review.

Fiscal 1993–94 has been an important year for the Geological Survey. As a result of strong industry support for the program of recent years, Government has provided Special Initiatives funding in addition to our normal budget to accelerate over the next four years our core program of regional geoscience mapping, and to undertake additional projects specifically requested by industry. The support and direction we have received from industry and other customers through the Geological Survey Liaison Committee has ensured that our efforts continue to be relevant to their needs. This customer focus has also given us a strong sense of purpose and motivated us to maintain what we believe is a high level of quality in our products and services.

I am confident that this Annual Review, and future editions, will convey to our clients a concise statement of what has been achieved in their interest, and inform them of matters of interest and importance that have arisen in the course of our program work.

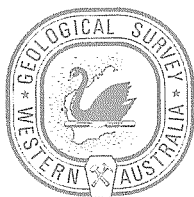
I am also confident that the client links established in recent years have been reinforced in 1993–94, and that this Annual Review will provide the stimulus for our clients to make more frequent and in-depth use of the Survey's products and services.

Pietro Guj
DIRECTOR



Contents

Foreword	v
Mission statement	ix
Feature articles	1
Technical papers	35
Program review	99
Appendices	145



Mission statement

Mission

Our mission is to provide up-to-date regional geological, geophysical, geochemical, hydrogeological, and resources information to the mining and petroleum industries and the public as a basis for resource exploration and landuse planning.

Role

The Geological Survey of Western Australia systematically records and interprets the geology of the State and provides this information to Government, industry and the general public to assist with the exploration, development and conservation of the State's mineral, petroleum and groundwater resources. It 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, landuse matters, and engineering developments.

Strengths

The main strengths of the Geological Survey are in field-based research, especially regional geological mapping in both the Precambrian and Phanerozoic provinces of the State. The Survey is also strong in the fields of basin studies, carbonate sedimentology, geochemistry, geochronology, geomechanics, geoscientific computer applications, hydrogeology, palaeontology, petrology, regolith studies, and structural geology. 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, the Geological Survey is 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.



Feature articles

The year in review	
by P. Guj	3
GSWA and the National Geoscience Mapping Accord	
by T. J. Griffin	5
Geological boundaries know no boundaries	
by P. Guj	10
AQWABase — a new groundwater database	
by A. T. Laws, P. Beveridge, and P. M. Farrell	14
GSWA and the Sensitive High-Resolution Ion Microprobe (SHRIMP) — an exciting new partnership	
by D. R. Nelson	18
Facilitating access to environmentally sensitive land and sea areas and Aboriginal reserves of Western Australia	
by A. J. Smurthwaite and V. Novak	20
Exploration in Western Australia	
by P. Guj, W. Preston, V. Novak, and J. Blockley	25
Inside the GSWA	32



The year in review

by P. Guj

Fiscal 1993–94 was a year of intense activity and considerable change for the Geological Survey of Western Australia (GSWA). The continuing and comprehensive annual work program was complemented by the introduction of a number of 'New Government Initiatives' designed to attract and facilitate mineral exploration in Western Australia. Output and productivity were also enhanced by a cultural shift towards greater customer focus and by a commitment at all levels in the organization to greater teamwork, more stringent project management, and continuous process improvement.

New Government initiatives included allocation of special funds to the first of a number of four-year programs designed to:

- improve the rate of acquisition, and subsequent image processing and interpretation, of aeromagnetic and radiometric data in order to assist the regional geological mapping program and to prepare these data for eventual release to industry;
- accelerate the completion of geological mapping, initially in the Eastern Goldfields and in the north Murchison area (Glengarry Basin);
- carry out a program of systematic regional regolith and geochemical mapping.

Areas of priority for these initiatives were established in consultation with the mineral industry, AGSO, CSIRO, and academia through both formal (e.g. Geological Survey Liaison Committee, Geochemical Mapping Advisory Committee) and frequent informal meetings and communications.

Funding was also resumed in 1993–1994 for a comprehensive drilling program to assess and investigate the groundwater resources of the State.

These new activities were superimposed on the standard GSWA program of geoscientific investigations, database administration, and policy support. The latter was in turn subject to considerable demand pressures from industry and other stake-holders as the year finally saw clear signs of economic revival in Australia, not surprisingly led by the exploration and mining industry in Western Australia.

The year also saw considerable changes in the philosophy and structure of the Australian Geological Survey Organisation (AGSO) including the gradual introduction of a policy of partial commercialization and cost-recovery that is likely to deeply affect their modus operandi in the future.

The National Geoscience Mapping Accord (NGMA) continued satisfactorily with joint mapping programs in the Eastern Goldfields and East Kimberley and individual activity by the GSWA in the Paterson Orogen and by AGSO in the Arunta Block.

Mapping was completed by the GSWA on a total of eleven 1:100 000 sheet areas. Of these, seven sheets were printed and released during the year and a

further four were in press at the year's end. The major emphasis was in the Paterson Province of the East Pilbara where field mapping of the Rudall Complex was brought to an end, and in the Eastern Goldfields for which KURNALPI*, NORSEMAN, MULGABBIE, and PINJIN were released, and EDJUDINA and YABBOO were in preparation for printing.

Work in the Eastern Goldfields included a significant geophysical component with acquisition of aeromagnetic and radiometric data on two 1:250 000 map sheets and the final release of the interpreted east–west seismic transect through the granite–greenstone terranes. The work culminated in a series of seminars that generated considerable discussion and controversy in geological circles.

In addition, a number of thematic maps and publications were printed and released to the public. These included a study of gold mineralization in the Menzies–Kambalda region; a synthesis of the geology and coal resources of the Collie Basin; a structural analysis of the southern Perth Basin; a study of mafic volcanic rocks in the Menzies–Norseman region; a report on the stratigraphy, biostratigraphy, and structure of GLENGARRY (1:250 000); a hydrogeological map covering KALGOORLIE (1:250 000); and a report and maps at 1:500 000 scale dealing with the vulnerability to contamination of groundwater in the Perth Basin.

During the year the SHRIMP (Super High Resolution Ion Microprobe), a joint venture between Curtin University (Curtin), the GSWA, and the University of Western Australia (UWA), finally became operational. The GSWA has already satisfactorily produced a number of ages for rocks in the Eastern Goldfields using this facility.

The GSWA was also the prime mover, together with AGSO, CSIRO, and UWA, in the organization of the very successful Kalgoorlie 93 Geological Symposium and of a number of other academic and industrial seminars. These included active participation in the Master's Courses in Ore Deposit Geology and Evaluation at UWA, to which the GSWA contributed intensive courses in project evaluation, financial analysis and management, geomechanics, environmental geology, and the resolution of landuse conflict.

Assistance was also provided to Curtin's W.A. School of Mines' Master's Course in Mineral Economics in the area of principles of finance, and geomechanics.

The GSWA was also active abroad, undertaking projects compatible with the pressing needs for increasing activities in Western Australia. Successful projects were completed in India, Vietnam, and Indonesia in groundwater, in China in geomechanics and mineral economics, and in Eritrea, where a review of their mining and fiscal codes, and mining investment strategy in general, was carried out.

* Capitalized names refer to standard map sheets.



GSA and the National Geoscience Mapping Accord

by T. J. Griffin

Introduction

The National Geoscience Mapping Accord (NGMA) was implemented in 1990 following a discussion paper by the Bureau of Mineral Resources (BMR) titled, 'Proposed projects for National Geoscience Mapping Accord'. This arose from the Woods Review of the BMR in 1988, which recommended that the BMR should increase its mapping activities in conjunction with the State and Northern Territory (NT) geological surveys. As a result, existing cooperative projects between the State/NT geological surveys and the BMR were placed under the NGMA banner, with an injection of additional resources in some cases, and new NGMA projects were started in 1990–91.

The BMR changed its name to the Australian Geological Survey Organisation (AGSO) in 1992.

Woods Review 1988

The Woods Review focused on the shortfall in the total national effort in geoscience mapping and recommended that:

'as a matter of priority BMR and the State/NT geological surveys, through the Chief Government Geologists Conference, and in consultation with industry and the academic community, develop a national geoscience mapping strategy (National Geoscience Mapping Accord)'.

The review further recommended that the BMR program and priorities should better reflect the needs of industry by:

- placing greater emphasis on geoscience mapping and related research, in collaboration with the State/NT geological surveys and other geoscience organizations, and developing and maintaining a range of national geoscience databases;
- using the national geoscience knowledge base to provide regional syntheses, analyses, and interpretations;
- applying the latest technology and concepts to data acquisition, management, and interpretation.

The BMR proceeded to undertake a comprehensive review of its programs and entered into a consultative process to meet the recommendations of the Woods Review. Following submissions from the State/NT geological surveys in which they assessed their needs for the next twenty years, the BMR concluded in 1989 that it would contribute to the NGMA by:

- participating directly in systematic mapping programs in collaboration with the State/NT geological surveys;
- providing specialist expertise/facilities in direct support of priority mapping programs;
- directing its geophysical mapping activities (both airborne and seismic) more closely towards the geological mapping priorities.

The BMR also stated that it remained committed to a number of major programs outside the NGMA (e.g. continental margins, resource assessment, nuclear monitoring, geophysical observatories). However, it was determined to increase the proportion of resources available to mapping programs, especially in the minerals and landuse area. The BMR would increase its emphasis in a wide range of regional programs on the production of systematic geoscience, while maintaining a commitment to an integrated, multidisciplinary approach to regional geoscience research.

General strategy of BMR

A general strategy was outlined and endorsed by the BMR Advisory Council:

‘BMR’s contribution will consist of a number of high-priority programs developed through bilateral discussions between individual States and the BMR, and incorporated into the overall Mapping Accord. Each program will contain a number of elements with agreed contributions from the State or States concerned and BMR, recognizing that systematic maps and datasets, supported where appropriate by published reports, are the most important products.

BMR will make every effort to contribute substantially to the geological mapping as well as to contribute airborne geophysical and seismic elements, and agreed specialist input’.

National Geoscience Mapping Accord. The Commonwealth Perspective: A discussion paper prepared by BMR, 1989.

Priorities for BMR

Priorities for BMR’s input into NGMA would take account of its national role and its responsibilities to the Commonwealth Government involving areas of mutual interest to the Commonwealth and State governments. Major influences on priorities are to include:

- the assessed value in filling gaps in the national geoscientific knowledge base relevant to petroleum, minerals, and water resources;
- the need for Commonwealth–State cooperation in provinces or basins that cross State boundaries;
- the need for specialist expertise and capabilities in BMR;
- the need to balance resources between mineral and petroleum programs;
- the recognition that the States/NT have some claim on national facilities.

Proposed projects

A discussion paper, titled ‘Proposed projects for National Geoscience Mapping Accord’, was prepared by BMR in 1990 following extensive discussions on the implementation of the Woods Review recommendations. The proposed projects covered the period 1990–2000 and would require double the then current level of BMR expenditure. It was suggested that the States would provide the additional resources for the Accord so that it truly represented Commonwealth–State cooperation.

The stated objectives in this proposal reiterated the general objectives of all State/NT geological surveys and included:

- optimizing the environment for mineral and fuel exploration through provision of geoscientific data, maps, and exploration models;
- providing a reliable base for the assessment of undiscovered mineral and fuel resources;
- strengthening the geoscientific base in order to facilitate environmental and landuse decisions.

These were designed to satisfy the previously outlined priorities. In addition, the BMR stated that the principal goal of NGMA is to produce a national geoscience digital database and a new generation of geological maps for Australia.

Airborne geophysical mapping would form the core of geological mapping in hard-rock terrains, whereas integrated basin studies and 'key horizon' studies would predominate in the soft-rock areas of the continent. A multi-disciplinary approach would be adopted involving remote sensing (satellite imagery and airborne multi-spectral scanning), airborne geophysics (aeromagnetism and radiometric surveys), seismic-reflection and refraction studies, and regional gravity studies.

The NGMA was endorsed by the Australian (now Australian and New Zealand) Minerals and Energy Council in 1990. There was an understanding that the funding of individual projects be on a 1:1 basis, but no formal commitment of resources was made on behalf of the participants.

The W.A. connection

In the minerals provinces, BMR felt that the main emphasis should be on updating 1:250 000 geological maps, along with larger scales of key regions. This is also a priority for the GSWA; however, industry has clearly indicated that more detailed geological maps at 1:100 000 scale are also a priority in areas of potential mineralization. Regolith mapping was also regarded as important to the discovery of concealed ore deposits.

The acquisition of airborne magnetic and radiometric data at 400 m line spacing seemed an appropriate scale to support the mapping. Closer line spacing would be far too costly in relation to the total budget for the projects.

The projects selected by BMR for the first of its five-year projects involving Western Australia were:

- Kimberley–Arunta — in collaboration with GSWA and the Northern Territory Geological Survey (NTGS);
- Eastern Goldfields — in collaboration with GSWA;
- Musgrave Block — in collaboration with the South Australian Geological Survey, GSWA, and NTGS;
- Pilbara–Paterson — in collaboration with GSWA.

The approach to projects in the petroleum basins emphasized the understanding of the architecture and geological evolution of sedimentary basins to assist oil and gas exploration, rather than surface mapping. This understanding is derived from the analysis of subsurface data, principally seismic-reflection data. BMR indicated work on petroleum basins in Western Australia would be in the Canning, Officer, Carnarvon, and Eucla Basins.

It was recognized in the 1990 document that the resources available for NGMA projects fell well short of those required to implement the proposed projects over 20 years. The projects that have received both State and Federal resources, and have been set up as NGMA projects involving BMR and GSWA, are the Kimberley–Arunta, Eastern Goldfields, and Canning Basin projects.

Kimberley–Arunta

Much of the Arunta work was completed prior to the NGMA by NTGS and BMR. The Kimberley work, involving remapping in the East Kimberley, had already been started by GSWA as the second stage of their program to re-evaluate the geology of the Proterozoic orogens in the Kimberley. The mapping in the West Kimberley had been completed over the previous four years.

The BMR plan was to map a strip of 1:250 000 map sheets from the Kimberley through the Granites–Tanami to the Arunta region. The GSWA was focused on, and remains committed to, the re-evaluation of the whole of the Halls Creek Orogen, as this rock unit has potential for substantial mineralization.

The establishment of the Kimberley–Arunta as a NGMA project essentially doubled the resources for the remapping of the Halls Creek Orogen from 1991 to 1993. The original GSWA program was revised and more detailed mapping became possible. Standard 1:100 000 geological maps, which had proved very successful in the Eastern Goldfields, became the first goal. This

was supported by new airborne geophysics for some areas. The 1:250 000 maps would be produced as a follow-on, by simplifying the more detailed 1:100 000 maps and undertaking additional field work in the areas not already covered.

To date, field mapping on DOCKRELL, ANGELO, RUBY PLAINS, HALLS CREEK, MCINTOSH, DIXON, and part of TURKEY CREEK (1:100 000 map sheets), and GORDON DOWNS (1:250 000) has been completed. ANGELO and DOCKRELL are ready for printing by GSWA. RUBY PLAINS, HALLS CREEK, and DIXON have been compiled. AGSO has provided access to SHRIMP dating, continuing work that started as a cooperative project with BMR in the West Kimberley in 1987. Preliminary reports have been published on the mapping from this NGMA project by both AGSO and GSWA.

AGSO is winding down its involvement in the Halls Creek Orogen and will work southeast to connect with their recent work with the NTGS in the Arunta. The GSWA will continue to complete its original project to re-map the Proterozoic rocks of the Kimberley orogens.

Eastern Goldfields

The Eastern Goldfields NGMA project embraced an existing GSWA project in the southern part of the Eastern Goldfields that began in 1980, and a new project by BMR in the central Eastern Goldfields. These projects were involved in producing 1:100 000 and 1:250 000 geological maps that incorporated interpretations of new airborne geophysical data. Under the NGMA, each organization continued to have responsibility for the separate areas. The GSWA concentrated on the publication of standard 1:100 000-scale geology maps of the major greenstone belts, and these have been well received by the exploration industry. AGSO has placed emphasis on second-edition 1:250 000 geological maps, adopting a digital approach involving data collection and compilation to achieve rapid release of the data. However, the 1:100 000 preliminary hard-copy map products from a computer plotter are not up to the standard of the published maps.

Publication of 1:100 000 geological maps covering the main greenstone belts from the southern part of the Eastern Goldfields will be completed in 1994. Three new 1:250 000 geological maps have been published (WIDGIEMOOLTHA, BOORABBIN, KALGOORLIE). These published maps include mapping that pre-dates the NGMA project. Computer plots of maps from the central part of the Eastern Goldfields are available. All the 1:100 000-scale maps will be available in digital form, including the maps produced before computer-aided map production was introduced.

Completed projects include special studies involving geophysical mapping, regolith mapping, and a deep seismic-reflection transect by AGSO. Interpretative maps such as the terrane maps and specialized gold deposit studies by GSWA, together with joint SHRIMP dating and numerous articles, also have been completed.

A new phase of the Eastern Goldfields NGMA project began in 1993 with the injection of extra funds to GSWA for accelerated mapping. GSWA and AGSO are working on adjoining 1:100 000 map sheets in the northern Eastern Goldfields between Wiluna and Laverton. This work has included the acquisition of new 1:25 000 colour aerial photography, airborne geophysical data on 400 m line spacing, regional gravity data, and detailed ground mapping on SIR SAMUEL and DUKETON. This data is currently being processed and the geological maps are being compiled. It is planned to incorporate these datasets into GIS packages.

Musgrave

The resources of GSWA could not support this project. However, because access to aboriginal land had been obtained in part of the area, AGSO proceeded with this project in a limited way, mainly in the Northern Territory and South Australia.

Pilbara–Paterson

The GSWA has a major mapping program in the Paterson Orogen that began prior to the NGMA. This has not become an NGMA project because

of resource constraints in AGSO. Work in the Pilbara will begin in 1994–95.

National databases

A key function of the NGMA has been to establish national digital databases. The GSWA has contributed to these, particularly the geophysical, geochemical, and geochronological databases. AGSO has also played a significant role in designing databases for use in GIS.

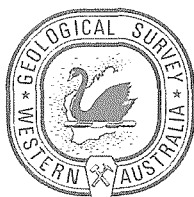
Richards Review 1993

In response to the Richards Review of AGSO, which recommended the acceleration of the NGMA, the Commonwealth Government undertook to renegotiate the NGMA. This process is to begin early in the 1994–95 financial year, and aims to conclude agreement on the revised NGMA at the Australian and New Zealand Minerals and Energy Council in September 1994.

Conclusion

The establishment of NGMA with its strong emphasis on geological mapping has fitted well with the philosophy of the GSWA, which always maintained a high level of activity in producing standard geological maps, principally to support and encourage the exploration and mining industry. High quality geological maps are critical to the optimal interpretation of the remotely sensed geophysical and multispectral data used extensively in geological models for generating exploration targets.

The NGMA projects have provided a focus for acquiring regional geophysical data and meant that more mapping has been achieved in Western Australia than was predicated without the extra resources from AGSO. The transition to digital products and datasets has been accelerated by the NGMA with considerable benefit coming from the closer cooperation. More work can be done in ensuring that the products from both organizations reach a similar standard. It is anticipated that benefits will continue to flow as current projects are concluded and new projects are established.



Geological boundaries know no boundaries

by P. Guj

Australia has in recent years adopted a more outwardly orientated stance in her foreign and trade policy. This policy has to some extent influenced the activities of the GSWA in 1993–94 both at the individual and at the organizational level.

A moderate level of activity abroad, provided it does not excessively interfere with work in Western Australia, is considered a desirable way of developing staff and broadening the GSWA outlook and expertise.

Individual international activities

At an individual level there were a number of scientific cooperation projects involving:

- Alec Trendall and John Myers who, for different projects, received invitations to visit India in the context of the international geological correlation of Archaean terranes;
- Richard Davy's attendance at the International Geochemical Congress in China and related field excursions;
- Alex Kern's participation in the International Groundwater Congress in Norway;
- Peter Dunn's attendance at the USGS Mineral Exploration Congress in Denver Colorado;
- Kath Grey's visits to Europe and the United States in connection with the completion of cooperative palaeontological studies.

In the majority of cases these initiatives were largely or totally funded by the individuals involved, which bears testimony to their and the GSWA's dedication to the geosciences.

Of greater duration and possibly greater significance were the international activities and exchanges of three officers, namely:

- Paul Morris' secondment as an Associate Professor of Geology at the Shimane University in Japan;
- Iain Copp's participation in the Argentinian geological mapping expedition to Antarctica;
- Cees Swager's exchange with the Geological Survey of Denmark to participate in its 1994 geological mapping campaign to Greenland. Cees was replaced by Dr Peter Dawes who over the same period has been carrying out geological mapping as a member of the Glengarry Basin Project team under the leadership of Franco Pirajno.

Corporate international initiatives

Consistent with the Western Australian Government's policy of establishing a constructive rapport and of promoting trade and investment with its northern neighbours in the Pacific Rim, the GSWA conducted a number of geoscientific initiatives primarily in China, Vietnam, India, and Indonesia. It was also active in the newly created country of Eritrea.

China The GSWA's interests in China focus at two distinct levels:

- Provincial, primarily with the Sister Province of Zhejiang.

In October 1993, the Director of the GSWA led a three-person delegation to Hangzhou in the first instance to participate in a UNDP-ESCAP symposium and study tour on industrial minerals. This was followed by technical exchanges with the Zhejiang Province Department of Geology and Mineral Resources (DGMR) mainly in the field of hydrogeology and engineering geology.

In April 1994, the Director of the Zhejiang Province DGMR led an exchange visit to Western Australia, which resulted in the signing of a Memorandum of Understanding (MOU) between the two organizations as well as facilitating the signing of a joint venture with a local explorer/miner. According to the MOU, it is intended that a three-geologist team from Western Australia will visit the Zhejiang Province in October–November 1994 at DGMR's expense to carry out an audit of their gold exploration program and in particular a review of the three most promising prospects. In exchange, Western Australia will host a team of two Chinese experts who will review the State's current status and potential for future industrial-minerals developments.

- National, mainly with the Ministry for Metallurgical Industry (MMI) but lately also with the Ministry for Geology and Mineral Resources (MGMR).

Since 1992, the GSWA has been leading a geomechanical research program designed to model the slope stability of deep opencut mines. This research is carried out through the Centre for Geomechanics and involves, besides the GSWA, personnel from UWA, CSIRO, and three Chinese research groups. The research is funded by the WA–China Economic and Technical Research Fund.

During his late 1993 visit to China, the Director discussed proposals for possible new cooperative research in the field of Economic Geology and Mineral Economics with both MMI and the MGMR.

Vietnam On his return from China in November 1993, the Director briefly visited Hanoi, where, building on an earlier visit by the Minister for Mines, the Hon. George Cash, he explored avenues for future cooperation between the two countries in the area of the geosciences. This culminated in the signing of a MOU between the GSWA and the Geological Survey of Vietnam (GSV) covering three initiatives:

- (i) Urgent assistance to Vietnam in addressing a number of significant groundwater management and related environmental issues along 250 km of the coastal region between Phan Thiet and Nha Trang in southern Vietnam. A joint GSWA – Water Authority of Western Australia team led by Mr Philip Commander and including two engineers (Mr Harry Ventriess and Dr Binh Anson) successfully completed a project-scoping study in March 1994. Their report will soon be considered by Vietnam's State planning Committee and may lead to the initiation of a number of projects and related contractual opportunities for Australian firms. The proposed projects are in arid areas of Vietnam with similar hydrogeological conditions to parts of Western Australia, and are complementary to existing Australian International Development Assistance Bureau funded water-supply projects.
- (ii) Organizing a seminar entitled 'Vietnam Mineral Resources: Vision and Opportunities' to promote better understanding and a

meaningful dialogue between Vietnamese mining and petroleum authorities and Australian exploration, mining, and investment companies.

The seminar, which was made possible by generous contributions from the mining industry, was successfully held on 28 June 1994. An audience in excess of 100 delegates was addressed by the Minister for Mines, the Hon. George Cash, by the Vietnamese ex-Deputy Minister for Heavy Industry, and by a range of senior representatives of both governments, the United Nations, industry, and academia. Following the seminar the Vietnamese delegation visited selected mining sites in the Eastern Goldfields.

- (iii) Provision of training in Project Evaluation and Financial Management as applied to mineral resources projects to be conducted in Vietnam.

It is intended that this shall take place in Hanoi, preferably late in 1994 or early 1995. Due to the considerable industry interest raised by the Seminar, arrangements are also being made with the GSV to invite the GSWA to lead a delegation of interested companies to visit Vietnam at that time.

Indonesia Western Australia has a sister-state relationship with East Java in Indonesia. The GSWA was invited to visit Surabaya late in 1993 to provide technical expertise and advice to the East Java Regional Planning Agency (BAPPDE) on groundwater contamination and on problems related to saltwater intrusion. Dr Steve Appleyard was a member of a team including officers of the Department of Environmental Protection and Office of Waste Management. During this visit the GSWA also had an opportunity to display posters on groundwater contamination at the 'Australia Comes to Indonesia' trade fair held on 23 June.

India World Geoscience Corporation (WGC) are currently carrying out a major five-year program of systematic airborne geophysical mapping of most of the State of Orissa in northeastern India. The project is mostly funded through AIDAB, with the main priority being the utilization of the resultant data to locate groundwater supplies.

At the request of WGC, Tony Laws visited Orissa early in 1994 in order to:

- review the hydrogeology and the hydrogeological interpretation of airborne and surface SIROTEM studies undertaken by WGC;
- assess the proposed drilling program, and identify possible problems and needs for further groundwater studies.

The groundwater-related studies are being undertaken in the Phulbani District, about 160 km inland, where the geology consists of structurally complex, highly faulted, Archaean crystalline rocks. While shallow wells often obtain polluted groundwater from the weathering profile, the occurrence of better quality groundwater, and its flow, is strongly structurally controlled within these crystalline rocks. The ability of the geophysical surveys to locate the deeper fractured zones, and therefore the more productive aquifers, is vital. At the time of the visit, the first test hole was successfully completed.

Considerable difficulties affecting the progress of the drilling program include the lack of a Program Manager, detailed specifications for drilling and equipment requirements, on-site supervision, monitoring and testing, and ancillary equipment. To overcome this, a program of training for the Orissan hydrogeologists and drillers has been formulated between WGC and GSWA, and has been submitted to AIDAB for consideration and funding.

Eritrea In 1991, after winning a bitter struggle with Ethiopia lasting over 30 years, Eritrea achieved its independence. The country must now address the

daunting task of rebuilding its economy, and, given its geological potential, exploration and mining may become its leading industry.

In April 1994, Dr Pietro Guj and Messrs Bill Phillips and Bill Preston were engaged by AIDAB to assist the Government of Eritrea to formulate strategies and to finalize their mining and mining income-tax legislation with a view to placing the country in a competitive position in terms of attracting foreign exploration and development investment.

Pietro Guj and Bill Phillips spent approximately three weeks in Asmara to produce, under the guidance of the Minister for Energy, Mines and Water Resources, a final draft of the legislation and a related strategic paper comparing the proposed regulatory regime of Eritrea to those of some 13 reference development countries.



AQWABase — a new groundwater database

by A. T. Laws, P. Beveridge, and P. M. Farrell

Since the formation of the GSWA, groundwater data, comprising information on bores, wells, soaks, and springs, has been collected, collated, interpreted, and stored. Over the years the amount of groundwater data has grown enormously as more and more information is collected by geologists and technical officers, or is transcribed from drillers', consultants', and industry reports.

While the amount of data has increased, so have the problems with storage, retrieval, and ready manipulation of that data. The volume of information has commandeered considerable office space, while manual retrieval of sequentially indexed bore-data is extremely time-consuming and inefficient.

It has long been recognized that the existing database should be converted to a fully computerized system where data can be retrieved, manipulated, and interpreted rapidly and efficiently. It is also essential that the final system should have full GIS (Geographical Information System) capabilities.

Existing system

The groundwater database currently used by the Hydrogeology Section was established in 1963. It is based on edge-punched cards that facilitate the recovery of records conforming to a set of selection parameters. Those data recorded on each card include bore/well number (related to the International Map Reference System), local name if any, owner, driller, construction details, depth, waterlevel, yield, water quality, and details of strata penetrated. Some cards have detailed hydraulic data, but many records are incomplete.

Accompanying the bore-data cards is a complementary set of cards containing detailed chemical analyses of water samples collected from some of the water datapoints. However, only a small percentage of points have been sampled, and the number of these cards is therefore considerably less than those containing the bore data.

At present there are in excess of 90 000 cards containing groundwater data, and they are currently being added to at a rate of about 500 per year. Water-chemistry cards number about 2000.

The bore-numbering system comprises the international 1:250 000 map number, followed by the four-digit numeral of the particular 1:100 000 map sheet. A following letter denotes the particular 1:50 000 quadrant of that map sheet, and this is succeeded by the bore number, which refers to its position, in the order of accession, on the map. The positions are marked on transparent maps at scales of 1:250 000 to 1:2000, depending on locality and bore density.

The existing database represents a valuable and important State asset, but in its present form it is time-consuming to interrogate, and data are not readily accessible or transferable for the numerous users of the information. It is particularly difficult to use for regional studies relating to groundwater assessment, allocation, and management, and in catchment planning and the

location of on-farm water supplies, for which there is increasing demand. The lack of a computerized database has affected the work of some State agencies and was an identified issue of concern to the Western Australian Water Resources Council.

It was essential therefore that this system should be replaced by a fully computerized database. While discussions had taken place, over several years, on the incorporation of the database into the State Water Resources Information System (SWRIS), run and maintained by the Water Authority of Western Australia (WAWA), staffing, funding, and time constraints prevented an early start on the data uptake. In the end, because SWRIS is essentially aimed at time-series data, and because of concern over its usefulness for GSWA data, it was decided to develop a new database package, specifically attuned to the needs of the GSWA, and with suitable ease of data uptake. For this reason, existing off-the-shelf packages were not considered.

Development of AQWABase

The development of AQWABase is proceeding in stages. The primary objective of Stage One is to translate data contained on the existing card system, together with associated coordinate details found on map sheets at various scales, into a digital form.

Stage Two will migrate the AQWABase database to a more secure and manageable database environment linked directly to a GIS. The improved database security will permit secure dial-in access to the database and simplify system administration. The GIS functionality will enable map sheets to be generated displaying any attribute held in the database (e.g. watertable depth, chemical parameters, stratigraphic-intersection depths) and allow whole or selected portions of map sheets, displaying similar information, to be displayed on a graphics terminal, principally to address public requests for information.

Specification of AQWABase commenced in mid-June 1993 with a funding-dictated deadline for data entry to be well under way by September 1993, a time frame of less than 10 weeks. In view of the imposed time constraints a personal computer environment was considered the only solution likely to deliver on time. This required a dual software development solution:

- a database management component to enable transcription of borehole details contained on cards into a relational database;
- a digitizing/Computer-Aided Design component to capture the borehole coordinate information contained on map sheets.

A Windows-based database-development package was selected. Two database-development packages in use by the Department were evaluated — Microsoft Access and Borland's Paradox. Access was selected because of its superior client/server capabilities at the time, and the greater availability of experienced contract programmers. Programmers experienced in Paradox were unavailable.

Microstation Intergraph, the software package used extensively by the Department's Cartographic Section, was purchased and a contract let to customize the package to the specified requirements.

Data entry commenced on 25 August 1993 and digitizing of borehole coordinate details commenced in mid-November 1993. The hardware utilized to run the system consists of four PCs (3 x 486DX-33 MHz and 1 x 486DX-66 MHz), each connected to the Department's local-area network; an A0-sized digitizer; an A1-sized pen plotter; and a laser printer.

Funding for the project to June 1994 was \$210 745, which was obtained from the Federal Water Resources Assistance Program (\$55 000), the National Landcare Program (\$49 945), and the Department of Minerals and Energy (DME; \$105 800). Continuing funding through to June 1996 (about \$200 000) will come from the National Landcare Program.

Procedures

The data capture and processing operations of AQWABase are performed by a contract team of one Geologist and two Data Processing Officers, under the supervision of a permanent officer.

Preparation of borehole details involves the coding and summarizing of strata logs, and the interpretation and allocation of dates to time-variant data. The data processing consists of data entry, generating reports, digitizing borehole locations, producing plots, and the verification of all data.

AQWABase was initially designed so that uptake of borehole details, chemistry data, and borehole locations could proceed in any order. However, software and procedural modifications were required to renumber a significant quantity of boreholes. Borehole details, associated chemistry, and borehole locations must now be captured in strict sequence. Replotting some bores to more appropriately scaled maps for digitizing is necessary in some cases to ensure accuracy.

Priority areas for data capture are decided on an ad hoc basis. The need for digital data in areas related to the GSWA Hydrogeological Mapping Program, Farm Water Strategy Zones, Catchment Management Plans, and Water Resource Reviews has, so far, dictated data-processing priorities.

Under the allocated priority, all water data from the cards are entered, in sequential order, into AQWABase on the basis of one 1:250 000 sheet at a time. At the completion of each sheet area, a printout of all data is obtained for checking and verification, and any errors are corrected immediately. While verification of the digital information is in progress, all chemistry data, for the same water datapoints, are also entered into AQWABase, and subsequently checked.

The next stage of data input for the particular 1:250 000 sheet is the digitizing of all datapoint locations from the existing maps, which can be at scales from 1:2000 to 1:250 000, depending on the density of data. Finally, a plot of the datapoints, at the digitized scale, is obtained in order to verify the correct locations as shown on the existing location maps. At this stage the only errors in the system will be the result of incorrect location of the points in the transcription of field data to the location plans. Such errors will be minimised in the future as more use is made of Global Positioning Systems (GPS) for site location.

Output

While data input progresses, the system can still be interrogated, and output provided, for a variety of information from the areas already processed. Such information includes:

- Standard reports: listing of data within a sheet boundary for use in studies such as hydrogeological mapping. This information can be provided as hard copy, or in digital form on disk, either as an Excel spreadsheet or in ASCII format.
- Ad-hoc queries and reports: listing of data within a specified boundary, for use in areas of special interest, such as public enquiries. These can be provided in the same format as the above.
- Map-sheet plots of datapoint locations, at appropriate scales, or at scales as required.
- Map-sheet plots of attributes associated with each datapoint: for example, watertable depth, waterlevel, salinity, and geology. Up to ten different attributes can be plotted.

As more interpretive data is added to AQWABase, through its projected GIS capability, further information, such as watertable contours and salinity isohalines, will become available.

Uses

While AQWABase will have many uses in the future, without doubt its main attribute will be its ability to rapidly and efficiently provide all groundwater

data within specific areas to prospective clients, from within the GSWA, other Government Departments and Agencies, industry, and the public.

For GSWA studies, the data output in its graphical form will provide the base for rapid interpretation of the information, and will enable production of the graphical layers of information that make up a hydrogeological map. Not only will this enable hydrogeological maps to be produced more rapidly, it will also reduce the initial input required from the Surveys and Mapping Division of DME.

The benefit of the database is already evident in the production of the basic dataset for a groundwater resources review of the Busselton–Walpole Region for the Water Authority. The previous procedure, of manual plotting and interpretation of the data for this area, would have had a time requirement of perhaps two to three weeks; using AQWABase, data was provided within two to three hours, and in a form which allowed ready interpretation and correlation with geological data.

AQWABase will also be able to provide external clients with the data required for an area under review within a considerably shorter period than before. This will be of particular use for customers requiring a subset of borehole details in a particular area, such as a listing of all bores with a geological log, or a plot of all bores within various salinity ranges. Provision of data to the general public will be further enhanced with the inclusion of topographical data into the system; derivative maps, such as a depth to watertable map for the Perth metropolitan area, will enable a rapid, accurate response to telephone enquiries.

As the database is further developed to enable external access to the system, information on groundwater will become more readily available to all who require it.

Progress

The transformation of the existing database into AQWABase is planned to be completed by June 1996, thirty-eight months after the first data was entered. Several years ago, when the incorporation of the GSWA database into SWRIS was considered, the estimated time-span for completion was about five years.

To June 1994, 32 000 water-data and chemistry cards have been entered into the database, while 16 500 water-data locations have been digitized. Information from datapoints for thirty-two 1:250 000 sheets are now within AQWABase. To date, locations on the equivalent of ten 1:250 000 sheets have been digitized: for seven of these sheets the data has been digitized at 1:50 000 scale (144 maps). As familiarity with the data input and digitizing increases, the rate of data uptake will improve, and the completion of the database will be achieved within the allocated time schedule.

Future developments

In the immediate future the database will be developed in two directions: for read access only, and for read/write access. The former is planned for provision of access to the database by external interrogation, such as from another Government Department or Agency, or industry. The latter will enable GSWA hydrogeologists to add new data and correct or manipulate existing data, particularly during the GSWA's hydrogeological mapping program.

More important will be the further development of links between the database and systems with GIS capabilities, so that the data contained within AQWABase can be graphically presented and overlain with cadastral, topographical, infrastructure, and other data and plans. This will provide the information required to produce hydrogeological maps, assess groundwater resources, and provide a wide range of technical advice to other State agencies and the public.



GSWA and the Sensitive High-Resolution Ion Microprobe (SHRIMP) — an exciting new partnership

by D. R. Nelson

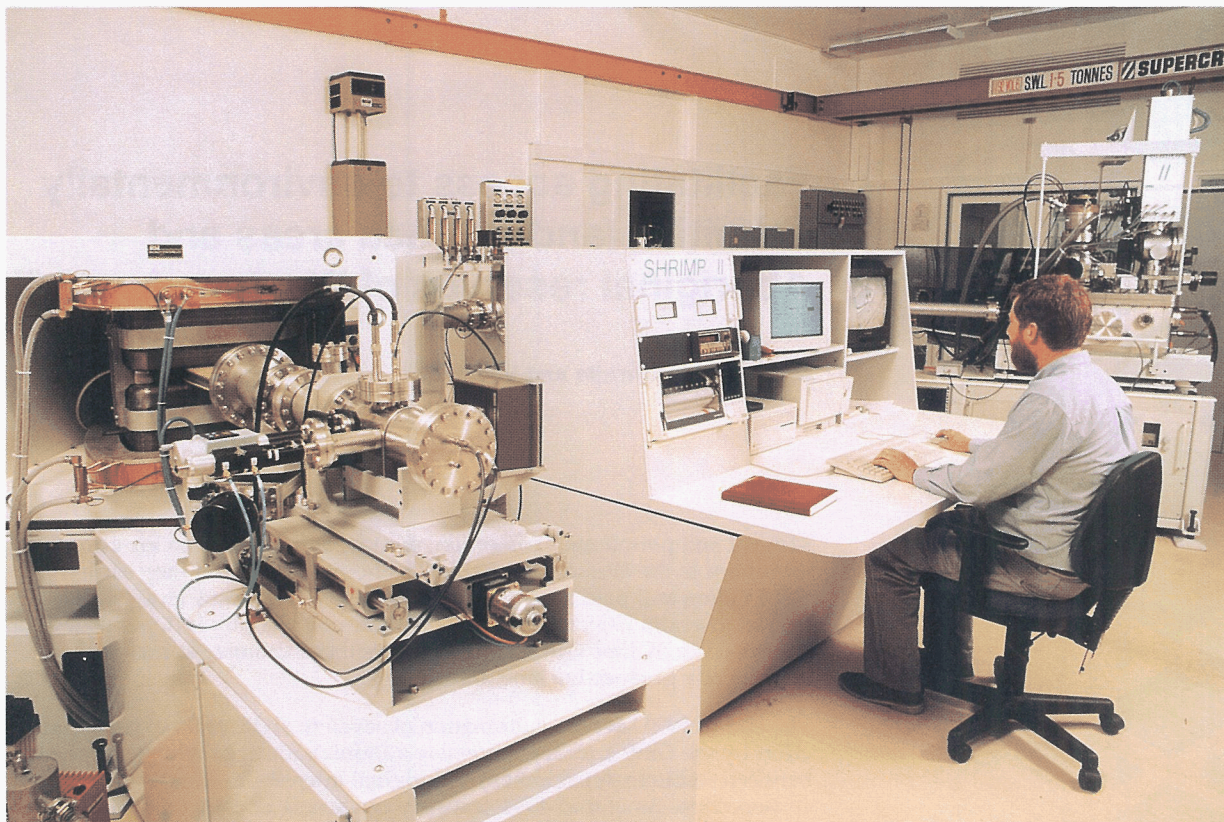
Geochronology is the science of dating rocks by measuring changes in the abundance of naturally-occurring radioactive isotopes. By measuring the proportion of a radioactive parent isotope, such as uranium, to a stable daughter element, such as lead, in a rock or mineral, and knowing the rate at which the parent isotope decays, it is possible to calculate the time during which radioactive decay has taken place. Such measurements are normally carried out using a mass spectrometer.

On the 17th December 1993 at the Curtin University of Technology, the Minister for Minerals and Energy, the Hon. George Cash, officially commissioned a new-generation mass spectrometer specifically designed to undertake such isotopic measurements within microscopic zones of individual mineral grains. The Sensitive High-Resolution Ion Microprobe (SHRIMP), now fully operational in Perth, promises to revolutionize our understanding of the geological evolution of the Australian continental crust. Western Australia contains a high proportion of rocks that are too old to contain fossils that can be used for dating purposes, and geochronology is therefore essential for the correlation of rock units and the investigation of possible links between regional geological events and mineralization processes throughout the State.

The prototype SHRIMP was designed and constructed at the Australian National University (ANU) in Canberra under the direction of Professor Bill Compston, and has been operating since 1982. This instrument has received international acclaim for its unrivalled ability to rapidly and precisely date geological samples, including samples that have experienced complex geological histories and that cannot be dated by more conventional techniques. It uses a beam of high-energy oxygen ions to ablate ionized material from a 30 micron area of a suitable target mineral, such as zircon. These ablated (or 'secondary') ions are passed into a high-resolution mass spectrometer for analysis. An analysis of a single mineral grain typically takes about 30 minutes, whereas the dating of a representative population of zircons extracted from a suitable rock sample can be achieved during a 24-hour analysis session.

The SHRIMP consortium

The remarkable success of the prototype instrument in Canberra led the ANU to establish a venture to manufacture SHRIMPs for commercial sale. In 1989, geoscientists from the GSWA and the University of Western Australia, and a group of physicists and geologists from Curtin University of Technology, formed a consortium to attract funding for the purchase of a SHRIMP for Western Australia. The \$2 million raised to set up the SHRIMP facility in Perth was provided by the Australian Research Council, the State Government, and the two universities, and represents the largest sum ever acquired for a research instrument in Western Australia. Professor John De Laeter, Deputy Vice Chancellor for Research and Development at Curtin University of Technology, played a key role in the consortium's fund-raising success. That the funding was eventually achieved is testimony to his



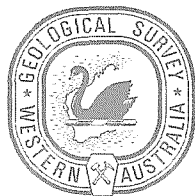
Dr David Nelson operating the W.A. consortium SHRIMP at Curtin University

vision and energy, and to the long and productive record of successful collaboration established by geoscientists from the GSWA, Curtin University, and the University of Western Australia. The facility is managed jointly by staff members from each of these three organizations.

SHRIMP and the GSWA

One of the key objectives of the Geology and Resource Information Program of the GSWA is to 'improve the knowledge of the geology of Western Australia and the quality of the regional geological, geophysical, and geochemical data and maps for use by industry, government, and the public'. If the GSWA is to continue to fulfil this role, particularly in the study of the vast, mineral-rich areas of Precambrian rocks throughout Western Australia, access to specialized geochronological facilities such as the SHRIMP is essential. Isotopic dating enables the precise correlation of geological and mineralization events, and allows these to be confidently placed in a broader geological perspective. The GSWA intends to use its access to the SHRIMP primarily to support its geological mapping program, in order to further improve the quality of the maps produced and maximize their value to all users, but particularly to support the minerals exploration industry in this state.

The use of the SHRIMP by GSWA geoscientists to investigate the formation of the Eastern Goldfields granite-greenstone terranes is the subject of a technical paper in this volume.



Facilitating access to environmentally sensitive land and sea areas and Aboriginal reserves of Western Australia

by A. J. Smurthwaite and V. Novak

Mineral and petroleum exploration, mining, and production are crucially important to the Western Australian economy. In 1993–94 they earned \$12.4 billion and paid \$411 million in royalties to the State and Commonwealth Governments. Their continued viability is dependent upon the existence of State Government policies that maximize access to all geologically prospective land and sea areas.

The end of 1993 saw the culmination of seven to eight years of painstaking effort by the GSWA under successive administrations to achieve a balance between resource development, Aboriginal interests, and nature conservation. As of mid-1994, industry can access all categories of reserved land and sea areas for resource assessment. The State Government now has three policy documents: Aboriginal, terrestrial, and marine. The following describes how this package came about and its principal features.

Of Western Australia's land area of 2.5 million km², some 10% is vested in the Aboriginal Lands Trust as reserves for the 'Use and Benefit of Aboriginal Inhabitants' proclaimed under the Aboriginal Affairs Planning Authority Act 1972. A further 7% is vested in the National Parks and Nature Conservation Authority (NPNCA) as national parks and various categories of conservation reserves or in the Lands and Forests Commission (LFC) as State forests and timber reserves. An additional 8% is proposed for reservation by the Department of Conservation and Land Management (CALM) in its regional management plans (e.g. Kimberley, Goldfields, South West Forests and South Coast).

Maintaining industry's access to this 25% of the State's land surface area is critical. The areas are relatively unexplored because of their remoteness and because of uncertainty in industry as to whether discoveries made on reserves could be exploited. Previously, the State Government was in the dilemma of having to decide about reservation proposals without adequate knowledge about their resource potential. Policies and procedures are now in place to facilitate exploration and, from the results obtained, to determine the relative merits of development as opposed to heritage and nature conservation.

The reservation of land and sea areas for nature conservation commenced in the latter part of the 19th century and has seen three periods (mid-1960s, 1970s, and early 1990s) of upsurge for new reserves.

Aboriginal reserves range in size from 0.5 ha to 79 797 km² whereas national parks and nature reserves vary in size from 56 ha to 15 000 km². Aboriginal reserves occur predominantly in the eastern and northern parts of the State. National parks and nature reserves are widely distributed but tend to be clustered in the South West. State forests are restricted to the South West whereas timber reserves are mainly in the goldfields and wheat belt regions.

The process of reservation is ongoing as areas of particular Aboriginal interest or ecological importance are progressively identified by relevant State

agencies or interest groups. The GSWA has a pivotal role in not only negotiating access to existing reserves but also in assessing the resource potential of proposed reserves or extensions to established ones. Large conservation reserves are commonly of interest to Aboriginal people for their traditional land practices and living areas. Consequently, their special concerns have to be increasingly taken into account during interagency and industry negotiations about access.

Aboriginal reserves

Most Aboriginal reserves were created early in the century with a small number being added over the subsequent years. Since they were established primarily for the protection of their Aboriginal residents, access to the reserves has always been controlled through the requirement for an entry permit, which must be obtained from the Minister responsible for the reserves, by everyone except Government personnel on official business.

Originally there were no specific legislative provisions guiding the grant of the entry permits and the decision was entirely at the discretion of the Minister for Native Welfare. Some earlier records, however, indicate that before issuing a permit to prospectors and miners, the Minister used to seek comments and approval of the Minister for Mines. In early 1966, the referral process between the two Ministers was formalized by a Cabinet decision which, however, was subsequently construed as preventing the grant of a mining tenement unless the entry permit had been guaranteed to be issued, thus reversing the original arrangements.

This practice continued unchanged despite the proclamation of the new Mining Act 1978, which introduced a statutory requirement for the Minister responsible for the Reserves to be consulted as part of the process of authorization of mining activities on the Reserves, but not necessarily prior to the tenement grant.

It appears that in the early years there were few difficulties with obtaining permits. The situation seems to have changed in the 1970s, probably partly as a result of various developments in the Aboriginal affairs area and partly due to the increased demand flowing from the upsurge in exploration activities. At the State level, the early 1970s saw the introduction of the Aboriginal Heritage Act for the protection of Aboriginal sites and the Aboriginal Affairs Planning Authority Act, replacing the old Native Welfare Act. No doubt the land-rights movement that led to the promulgation of the Aboriginal Land Rights (Northern Territory) Act 1976 also had a considerable effect as it raised expectations of Aboriginal people across the nation for more control and autonomy in the management of the Reserves.

Whatever the reasons may have been, permits became extremely difficult to get with the effect that some tenement applications were withdrawn by applicants out of frustration, some were refused at the recommendation of the Minister for Aboriginal Affairs, and others accumulated awaiting determination.

There were some attempts over the years to resolve the situation but with little success. The most promising was the establishment of a three-member Entry Permit Committee in 1986 intended to reconcile the difference between the mining industry and Aboriginal interests. But even the committee found the task too hard and very little changed.

More recently the situation became even more complex as a result of the Minister for Aboriginal Affairs' requirement that an agreement between mining companies, the Aboriginal Lands Trust, and a local Aboriginal body be reached as a prerequisite for the entry-permit grant. The agreement concept was broadly modelled on the Northern Territory regime, and aimed at defining the rights and responsibilities of all parties and forming a basis for conditions of the entry permits. Although well intended, in practice, however, the differences of opinion remained, particularly on the methodology of Aboriginal heritage protection and the duration of the agreements, and negotiations of agreements turned into an extremely time-consuming and costly process. As a result, only three agreements, allowing two exploration projects on the Central Australian Aboriginal Reserve and one on the Forest

Reserve, were completed by the second half of 1993, with about 250 tenement applications still awaiting determination.

By then it had already become obvious that the old practice of delaying the granting of tenements until entry permits have been issued is not desirable and the formulation of individual agreements for each mining project is entirely impractical. This led to renewed efforts by the Department of Minerals and Energy (DME), with the cooperation of the Aboriginal Affairs Planning Authority, to develop a policy that would more appropriately reflect the current statutory provisions in regard to the authorization of mining activities on Aboriginal reserve land, and facilitate negotiations between the mining industry and Aboriginal groups in relation to land access.

Following consultations with major industry groups and Aboriginal interests, a new policy was designed, and was endorsed by State Cabinet on 13 December 1993.

The policy involves the following principles:

- mining activities around Aboriginal communities on Reserves will be restricted at the discretion of the Minister for Mines to prevent social disruption to the residents;
- mining tenements will be granted subject to the applicants' compliance with the provisions of the Mining Act 1978;
- a standard access agreement, which would cover access for all phases of mining activity while allowing renegotiation of compensation before the commencement of mining operations, will be adopted;
- subject to the compliance with the access agreement, the tenement holder will be granted consent to mine and an entry permit for the Reserve;
- the Ministers for Aboriginal Affairs and Mines will jointly appoint an independent mediator if the parties cannot reach an agreement within 30 days. In the case of the failure of the mediator to resolve the matter, the Minister for Aboriginal Affairs will make a determination within a further 30 days period.

The policy enabled the processing of most of the 250 outstanding tenement applications by the end of December 1993. The tenements have been granted on 'non-mining' condition, which will be removed once their holders have obtained the entry permit, and the Minister for Aboriginal Affairs has made a recommendation in regard to the written 'consent to mine' required to be granted by the Minister for Mines under Section 24 of the Mining Act.

The fulfilment of the obligations of the Minister for Aboriginal Affairs will be assisted by a standard access agreement currently being finalized for endorsement by Cabinet in the near future.

While the policy was under consideration, the State promulgated a new legislation, the Land (Titles and Traditional Usage) Act 1993, which contains statutory provisions for consideration of traditional usage rights before the grant of mining tenements.

The access to Reserves will, therefore, be subject to two slightly different regimes, one affecting the tenement applications lodged before 2 December 1993 when the Act came into existence, and another which applies to applications received after that date. It is, however, expected that some elements, such as the standard access agreement, could be used in either process.

Neither the new policy nor the legislation have been in existence long enough to enable assessment of their success. However, both have an ability to adequately cater for the Aboriginal as well as the mining industry's interests, and make the negotiation process more efficient and cost effective for both parties.

National parks and nature reserves

The question of access to national parks and nature reserves came into prominence when the Mining Act 1904 was replaced by the Mining Act 1978 and put into effect in 1982. The Mining Act stipulates that the concurrence of the Minister for the Environment is mandatory before the Mining Act tenements can be granted in conservation reserves. Since then, there have been four major reviews and three policy formulations for exploration of terrestrial nature reserves, State forests, and national parks. The January 1994 policy emphasises the provisions of the Mining Act 1978, Conservation and Land Act 1990, and Environmental Protection Act 1986 to protect the environment during exploration and mining. The three Acts combine to achieve enforceable environmental safeguards and ecologically sustainable rehabilitation.

The DME, CALM, and the Department of Environmental Protection (DEP) collaborated to oversee exploration and mining, and have enabled the State Government to increase the areal extent of nature reserves and national parks without impeding the investigation, identification, and exploitation of major resource areas such as the D'Entrecasteaux, Kennedy Range, Rudall River, Watheroo, Francois Peron, and Karijini National Parks. The creation of 670 Class A and 65 Class C nature reserves has also resulted from this process. Work continues with respect to evaluating the proposed extension to the Cape Range National Park and the proposed upgrade of the Dampier Archipelago to a national park.

Exploration of conservation reserves and environmentally sensitive areas is arranged under the procedures in two phases: a non-ground disturbing and a ground-disturbing phase. The involvement of CALM and DEP is greater in the second phase. The DME plays an important role throughout the proposed exploration of national parks and nature reserves: not only does its environmental officers assume responsibilities to monitor the effects of field activities but its geologists assess the resource potential of the ground applied for as well as the competence of the planned exploration program. In this way, genuine explorers are supported whereas those seeking commodities such as gravel and sand, which can be found on land outside parks and reserves, are barred from entering reserved land.

Environmental conditions appropriate for each reserve category and exploration phase have been formulated. They are based on experience gained over the past eight to ten years; and ensure that minimal impact on conservation values occurs during the course of exploration. The Minister for the Environment has to give his concurrence before prospecting and exploration leases are approved by the Minister for Mines. This process has resulted in the grant of nearly 900 Mining Act tenements in nature parks and nature reserves over the past few years.

The Environmental Protection Authority (EPA), through the DEP, has devolved much of its environmental-impact assessment responsibilities to CALM and to CALM's two policy bodies, the National Parks and Nature Conservation Authority (NPNCA) and the Lands and Forest Commission (LFC), as well as to the DME as the principal agency for mineral exploration and mining. However, this devolution does not mean that the DEP cannot process any referral made to the EPA by any person at any stage in the exploration/mining sequence. DEP will seek the advice of CALM, DME, and the NPNCA (or LFC) before reporting to the EPA. It is then the EPA's decision whether or not to formally assess the exploration or mining project.

Marine parks and nature reserves

Western Australian coastal and marine environments are very prospective for mineral and petroleum resources. In 1988, access for petroleum exploration into the State's existing marine parks (Marmion, Ningaloo, Rowley Shoals, and Shark Bay) was under review. Marine parks and nature reserves comprised 11 442 km² (or 10%) of the 110 000 km² of the offshore waters that came under State Government jurisdiction.

Section 13 of the Conservation and Land Management Act 1984 provides for the reservation of waters as marine parks and marine nature reserves. The Act also provides for the establishment of land portions of marine parks and

marine nature reserves under the Land Act 1933 (under review). Vesting of these areas is in the NPNCA.

Marine parks are created in recognition of biological conservation, recreational, and aesthetic values. The purpose of marine parks is for the conservation of flora and fauna along with public recreation. The CALM Act specifically provides for fishing (commercial and recreational), managed under the Fisheries Act 1905 (under review), in marine parks. There are six marine parks ranging in size from 350 ha (Swan Estuary) to 748 735 ha (Shark Bay).

Marine nature reserves are selected for their ecological and biological values. Their purpose is to ensure stringent biological conservation with far less emphasis on public recreation access and no extractive activities. The Hamelin Pool marine nature reserve (132 000 ha) is the only such reserve in Western Australia.

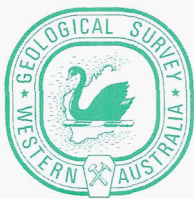
A special task force was commissioned by State Government in mid-1993 to negotiate procedures and to agree about respective areas of environmental responsibility between DME, CALM, and DEP for marine parks and reserves. Considerable time and effort were required because of the complexity and acute ecological sensitivity of the marine and coastal localities.

Draft procedures have been agreed between State agencies covering seismic survey, exploration, and production permits. Each marine park, marine nature reserve, and marine management area category has been afforded its set of environmental safeguards. Marine parks and reserves have been given a defined depth of 200 m and all exploration on existing permits is subject to EPA approval. Zonation of existing marine parks is presently being evaluated with respect to petroleum and fishing interest. It is likely that a marine Authority will be established.

The creation and declaration of new marine reserves will require detailed biological and resource assessment of the 70 proposals recommendations contained in the May 1994 report of the Marine Parks and Reserves Study Group. Some ten to fifteen years of careful investigation lie ahead.

Conclusion

The role of achieving a balance between resource development and nature and heritage conservation is unending. More sophisticated exploration techniques and revised geological models compete with the acquisition of biological knowledge and pressures for new and larger conservation reserves. This dual process reflects the aspirations of a post industrialized society, which, while wanting the benefits of an economy based on the State's rich mineral endowment, is very mindful of its responsibilities for the well-being of indigenous people and management of an irreplaceable environment.

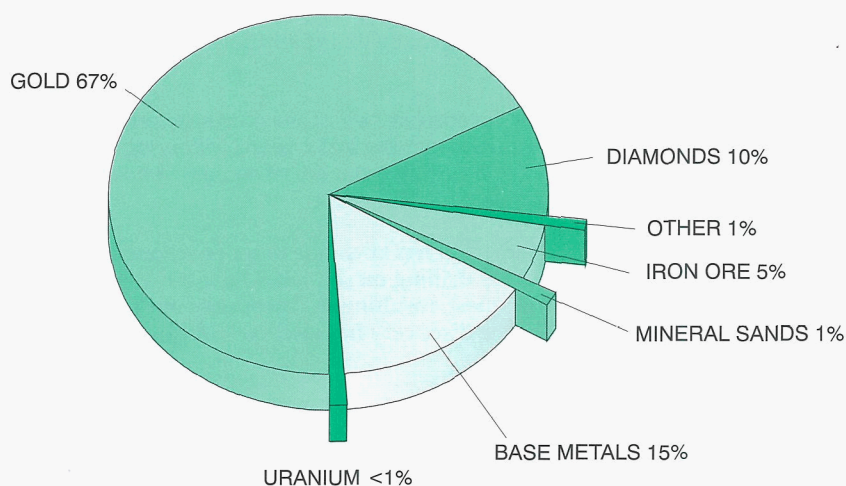


Exploration in Western Australia

by P. Guj, W. Preston, V. Novak, and J. Blockley

Establishment of a modern minerals industry in Western Australia began effectively in the 1960s. After 70 years of producing mainly gold and coal, the range of commodities spread rapidly over the succeeding ten-year period to include bauxite-alumina, heavy-mineral sands, iron ore, nickel, salt, talc, and petroleum. In addition to gold, the production of all these minerals has increased considerably since then. Diamonds have also become a major new addition, and, on a lesser scale, tantalite, spodumene, and base metals have added to the diversity. In 1993–94 the value of mineral production was an estimated \$12.6 billion and export earnings around \$11 billion. The industry is clearly of crucial importance to the State, and indeed to Australia. On the world scene, Western Australia is a major source of nine of these commodities.

Exploration is the lifeblood of the long-term future of mining. Its importance to Western Australia cannot be overstressed, not only in terms of sustaining current levels of production, but also in terms of growth potential. Continuing discoveries, not only in 'virgin' territory, but also in areas worked-over for the last 100 years, indicate that the geological prospectivity of Western Australia is far from fully defined. Perhaps many of the easily won, near-surface deposits have now been delineated, but deep weathering and surficial cover over about 90% of Western Australia make the discovery of concealed or 'blind' orebodies a continuing challenge to the ingenuity of the explorer.



Source ABS

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Figure 1.
Mineral exploration expenditure
1993–94 in Western Australia

About \$450 million was expended on mineral exploration in 1993–94, split as shown in Figure 1, and an estimated \$210 million was spent on petroleum exploration. This is commensurate with the importance of the Western Australian industry compared with that of the other Australian states. These levels translate to 57% of Australia's total exploration expenditure on minerals and over 40% on petroleum. At the end of June 1994 there were about 12 500 active exploration and 6 700 development titles under the State's Mining Act, covering about 11% of the State's 2 500 000 km² area.

Similarly there were 123 exploration permits plus drilling reservations out of a total of 190 titles in force under petroleum legislation.

Gold

Gold currently attracts the highest proportion of exploration spending in the minerals sector, with around \$300 million recorded for 1993–94, which is about two thirds of Australia's total exploration budget for gold.

Following the exponential growth in gold production in the State through the 1980s, most commentators were predicting a decline in output during the

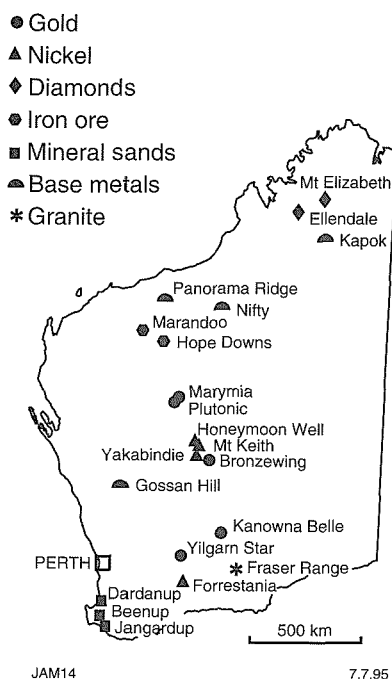


Figure 2.
Recent significant mineral discoveries and
new developments in Western Australia

1990s as additional resources became more difficult to discover; however, new discoveries continue to be made, and gold production continues to climb, albeit, at a lesser rate than previously.

Increasingly sophisticated geochemical, geophysical, and geological techniques are being used to find new orebodies under considerable thicknesses of overburden, or to locate extensions or repetitions of deposits worked in the many relatively shallow pits opened up during the 1980s boom. One measure of the current success is the addition to the measured and indicated resources inventory of the State between 1993 and 1994. The combined estimate of nearly 2800 t (89 million ounces) of contained gold is over 450 t (14.7 million ounces) higher than the estimate for the previous year. Taking into account the 183 t (5.9 million ounces) produced during 1993, the newly defined/upgraded gold resources approach 650 t (21 million ounces): a very substantial figure for \$260 million expenditure and one which, if continued, could sustain current levels of production well beyond the turn of the century. At \$0.4 million/t or just over \$12.5/ounce of gold in the ground this represents, on average, excellent value for the exploration investment. It should be noted, however, that this was an exceptional year for major resource announcements because the discovery costs over the past 10 years have averaged around \$23/ounce.

Although the share market crash of 1987 and the imposition of a tax on gold dampened investor enthusiasm for the metal for a number of years, more recent discoveries, some extremely large, have since generated a high level of new interest. The Plutonic discovery of 1988 led to a rush to the Marymia Dome, a relatively neglected granite-greenstone inlier to the north of Meekatharra (Fig. 2). The success has resulted in two operating mines in this new region and substantial defined resources in the nearby Freshwater leases.

Yilgarn Star, near Marvel Loch, was the next discovery to 'whet the appetite' in 1990, followed by Kanowna Belle, the true worth of which unfolded through 1991. Current resource estimates indicate that the total contained gold is 127 t (over 4 million ounces). Hidden below 40 m of 'overburden', but adjacent to a long-standing deep-leads production centre, Kanowna Belle truly has rekindled greenfields exploration in the Eastern Goldfields.

The current rush to the Yandal Greenstone Belt of the Northeastern Goldfields has been the major move over the last 2 years, following the discovery of Bronzewing (83 t or 2.7 million ounces of contained gold to 500 m depth).

The belt from Kambalda to Norseman has been one of quiet achievement for a number of years. Techniques for drilling on salt lakes have proven an important success factor in this quest, resulting in discoveries at St Ives and beneath Lake Cowan. The Chalice discovery has also excited considerable interest.

Nickel

A sharp rise in prices in 1988 rekindled the long-dormant interest in nickel in the State, with most effort focused on deposits discovered during the nickel boom of the late 1960s and early 1970s. Activities largely involved resource delineation and evaluation of these deposits, with little greenfields exploration being undertaken. Most of these projects subsequently reverted to a holding position as prices plummeted, but two, Forresteria and Mount Keith, have moved into development. The first was to secure supply of concentrate for Outokumpu's Finnish smelters, and the second formed a major part of a bold expansion strategy by WMC (from 55 000 to 90 000 t of contained nickel output per annum) to ensure its continued position as a substantial world producer of nickel.

Expenditure on nickel exploration in the State is estimated at \$25–30 million per annum over the last four years. Almost half has been dedicated to the Northeastern Goldfields, where, in addition to Leinster, the evaluation of low grade (0.6–0.9% Ni) sulfide bodies in the Mount Keith, Yakabindie,

and Honeymoon Well projects has been the focus (Fig. 2). Major exploration drilling has recently been undertaken on Honeymoon Well, where a resource of over 90 Mt has been defined, and CRA has just announced that it is optimistic in progressing through to a feasibility study.

About 40% of the exploration effort is dedicated to the rest of the Eastern Goldfields (mainly Kambalda–Widgiemooltha), with the other 10% widely spread throughout the State. Of these other areas, the Maggie Hays prospect, to the northeast of Forrestania, is the only one on which there is significant activity at present.

Base metals

It is estimated that base-metal exploration has varied over the last five years in the range \$15–\$25 million per annum. Activities are spread widely throughout the State in a variety of geological settings and mineralization styles, including Mississippi Valley-type (MVT), volcanogenic massive sulfides (VMS), sediment-hosted, and shear zone-type associations.

MVT lead–zinc mineralization is characteristic of the Lennard Shelf in the Kimberley region. Exploration undertaken mainly by BHP and Billiton over a period of 20 years located a number of prospects, but only the high-grade Cadjebut deposit was brought into production. Reserves for Cadjebut are now nearly depleted, but the new owners of the project, Western Metals, may develop the nearby Kapok deposit to extend the life of the operation. Regional exploration on the Lennard Shelf is currently at a very low level, with projects such as Blendevale being placed on hold. Work on other MVT deposits, such as Sorby Hills in the Bonaparte Basin, and Admiral Bay, located at a depth of around 1.4 km in the central Canning Basin, has also been suspended.

VMS copper–lead–zinc–silver mineralization continues to be investigated in the Kimberley region near Halls Creek, but the main focus of activity is the Panorama project in the North Pilbara region (Fig. 2). Outokumpu has committed to spending \$2 million per annum and, so far, indicated resources of 7.5 Mt at 4.5% Zn, 1.3% Cu, and 23 g/t Ag plus a further inferred 3.2 Mt have been announced for the Sulphur Springs prospect. A number of other promising prospects are still to be fully investigated in the general region. The Golden Grove Joint Venture, with its Scuddles zinc–copper mine south of Yalgoo, is another major explorer. It has recently announced its intention to carry out underground evaluation on its Gossan Hill copper–gold deposit, 4 km southeast of Scuddles.

The Nifty copper mine, located in sedimentary rocks of the Yeneena Group, started operations late in 1993. It represents the first development after more than 10 years of detailed, systematic exploration for sediment-hosted base-metal deposits in this sequence. The other region of significant untapped potential is the inland Gascoyne, where the Glengarry, Earaheedy, and Bangemall Basins are the focus of attention. Renison Goldfields Consolidated recently announced pre-resource figures of 220 Mt at 2% Pb for its Magellan prospect in the southern Glengarry Basin.

Various prospects in the Yilgarn and North Pilbara greenstone belts, which were worked in earlier cycles, are also periodically re-examined.

Diamond

Over the past two years there has been a marked revival of interest in diamond exploration that has been reflected in the stock market. The ability of new companies to raise equity through floats has progressively improved of late, and many exploration companies with a strong, in some cases exclusive, portfolio of diamond prospects have been placed in a position to mount vigorous exploration programs.

Over three-quarters of the diamond exploration dollar in Australia is currently being spent in this State. At an estimated \$46 million for 1993–94, this is the highest level since the surge following the Argyle discovery in 1979. Although the Kimberley region, both onshore and offshore, provides the main focus of activity, areas such as Nullagine and the Nabberu and Bangemall Basins also feature prominently among the areas being assessed.

There are at least 20 exploration companies seriously active in the diamond search, with offshore channel accumulations, alluvial concentrations, and pipes all being targeted.

One of the most advanced of the prospects is the Aries pipe at Phillips Range (Mount Elizabeth) in the central Kimberley region (Fig. 2). Here an \$8 million program, including a shaft and access drive, is planned to facilitate bulk sampling. Earlier bulk testing and diamond marketing have indicated a high gem percentage of around 90%. Other advanced-stage prospects on which bulk sampling is being carried out include Ellendale Pipe 17, in the West Kimberley, and Beta Creek, in the north of the East Kimberley. Recent exploration offshore in Bonaparte Gulf represents a new phase in the search for diamond in Western Australia, with some encouraging finds of gem-quality stones being announced.

Iron ore

From a stable base of around \$10 million per annum, expenditure on exploration for iron ore increased significantly to \$36 million in 1991–92 and has remained at a relatively high level ever since. This rise has largely reflected a move towards finding further sources of ore to sustain existing operations, and has been due mainly to additional evaluation of deposits held since the 1970s, although some greenfields exploration is also included.

Major deposits that have been subjected to further detailed drilling include Marillana Creek, Jimblebar, Deepdale Mesa J, Marandoo, Yarrie, Yandicoogina, Hope Downs, and Mining Area C (MAC; Fig. 3). Of these, the first three have been brought into production, while development is proceeding at Marandoo and Yarrie.

The search for new deposits has focused mainly on detrital ores, particularly those in buried stream channels, and new methods of locating concealed bodies of premium-grade hematite ores are also being investigated. Such ores will be needed to maintain Western Australia's position as a supplier of high-grade lump ores to the international market.

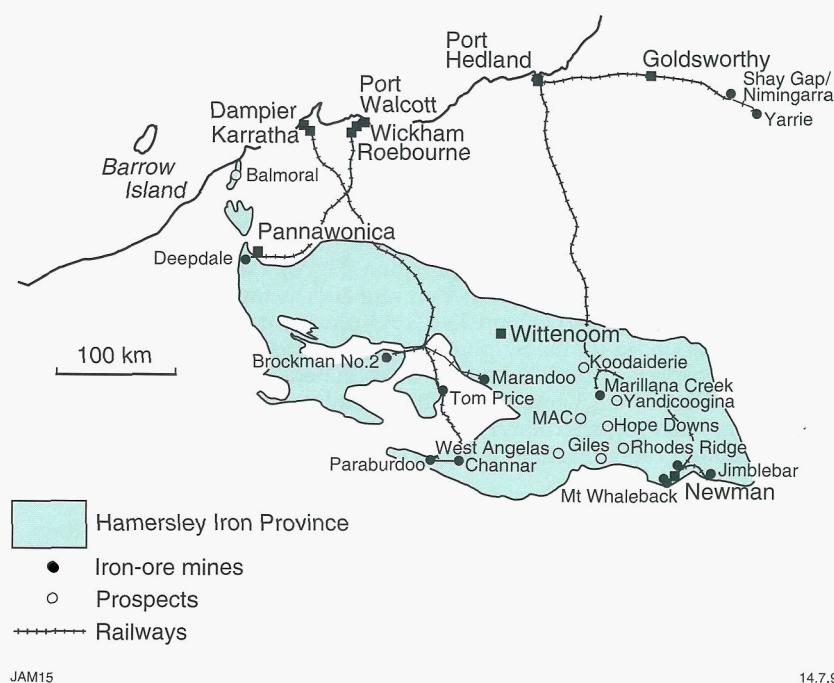


Figure 3.
Prospects and developments in iron ore
in the Pilbara Region

Another factor contributing to the rise in expenditure is the promotion of smaller operations, often linked to boutique integrated iron and/or steel-making proposals, that has led to the revisiting of a number of 'long forgotten' deposits like Koolyanobbing, Talling Peak, and the Fortescue banded iron-formation deposits.

Other minerals

A number of commodities, such as bauxite in the Darling Range, have a large resource base, and exploration is largely restricted to annual upgrading of sufficient reserves to replace those exploited.

Heavy-mineral sands exploration has suffered due to the prolonged downturn in the industry, with the search for new deposits being restricted to some of the more promising areas on the Swan Coastal Plain, and in and around the D'Entrecasteaux National Park, where mining at Jangardup commenced in May (Fig. 2). The large Beenup deposit near Augusta was bulk sampled early in 1993 for market appraisal, but a decision on development has been delayed. Work on the Eucla Basin 'greenfields' region has essentially been abandoned.

The redevelopment of the Woodie Woodie manganese deposits by Portman Mining in the early 1990s brought about a minor resurgence in exploration for this mineral, aimed at maintaining production from these high-grade, but small and irregular orebodies. The Woodie Woodie operation closed in May 1994, but Valiant Consolidated has begun trial shipments to Japan from the nearby Mike deposit.

Interest in PGE exploration has waned in the State in recent years, except for one prospect at Range Well – Weld Range in the Murchison district where chromite in lateritic zones is also being evaluated for possible separate development.

Similarly, the search for rare-earth elements (REE) has declined because international markets are flooded with supplies from China. The Mount Weld project, near Laverton, has been put on hold until the situation improves.

Petroleum

Western Australia continues to be the main focus for petroleum exploration in Australia, attracting between 40 and 55% of the total expenditure over recent years. In 1993, the figure was estimated at over \$260 million, but could fall to below \$230 million in 1994 (i.e. just below 40% of the total estimated for Australia).

The drilling success rate since the early 1980s has been maintained at an exceptionally high level and the continuing development of new fields is testament to this success. As well as the massive Goodwyn gas-condensate development, carried out as part three of the North West Shelf Joint Venture project, a major oil development has recently come onstream at Griffin, and other significant developments are taking place offshore in the Carnarvon Basin at Wanaea–Cossack, Roller–Skate, and Wandoo (Fig. 4). These developments are progressively leading Western Australia towards becoming the premier oil-producing region in Australia as reserves are depleted in Bass Strait. In 1993–94 the total value of petroleum production (including LNG) in the State was close to \$2.6 billion.

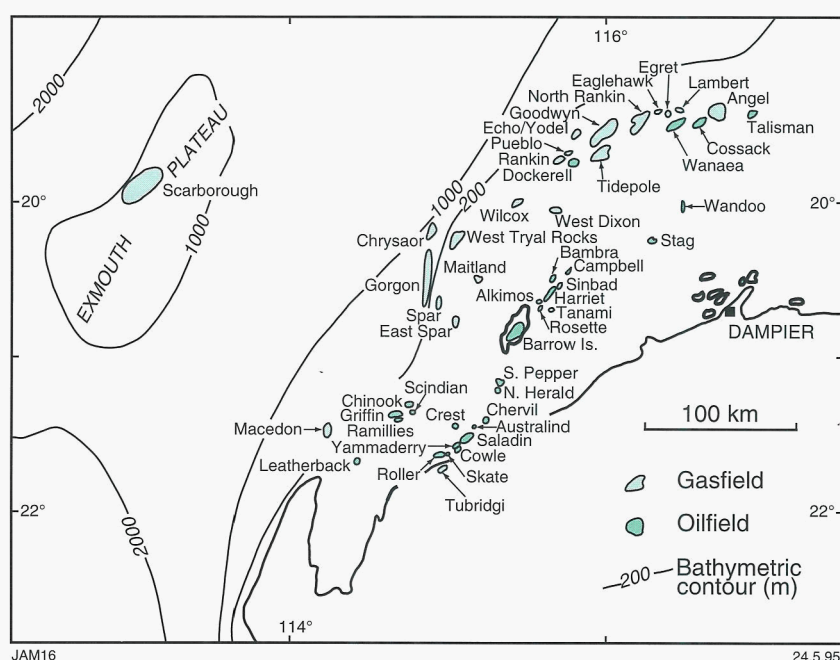


Figure 4.
Petroleum discoveries in the Northern
Carnarvon Basin

Exploration, and particularly drilling, are closely related to world petroleum prices. Drilling in 1993–94, at nearly 60 800 m, was up significantly on the previous year. Of the 28 new-field wildcat wells spudded, three resulted in discoveries.

With such success, the focus on the Carnarvon Basin is understandable, with the region attracting nearly two-thirds of wildcat wells and the bulk of appraisal and development drilling. Despite this activity, there has been very little exploration for petroleum in the State's large onshore sedimentary basins, even though they may offer considerable potential for future discoveries. The number of exploration petroleum titles is, however, increasing and it is pleasing to see increased interest, particularly in the onshore Canning Basin.

A total of 140 000 line km of seismic acquisition was recorded from 58 surveys in 1993. Some 91 300 km were attributed to three-dimensional surveys, mostly in the Carnarvon Basin. This technique is proving to be an invaluable tool in reinterpreting the geology of this basin, and should result in a major rise in future exploration, particularly in the offshore areas.

The Perth Basin is also attracting further attention, with the three-dimensional seismic survey at Dongara the first of this type carried out onshore in the State.

Land access

Relatively unrestricted access to large areas of land for exploration activities is one of the most significant requirements to ensure success of the mining and petroleum industries.

Although in a legal sense there have been few impediments in that regard, in reality past policies and practices made access to certain categories of land such as conservation estate and Aboriginal reserves extremely difficult. The situation became further complicated as a result of the High Court's decision in June 1992 to recognize a form of common-law native title. This has the potential to restrict the availability of some Vacant Crown Land (which represents over one third of the land area of the State) to industry's activities. Resolution of this issue is likely to be one of the greatest challenges confronting the industry for some time into the future.

In an attempt to offset the effects of the Federal legislation, the State introduced the West Australian Land (Titles and Traditional Usage) Act 1993 that brings common-law native title into a single land management system and enables the grant of mineral and petroleum titles by the State with minimum delays.

At the time of writing there is still uncertainty as to how this legislation will operate in light of the Federal Native Title Act which became operational on 1 January 1994. With time, policies and procedures will no doubt be established to reconcile the legitimate aspirations of Aboriginal people with the economic need to maintain exploration and development. In the meantime, however, the uncertainty surrounding security of tenure is likely to continue to act as a strong disincentive to investment in exploration.

Other recent measures to improve land access have included:

- the establishment of a Geoscientific Survey Permit to facilitate exploration activities not likely to disturb the ground, on conservation and Aboriginal reserves;
- the streamlining of environmental conditions attached to the granting of tenements and updating of guidelines for their application;
- the adoption of a new policy for access to Aboriginal reserves that has enabled the granting of almost 250 mining tenement applications, some of which were outstanding for a number of years.

Conclusions

Although Western Australia is still the scene of a large and growing exploration industry, many observers point out that for Australia as a whole, factors such as land-access problems, delays in approvals, restrictive work practices, and now security of title over any exploration discovery are causing an increasing proportion of exploration capital to be spent overseas.

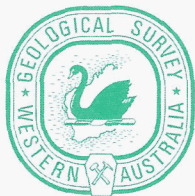
It has been estimated that around 26% of the exploration budgets of Australian exploration companies are now targeting overseas prospects. This includes over 30% of the budgets of the 15 biggest mining companies in the country.

Thus, even though levels of exploration activity in Western Australia are growing, the State cannot afford to become complacent. A number of Government and Departmental initiatives are taking place, and others are being proposed, to counteract the above disincentives. Some of the most significant include:

- the provision of a geoscientific framework for exploration, by an accelerated program of geological, geochemical, and airborne geophysical mapping to supplement the substantial level of regular activity in this area already undertaken by the Geological Survey;

- a computerized graphical mining titles system (TENGRAPH) to facilitate companies' identification and pegging of available ground and related administration, which is already available for the Kalgoorlie region and will eventually extend throughout the State;
- amendments to petroleum legislation to stimulate exploration in remote offshore basins;
- proposed further stimulation of onshore petroleum exploration through the funding of basic airborne geophysical mapping and basin studies, hopefully including some stratigraphic drilling and geochemistry.

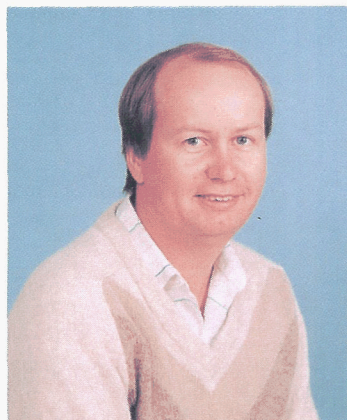
The GSWA prides itself on the range and quality of services provided to industry and is actively seeking resources to allow these to be extended to encompass such initiatives as geographic information systems for geological and exploration data.



Inside the GSWA

The GSWA is staffed by people from a variety of backgrounds with a wide range of skills and interests. Profiles of three staff members are presented here.

Hugh Thomas



Hugh Thomas, our whimsical, liberally talented curator of the Geological Survey Museum, was born near Llantrisant ('Church of the Three Saints'), Wales, in 1952. He left school at eighteen to work with Barclay's Bank, rather than down a coalmine, and three years later migrated to Western Australia and a boring job in a local bank. This tedious tenure was terminated when a phone call to the Survey was rewarded with near-instant hiring as a Geological Assistant. Hugh thus became, as he put it, 'part of the 1974 draft'.

Following several years of bushwork — bore census, seismic surveying, damsite investigation etc — in the Pilbara, Metro, and South West regions, Hugh's professional life took a major turn when an enlightened management placed him in charge of the museum. It is plain to see that from this time, both Hugh and his domain have thrived. Not only are his design and display skills evident in the mix of static and dynamic exhibits on the ground floor, Hugh also gains a quiet enjoyment from talking to the increasing numbers of teachers and students as the fame of his museum spreads.

At this point, he sees his future at the Survey intrinsically bound with that of the museum, especially in developing educational programs and documenting and displaying the extensive, and beckoning, collection of historical non-geological items. Hugh asserts that in no small measure his contentment here lies in the freedom he's been given to follow up his ideas. This enthusiasm is underscored by his having recently completed the Certificate in Museum Studies at Edith Cowan University.

On a personal note, Hugh Thomas married his wife Christine in 1981 and they have two boys and a girl of ages two to ten. He lives in 'the Hills', collects model Formula 1 racing cars and, not all that long ago, retired from active participation in his other passion — playing rugby for the Kalamunda club as a centre/winger.

Hugh's priceless asset is his great good humour: he inevitably brightens the lives of friends and colleagues alike.

Although he has only been with the Survey for just over a year, Franco Pirajno is well known throughout the Survey as the gung-ho Project Manager of the Glengarry Basin Geological Mapping Team.

Franco was born in the delightful town of Treviso near Venice and grew up in Naples in the shadow of Mount Vesuvius, from which his inspiration came to become a geologist.

Franco completed his doctorate in Geological Science in 1963 at the University of Naples and began his career with a postdoctoral research position at the Vesuvian Volcanological Observatory. He subsequently joined Anglo American Corporation as an exploration geologist. This work took him from Europe to Africa, southeast Asia, Australia, New Zealand, and the southwestern Pacific over a period of 19 years.

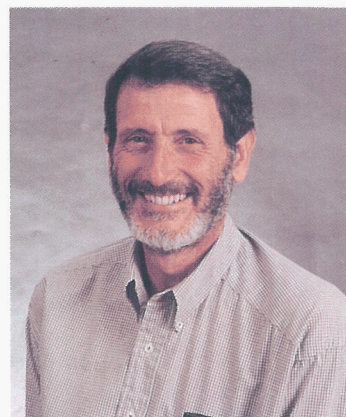
From 1983 to 1990 Franco was Professor of Exploration Geology at Rhodes University (South Africa) where he was also Director of the MSc course in Economic Geology. Franco moved to Australia in 1991 and worked as a consultant specializing in target generation, before joining the GSWA in 1993.

Franco has achieved many things in the course of his career. In addition to publishing many papers, he has published two books. He counts this as one of his more noteworthy achievements, but says he found writing a book a most humbling experience.

Franco is happily married, despite the fact that he dragged his wife off to the jungles of Northeastern Angola on a geological field trip for their honeymoon. He loves mountaineering, especially climbing volcanoes, and enjoys all the aspects of being a geologist, including travelling. He has a special interest in planetology, and enjoys studying ancient Roman history, when he's not studying geology.

Franco is a welcome addition to the Geological Survey, and is an enthusiastic and energizing member of the team.

Franco Pirajno



Laslo Kevi



Laslo Kevi was born in Hungary in 1928, but completed his tertiary education at the University of London (B.Sc. in Physics and Geology, 1961, and DIC in Applied Geophysics, 1962). He worked for six years with the Bureau of Mineral Resources, mainly on seismic-refraction, electrical resistivity, gravity, and radiometric projects. In 1968, he joined the Queensland Geological Survey, but left in the same year for Coffey and Hollingsworth Consulting Engineers as geophysicist responsible for engineering geophysical investigations in Queensland and Papua New Guinea. Between 1972 and 1979 he was an independent consulting geophysicist. For one year, in 1980, he worked for the Darwin section of the Northern Territory Geological Survey.

Laslo Kevi joined the GSWA in 1980 and became the chief of the Geophysics Section in 1983. In addition to supervising the activities of the section he continued to be active in geophysical fieldwork, controlling seismic-refraction surveys and regional gravity mapping. He retired in 1993 and moved to the east coast of Australia (Port Stephens) where he enjoys sailing and playing chess.



Technical papers

Are there terranes within the Lamboo Complex of the Halls Creek Orogen?	
by I. M. Tyler, T. J. Griffin, R. W. Page, and R. D. Shaw	37
Investigation of corrosion behaviour of friction rock stabilizers used in underground mines in Western Australia	
by J. Ranasooriya, G. W. Richardson, and L. C. Yap	47
The Collie Coalfield: a starting point for Permian Gondwana correlation in a transtension extensional basin	
by G. Le Blanc Smith and J. Backhouse	55
Base-metal deposits in the Early Proterozoic Glengarry terrane, Western Australia	
by G. Le Blanc Smith, F. Pirajno, D. Nelson, and K. Grey	59
Pillow lavas in the Peak Hill and Glengarry terranes	
by F. Pirajno, S. Occhipinti, G. Le Blanc Smith, and N. Adamides	63
Tectonic evolution and economic geology of the Paterson Orogen — a major reinterpretation based on detailed geological mapping	
by A. H. Hickman and L. Bagas	67
Radon-222 content of groundwater in Western Australia	
by P. M. Thorpe	77
Newly recognized Eocene sediments in the Beaufort River Palaeochannel	
by J. D. Waterhouse, D. P. Commander, C. Prangley, and J. Backhouse	82
U–Pb zircon dating of Archaean greenstones from the Eastern Goldfields	
by D. R. Nelson, C. P. Swager, A. L. Ahmat, and R. H. Smithies	87
Onshore northern Perth Basin gravity project	
by R. P. Iasky	92

Are there terranes within the Lamboo Complex of the Halls Creek Orogen?

by I. M. Tyler, T. J. Griffin, R. W. Page¹, and R. D. Shaw¹

Abstract

The Early Proterozoic rocks of the Lamboo Complex of the Halls Creek Orogen can be divided into three zones that are interpreted as separate terranes. The trend of the zone boundaries is interpreted to have been originally to the northwest, and these zone boundaries are thought to have controlled the development of younger fault systems.

The western zone has much in common with the Hooper Complex of the King Leopold Orogen in that it is dominated by 1860–1850 Ma felsic volcanic rocks and associated granitoids that have been intruded into metasedimentary rocks and mafic sills that are between 1870 and 1860 Ma old. The central zone is dominated by the low- to high-grade mafic and metasedimentary rocks of the Tickalara Metamorphics. These were intruded by granitoid sheets at c. 1860 Ma, before being deformed and metamorphosed at c. 1855 Ma. This was followed closely by the intrusion of layered mafic–ultramafic bodies. Felsic volcanic rocks were erupted at c. 1840 Ma. The eastern zone is dominated by the mafic volcanic and metasedimentary rocks of the Halls Creek Group, the upper part of which was still being deposited at c. 1855 Ma. All three zones were intruded by c. 1820 Ma granitoids and gabbroic rocks.

The presence of tectonostratigraphic terranes and the different geophysical nature of the basement on either side of the Halls Creek Orogen are consistent with the operation of plate tectonics during the Early Proterozoic development of northern Australia.

KEYWORDS: Halls Creek Orogen, Lamboo Complex, Proterozoic, terrane analysis, plate tectonics.

The Halls Creek Orogen developed initially during the Early Proterozoic (Page, 1976, 1988) between a postulated Kimberley Craton, underlying the Kimberley Basin to the northwest, and a composite craton that included Archaean rocks within the Pine Creek Geosyncline and possibly within the Granites–Tanami Inlier. Most of this composite craton is now overlain by Middle Proterozoic, Late Proterozoic, and Palaeozoic basins (Fig. 1). The different nature of these

two cratons is evident in geophysical data used to produce a basement-elements map of Australia (Shaw et al., 1994). The rocks which were formed during the Early Proterozoic orogenic event are exposed in the Lamboo Complex (Griffin and Grey, 1990), and consist of deformed and metamorphosed plutonic and volcanic igneous rocks and sedimentary rocks.

Hancock and Rutland (1984) put forward a tectonic model for the evolution of Early Proterozoic rocks in the east and west Kimberley in

which they identified a style of orogeny that they regarded as distinct from that which typifies Phanerozoic orogenic belts. Rather than being the products of a complete plate-tectonic 'Wilson Cycle' involving the subduction of oceanic crust, the King Leopold and Halls Creek Orogens were regarded to be the result of initial extension where large areas of thinned Archaean crust were formed, followed by convergence. The Halls Creek Group, a sequence of metavolcanic and metasedimentary rocks, was thought to occur throughout both orogenic belts, and this was used as evidence that crustal separation did not take place. The thinned Archaean crust subsequently underwent limited A-subduction (Kröner, 1981, 1983) producing deformation, metamorphism, and igneous activity.

This model was modified by Etheridge et al. (1987) and extended throughout the Early Proterozoic of northern Australia. They envisaged a linked polygonal system of rifts, formed above a series of small-scale mantle-convection cells. Extension resulted from gravitational spreading of the hot, uplifted belts that had been thickened significantly by underplating. Subsequent thermal relaxation and flexural loading produced sag basins overlying the rift stage. Orogeny was driven by lithospheric delamination during cooling and sediment loading. This orogenic event was regarded as essentially synchronous throughout northern Australia between about 1880 and 1850 Ma (Page, 1988; Page and Williams, 1988; Wyborn, 1988), and was referred to as the Barramundi Orogeny.

¹ Australian Geological Survey Organisation

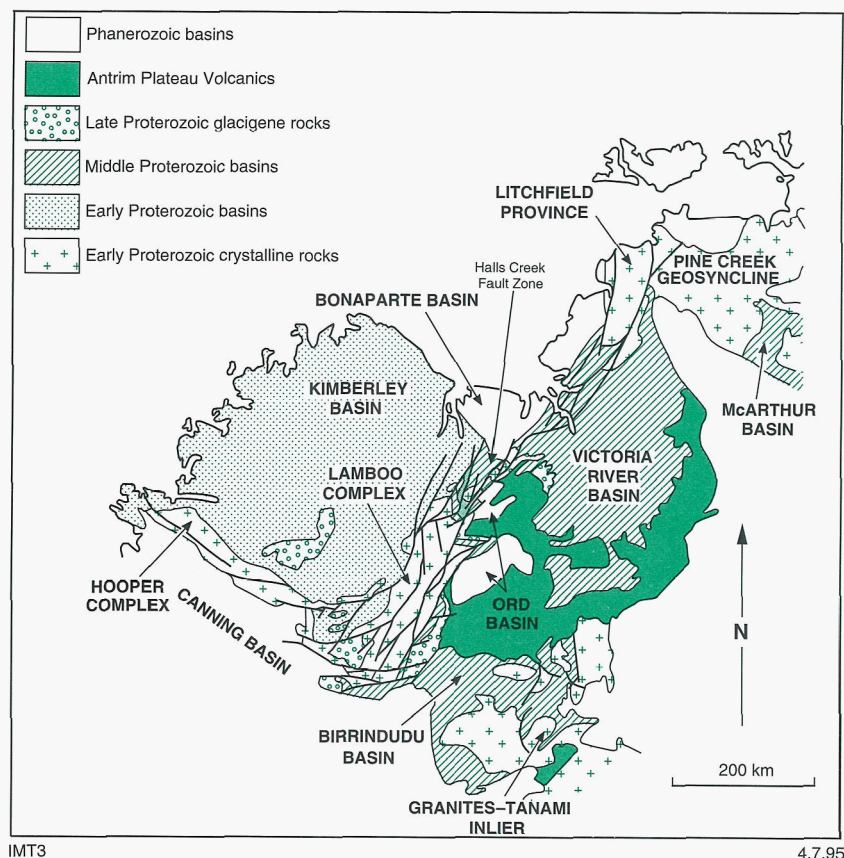


Figure 1. The main tectonic units of the Kimberley region

This intracratonic, essentially 'fixist', view of the Early Proterozoic evolution of Australia contrasts with the more dynamic views of workers on the Early Proterozoic of North America, Europe, and Africa. Recent models, such as those of Hoffman (1988, 1989, 1991) and Windley (1993), envisage the aggregation of Early to Middle Proterozoic continents by plate-tectonic processes similar to those operating in the present. Subsequent Middle and Late Proterozoic events involved the breakup of these continents, followed by the formation of a Late Proterozoic supercontinent (Hoffman, 1991; Dalziel, 1992). Myers (1993) has shown that the Precambrian history of southwest Australia can also be interpreted in a similar way.

Remapping of the King Leopold Orogen was commenced by the Geological Survey of Western Australia (GSWA) in 1986 (Griffin and Myers, 1988; Griffin, 1989; Tyler and Griffin, 1990, 1993; Griffin et al., 1993) and was subsequently

extended into the Halls Creek Orogen in 1990. The GSWA Halls Creek Orogen Project is being carried out in conjunction with the Australian Geological Survey Organisation (AGSO) as part of the National Geoscience Mapping Accord Kimberley-Arunta Project (Blake et al., 1991; Griffin and Tyler, 1992a; Blake and Hoatson, 1993; Hoatson, 1993; Hoatson and Tyler, 1993; Griffin and Tyler, 1994; Tyler and Griffin, 1994; Page et al., in prep.). This remapping, together with geochronological, geochemical, petrological, and remote-sensing studies, has allowed reassessment of the tectonic evolution of the King Leopold and Halls Creek Orogens.

The terrane concept

A terrane is defined as 'a fault-bounded body of rock of regional extent, characterized by a geologic history different from that of contiguous terranes' (Bates and Jackson, 1987, p. 679). Discrete terranes have been recognized

within the North American Cordillera along the margin between the oceanic Pacific and Juan de Fuca Plates, and the continental North American Plate (Coney et al., 1980). This led to its interpretation as a vast mosaic or collage of discrete allochthonous fragments of oceanic or continental crust that had been added to an active continental margin by accretion during subduction of the oceanic plates beneath the North American continent. Tectonostratigraphic terranes have also been recognized in other Phanerozoic orogenic belts (Hutton, 1987; Coney et al., 1990; Sengor et al., 1993), within Proterozoic orogenic belts (Kröner, 1985; Rivers et al., 1989; Park, 1991), and within the Archaean cratons (Card, 1990; de Witt et al., 1992; Myers, 1993), and in each case plate-tectonic processes have been invoked (Windley, 1993).

Hancock and Rutland (1984) divided the Halls Creek Orogen into four distinct zones, each with particular geological characteristics. Griffin and Tyler (1992a) subsequently reduced the number of zones to three, amalgamating zones II and III of Hancock and Rutland (1984). In this paper we also recognize three zones (Fig. 2), although the boundaries differ from those of the previous workers to take account of new data. The geological histories of these zones (Fig. 3), based on geochronological data and field relationships identified during remapping, can be compared to see whether the conclusions of Hancock and Rutland (1984) are upheld (that geological units, and deformation, metamorphism, and igneous events can be correlated between zones), or whether one or more of the zones actually constitute distinct tectonostratigraphic terranes with independent histories.

The eastern zone

The eastern zone is characterized by the low- to medium-grade meta-sedimentary and metavolcanic rocks of the Halls Creek Group. The oldest rocks within the zone, from which Sensitive High Resolution Ion Microprobe (SHRIMP) U-Pb ages of c. 1910 Ma have been obtained from zircons, are the bimodal volcanic rocks of the Ding Dong Downs Volcanics, and their associated high-

level granitoid intrusions (e.g. the Sophie Downs Granite). The Ding Dong Downs Volcanics were originally included within the Halls Creek Group (Dow and Gemuts, 1969), but the identification of an unconformity between the Sophie Downs Granite and the Saunders Creek Formation at the northern end of the Sophie Downs Dome (Griffin and Tyler, 1992a; Blake et al., in prep.) resulted in the redefinition of the Halls Creek Group by Griffin and Tyler (1992a) to exclude them.

The Halls Creek Group consists of three formations. The lowest unit is the Saunders Creek Formation, which is a thin fluvial sequence of cross-bedded sandstone and conglomerate. It overlies the Ding Dong Downs Volcanics and associated granitoids with minor angular discordance. The Biscay Formation consists of mafic volcanic rocks interbedded with minor felsic igneous rocks (with a SHRIMP U–Pb zircon age of c. 1880 Ma), and siliciclastic and calcareous meta-sedimentary rocks, and overlies the Saunders Creek Formation. The mafic volcanic rocks include massive and pillowed metabasaltic lava flows, together with fragmental, agglomeratic deposits, and fine-grained volcanoclastic deposits.

The Biscay Formation is overlain by the uppermost unit of the Halls Creek Group, the Olympio Formation, which consists of a monotonous sequence of turbiditic quartz wacke, greywacke, arkosic sandstone, and quartz sandstone, interbedded with siltstone and mudstone. Provenance and palaeo-current data obtained by Hancock (1991) indicate that at least part of the unit was derived from a predominantly granitic source to the northwest. A distinctive alkaline volcanic unit, the Butchers Gully Member (Griffin and Tyler, 1992a), occurs in the lower part of the Olympio Formation. This consists of trachyandesite lavas and intrusions, together with associated volcanoclastic deposits (Esselmont, 1990). SHRIMP U–Pb ages on zircons from a mineralized unit at the base of the member give a date of c. 1870 Ma (Taylor et al., in prep.). Remapping to the north of the Sophie Downs Dome (Blake et al., in prep.; Warren and Tyler, in prep.) indicates that the conventional zircon U–Pb age of



Figure 2. Map showing zones and zone boundaries within the Lamboo Complex of the Halls Creek Orogen

1856 ± 5 Ma obtained by Page and Hancock (1988), from what they thought to be the Biscay Formation, actually corresponds to a lava flow within rocks similar to those of the Butchers Gully Member. SHRIMP ages give a similar result. The two ages indicate that the lower Olympio Formation was deposited between 1870 and 1855 Ma.

The Halls Creek Group has been intruded by the Woodward Dolerite, which consists of a number of relatively thin, massive metadolerite sills that are conformable with bedding.

The earliest deformation (D_1) in the eastern zone involved layer-parallel shearing, with the development of mylonitic rocks at the contact between the Saunders Creek Formation and underlying rocks. Warren (1994) described an area where parts of the upper Biscay Formation and lower Olympio Formation stratigraphy are missing,

suggesting that this event was produced by extension. Shear criteria within the mylonites indicate that this extension was to the south. Thin phyllonitic zones occur along bedding planes within the Olympio Formation.

The second deformation (D_2) was pervasive, producing upright to moderately inclined folds at all scales, with horizontal to moderately plunging hinges. In the southern part of the zone, deformation was accompanied by medium-grade, low-pressure metamorphism.

To the southwest of Halls Creek the Mount Christine Monzogranite has been intruded into the Halls Creek Group. SHRIMP U–Pb ages from zircons indicate an intrusion age of c. 1810 Ma.

Deformed rocks of the Halls Creek Group are unconformably overlain by the Moola Bulla Formation, a

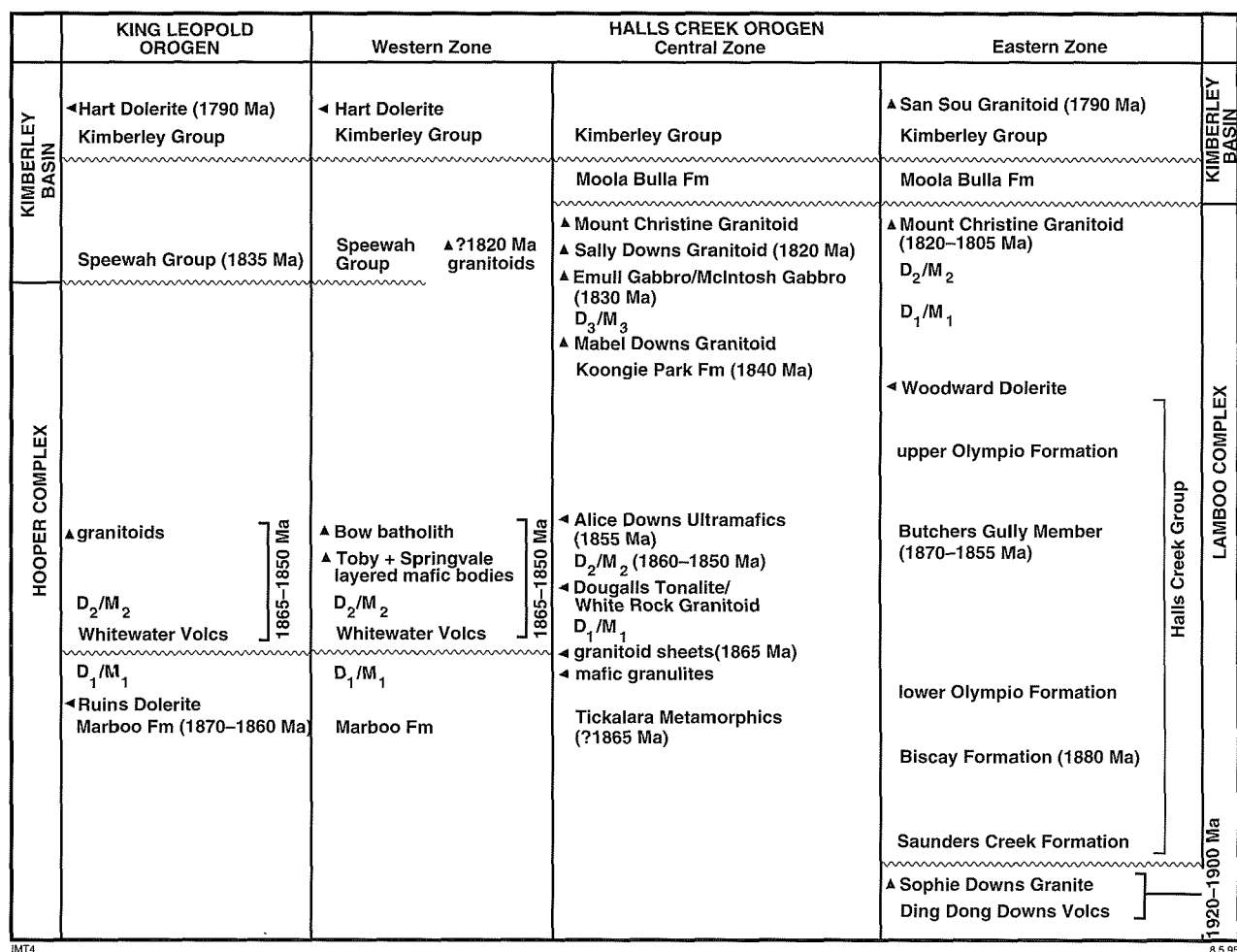


Figure 3. Comparative chart showing the geological histories of the Hooper Complex and zones within the Lamboo Complex

sequence of coarse clastic deposits of fluvial origin. The Moola Bulla Formation is itself overlain with minor angular discordance by the Kimberley Group, a sequence of fluvial and shallow-marine clastic deposits, and mafic volcanic rocks.

Towards the southern end of the eastern zone, the San Sou Monzogranite has been intruded into the Ding Dong Downs Volcanics and associated granitoids, as well as the Halls Creek Group. A SHRIMP U–Pb zircon age of c. 1790 Ma has been obtained from the San Sou Monzogranite.

The central zone

The boundary between the eastern zone and the central zone is taken as a combination of the Angelo Fault, the Halls Creek

Fault, and the Osmond Fault (Fig. 2).

The oldest rocks in the central zone are the Tickalara Metamorphics, a deformed sequence of interbedded mafic volcanic rocks, and siliciclastic and calcareous sedimentary rocks, which have undergone low- to high-grade metamorphism. Metamorphic grade increases from southwest to northeast along the zone. In the lower grade areas the mafic volcanic rocks consist of massive, amygdaloidal, and pillowed basaltic lava flows, together with fragmental, agglomeratic deposits, and fine-grained volcanoclastic deposits. The sedimentary rocks consist of interbedded mudstones, siltstones, and sandstones, together with mappable carbonate and calc-silicate units.

The Tickalara Metamorphics have been intruded by a number of

phases of both felsic and mafic magmas. Amphibolites and mafic granulites derived from intrusive rocks occur in the higher grade areas. Also present are layer-parallel sheets of granitoid that contain zircons which yield SHRIMP U–Pb ages of c. 1860 Ma. These units are affected by a strong layer-parallel fabric, which was produced during D₁. Although large-scale D₁ folds are not recognized, small-scale, layer-parallel D₁ isoclinal folds occur in the metasedimentary rocks. High-grade metamorphism (M₂) occurred synchronously with the second deformation (D₂), which produced tight to isoclinal, moderately inclined to recumbent folds on all scales. Extensive migmatization of the metasedimentary rocks and the early-formed granitoid sheets occurred during M₂. SHRIMP U–Pb zircon results are consistent with a conventional zircon U–Pb date of

1854 \pm 6 Ma obtained by Page and Hancock (1988) from migmatitic rocks in the Tickalara Metamorphics, and this date is regarded as the age of peak metamorphism in the northeastern part of the central zone. Further granitoid sheets were intruded into the metamorphics during and after M_2 .

A number of major layered mafic-ultramafic bodies (Groups 1 and 5 of Hoatson, 1993) were intruded into the deformed Tickalara Metamorphics. Contact aureoles around these intrusions post-date D_2 and M_2 . A SHRIMP U-Pb zircon age of c. 1855 Ma obtained from an anorthosite within a Group 1 intrusion in the central part of the zone suggests that peak M_2 metamorphism may have been diachronous, occurring earlier in the southwest than the northeast.

The Koongie Park Formation (Griffin and Tyler, 1994), which is a sequence of felsic volcanic rocks and associated high-level intrusions, occurs in the southwestern part of the zone. A SHRIMP U-Pb zircon age of 1843 \pm 2 Ma has been obtained from these rocks (Page et al., in prep.). To the northeast, felsic veins probably correspond to this felsic event, and intrude medium-grade rocks of the Tickalara Metamorphics deformed during D_2 . Further to the northeast, the Mabel Downs Granodiorite forms a large, linear pluton that also post-dates D_2 .

The Group 1 mafic-ultramafic intrusions are folded by tight to isoclinal, upright, moderately to steeply plunging D_3 folds. A well-developed foliation in the Mabel Downs Granodiorite is also attributed to D_3 . These units have undergone medium-grade metamorphism, together with the felsic veins thought to correspond to the Koongie Park Formation. This metamorphic event (M_3) has also resulted in retrogression of the high-grade mineral assemblages in the Tickalara Metamorphics.

Extensive intrusion of granitoid rocks into the Tickalara Metamorphics and the Koongie Park Formation occurred throughout the central zone after D_3 . Preliminary SHRIMP U-Pb zircon ages for these intrusions (which include the Mount Christine Monzogranite, the Sally Downs Tonalite, and the McHale

Monzogranite) range from c. 1830 to 1805 Ma.

Large gabbroic and layered mafic-ultramafic bodies (Groups 2, 3a, and 4 of Hoatson, 1993) were also intruded at about this time. A SHRIMP U-Pb zircon age of c. 1830 Ma has been obtained from migmatitic rocks within a high-grade contact aureole developed at the margin of a Group 3a intrusion, and is interpreted as the age of the adjacent igneous body.

In the southwestern part of the zone, the Koongie Park Formation is unconformably overlain by the Moola Bulla Formation, whereas younger Kimberley Group rocks lie unconformably on rocks of the Koongie Park Formation and on granitoids. To the northeast of Halls Creek the Red Rock beds (Dow and Gemuts, 1969), the lower part of which are probably equivalent to the Moola Bulla Formation, unconformably overlie the Tickalara Metamorphics. The upper part of the Red Rock beds together with the Fish Hole Dolerite, are equivalent to the Kimberley Group (Griffin and Tyler, 1992a).

The western zone

The boundary between the central zone and the western zone is taken to be a combination of the Ramsay Range Fault, the Springvale Fault, and the northern part of the Halls Creek Fault.

The western zone shows many similarities with the geological history of the Hooper Complex in the King Leopold Orogen (Tyler and Griffin, 1990, 1993; Griffin et al., 1993). The oldest rocks in the Hooper Complex are those of the Marboo Formation, which is a sequence of turbiditic quartz wacke, siltstone, and mudstone, and similar rocks occur in the western zone of the Lamboo Complex. Provenance and palaeocurrent data presented by Hancock (1991) indicate that this unit was derived from a continental source to the north-northeast. A maximum age for the Marboo Formation may be indicated by the presence of a suite of detrital zircons which give SHRIMP U-Pb ages of c. 1870 Ma.

In the Halls Creek Orogen, the earliest deformation to affect these

rocks in the western zone of the Lamboo Complex (D_1) produced large-scale recumbent folds. In the Hooper Complex, high-grade metamorphism of the Marboo Formation post-dates D_1 and occurred at c. 1860 Ma (based on SHRIMP U-Pb zircon ages from the Mount Joseph Migmatite), providing a minimum age for deposition.

The Marboo Formation is unconformably overlain by the felsic volcanic rocks and associated sedimentary rocks of the Whitewater Volcanics. Page and Hancock (1988) reported a conventional U-Pb zircon age of 1850 \pm 5 Ma for this unit. A SHRIMP U-Pb zircon age of c. 1855 Ma has been obtained from the Whitewater Volcanics in the Hooper Complex. Both the Whitewater Volcanics and the Marboo Formation have been folded into upright D_2 folds with moderately plunging hinges, and have been intruded by extensive granitoid plutons. In the Hooper Complex, geochemical data indicate that the felsic volcanic rocks and the granitoids are co-magmatic (Griffin and Tyler, 1992b). SHRIMP U-Pb zircon ages from the granitoids cover a range from c. 1865 to 1850 Ma. In the western zone of the Lamboo Complex in the Halls Creek Orogen, preliminary SHRIMP U-Pb zircon ages are similar (c. 1860 to 1855 Ma).

Major layered mafic-ultramafic bodies (Group 3b of Hoatson, 1993) are associated with the c. 1860 Ma plutonic granitoids of the western zone of the Lamboo Complex and give similar SHRIMP U-Pb zircon ages. This is consistent with the broadly coeval intrusion of both felsic and mafic magma (Griffin and Tyler, 1992a; Blake and Hoatson, 1993).

As yet no c. 1820 Ma granitoids have been dated from the western zone, although they may be present (Figs 3 and 4).

The western zone of the Lamboo Complex is unconformably overlain by fluvial and shallow-marine deposits of the Speewah Group, which form the lower part of the Kimberley Basin sequence. A felsic volcanic unit from the Speewah Group has a SHRIMP U-Pb zircon age of 1834 \pm 3 Ma. The Kimberley Group unconformably overlies the

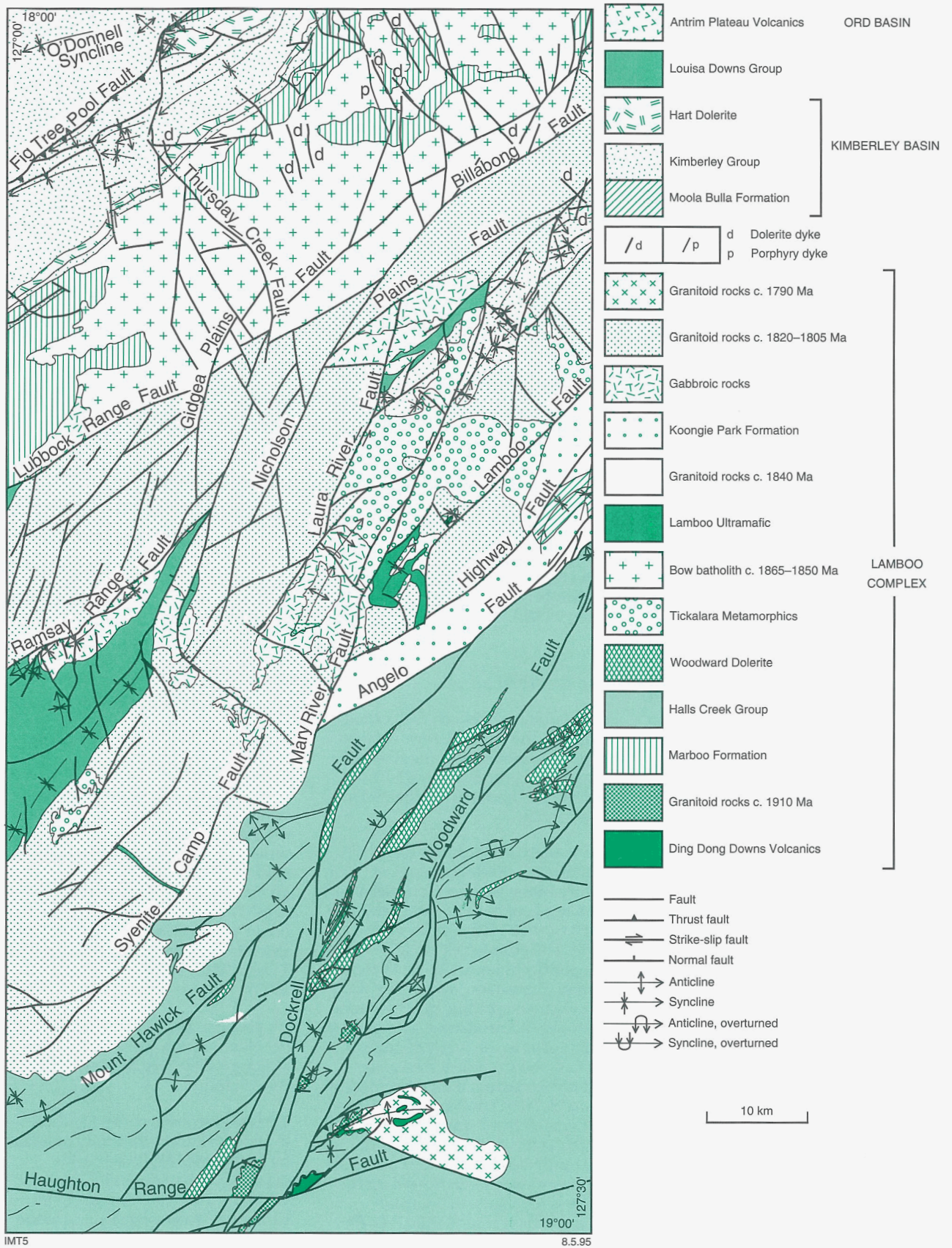


Figure 4. Tectonic sketch of ANGELO and DOCKRELL

Speewah Group with only minor angular discordance, and oversteps it onto the Lamboo Complex. The Kimberley Basin sequence is intruded by mafic sills, collectively called the Hart Dolerite, for which SHRIMP U–Pb–zircon ages of c. 1800 Ma have been obtained.

Reactivation of the zone boundaries

A striking feature of the Halls Creek Orogen is the pattern of steeply dipping, north-northwesterly to north-northeasterly trending sinistral faults and easterly to east-northeasterly trending dextral faults (Figs 2 and 4) that cut rocks which are as young as Devonian in age. This pattern can be interpreted as that produced by synthetic and antithetic faults developed during overall sinistral strike-slip movement, controlled by deep-seated, northeasterly trending structures (Wilcox et al., 1973). The faults that define the zone boundaries have a northeasterly trend that has been offset by the later north-northwesterly to north-northeasterly trending sinistral faults. The Halls Creek Fault and associated structures offset the Angelo and Osmond Faults by 90 km. The zone boundaries are interpreted to reflect deeper structures that originated in the Early Proterozoic and which have controlled Middle Proterozoic, and younger, deformations.

Middle Proterozoic deformation (regionally $D_{4/5}$) was initially ductile in nature, and took place under low- to medium-grade metamorphic conditions. This faulting affected rocks of the Kimberley Basin, and mylonites were developed in rocks in both the Halls Creek and Kimberley Groups along the Halls Creek Fault and its associated structures. Oblique, upright, tight folds with an axial-planar crenulation cleavage also developed. This cleavage affects pegmatite dykes that have preliminary SHRIMP U–Pb zircon ages of c. 1740 Ma. Close to the faults the folds become subparallel to them, suggesting a transpressive regime, possibly developed synchronously with the intracratonic, c. 1.3 to 1.0 Ga Yampi Orogeny in the King Leopold Orogen (Tyler and Griffin, 1990). Gold mineralization in the Halls Creek Orogen appears to be

controlled initially by this fault system.

Younger, brittle reactivations of the fault zones, again as sinistral strike-slip structures but at low- to very low-grades (D_6 and D_7), affected Late Proterozoic and Cambrian rocks. These reactivated structures are characterized by extensive, locally gold-bearing, quartz veins, and the development of kink-bands and an associated crenulation cleavage. Similar, young reactivations in fault zones in the King Leopold Orogen have K–Ar ages of c. 560 and 500 Ma (Shaw et al., 1992). Faulting and large-scale open folding of Devonian rocks may represent further reactivation due to the effects of the Late Devonian to Carboniferous (c. 300–370 Ma) Alice Springs Orogeny.

Discussion

From the above description of the geological history of each zone (summarized in Fig. 3), it appears that each constituted a discrete terrane early in its history, although the similarities between the Hooper Complex and the western zone of the Lamboo Complex suggest that the two may have originally formed a continuous belt. In the eastern zone the oldest unit is the Ding Dong Downs Volcanics, which was formed at c. 1910 Ma. This does not appear to have an equivalent in either of the other two zones. In the western zone the Marboo Formation has previously been correlated with the Olympio Formation of the Halls Creek Group (Gellatly et al., 1974; Hancock and Rutland, 1984; Hancock, 1991); however, the depositional age of the Marboo Formation must be older than metamorphism at c. 1860 Ma, while the deposition of the Olympio Formation continued after eruption of the Butchers Gully Member at c. 1855 Ma. Hancock and Rutland (1984) speculated that the Biscay Formation of the Halls Creek Group may outcrop within the Hooper Complex on MOUNT RAMSAY*; however, remapping (Tyler et al., in prep.) has shown the mafic rocks in question to be gabbroic intrusions.

There are many similarities between the lower part of the Halls Creek Group in the eastern zone and the

Tickalara Metamorphics in the central zone, and it has been assumed that the two are equivalent (Dow and Gemuts, 1969; Hancock and Rutland, 1984; Allen, 1986). The correlation is difficult to resolve, however, given the intrusion of granitoid sheets into the Tickalara Metamorphics at c. 1865 Ma, followed by two deformation events, the second being coincident with high-grade metamorphism at c. 1855 Ma, at a time when the lower part of the Olympio Formation was being deposited in the eastern zone. There is no evidence that deformation and metamorphism affected the Biscay Formation prior to the deposition of the Olympio Formation. In fact, the first deformation to affect the eastern zone must post-date c. 1855 Ma, and must therefore be younger than both D_1 and D_2 in the central zone. The differences in the ages of deformation and metamorphism also appear to rule out the possibility that the central zone is a deeper crustal equivalent of the eastern zone.

The suggestion by Allen (1986) that the Saunders Creek Formation can be recognized within the Tickalara Metamorphics has not been substantiated during recent remapping. The sandstones in question occur as low-strain pods strung out within mylonitic rocks along the Halls Creek Fault and its associated structures, and are most likely to correlate with the Red Rock beds.

In the western zone the earliest deformation pre-dated metamorphism of the Marboo Formation at c. 1860 Ma, and was followed by eruption of the Whitewater Volcanics, deformation, and the intrusion of granitoid plutons between c. 1860 and 1850 Ma. This style of felsic magmatism is not evident in either the central or eastern zones, but occurred at about the same time as the intrusion of granitoid sheets, deformation, high-grade metamorphism, and the intrusion of layered mafic–ultramafic intrusions, in the central zone, and the eruption of the alkaline volcanic rocks of the Butchers Gully Member in the eastern zone. The near synchronicity of these differing magmatic and thermal events within the orogen was recognized by Page and Hancock (1988) and was attributed

* Capitalized names refer to standard map sheets.

to a rapid tectonic transition from sedimentation to orogenesis, and then to cratonization. An alternative view inherent in the terrane concept is that these different events did occur at about the same time, but in geographically separate terranes that were brought into their current juxtaposition by subsequent tectonism.

The zones continued to evolve separately after c. 1850 Ma, with the central zone experiencing the eruption of felsic volcanic rocks, and the intrusion of further granitoids, gabbros, and layered mafic–ultramafic bodies, as well as deformation and metamorphism. Both deformation events that affected the eastern zone occurred after eruption of the Butchers Gully Member at c. 1855 Ma, but before intrusion of the c. 1820 Ma granitoids.

The intrusion of the c. 1820 Ma granitoids appears to be the first event that can be correlated with certainty between the central zone and the eastern zone, with the Mount Christine Monzogranite intruding into the Halls Creek Group. The deposition of the Speewah Group onto the Lamboo Complex of the western zone began before c. 1835 Ma, while granitoids were still being intruded into the central and eastern zones. The deposition of the Kimberley Group appears to be the earliest event that can be correlated between all three zones.

Tectonic implications

The intracratonic models of Hancock and Rutland (1984) and Etheridge et al. (1987) are inadequate to explain the tectonic evolution of the Halls Creek and King Leopold Orogens because they are based on correlations of units and events that are now regarded as invalid. Griffin and Tyler (1992b) have shown that the Early Proterozoic felsic igneous rocks in the Hooper Complex of the King Leopold Orogen have a calc-alkaline trend, and interpreted them to be subduction related, having formed as part of a magmatic arc. The overall evolution of the complex was consistent with a collisional orogeny, albeit involving thinner continental crust and higher heat flows than Phanerozoic collision orogenies.

Any model that seeks to explain the tectonic evolution of the Halls Creek Orogen must account for the differences between the three zones described here. Windley (1993), in a review of Precambrian orogenic belts, mainly from North America, Europe, and Africa, concluded that tectonophysical and geochemical processes that produced oceanic and continental rocks since the

early Archaean were not fundamentally different from those that operate in the present. The recognition of tectonostratigraphic terranes within the Halls Creek Orogen, and the different geophysical nature of the basement cratons on either side of it, are consistent with the operation of plate-tectonic processes in the Early Proterozoic.

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Investigation of corrosion behaviour of friction rock stabilizers used in underground mines in Western Australia

by J. Ranasooriya, G. W. Richardson¹, and L. C. Yap¹

Abstract

Friction rock stabilizers are the most common steel-based ground reinforcement used in underground mines in Western Australia. The effect of corrosion is considered to be severe for this type of reinforcement due to the thin-wall tube construction and large surface area. Investigations have been carried out to determine the nature and extent of corrosion attacks and their influence on the ultimate tensile load-capacity of reinforcement.

KEYWORDS: Corrosion, friction rock stabilizer, ground water, underground mine, reinforcement, rock bolt.

Friction rock stabilizers (FRS) are the most commonly used ground reinforcement in underground mines in Western Australia. There are several advantages of FRS including the ease of installation, immediate effectiveness, and economy, and because of these advantages, FRS have become more popular than any other ground reinforcement currently available within the mining industry. A survey conducted by the Department of Minerals and Energy of Western Australia (DME; Ranasooriya, 1993) has shown that over 93% of the underground mines in Western Australia use them as a method of ground control.

The application of FRS exposes them to a wide range of mine-water, mineralogical, and atmospheric conditions. Mine-water and atmospheric conditions often change with variations in climate and changes in mining activities. Operating experience has shown that FRS corrode with time due to

their interaction with the physical and chemical characteristics of the environment. Corrosion reduces their integrity and load-bearing capacity, leading to unexpected rock falls, which may cause potentially fatal accidents.

Corrosion of ground reinforcement and other steel and iron products has been a widely known problem in underground mines throughout the world. Studies have been carried out on the corrosiveness of underground mine waters (Rawat, 1976; Higginson and White, 1983), and corrosion behaviour of mild steel in underground mine waters in general (Subramanyam and Hoey, 1975; Mursolo et al., 1988). Sundholm (1987) and Dahl (1989) reported comparative studies of the corrosion behaviour of different ground-reinforcement types used in underground mines. Because of their thin-wall tube construction and large surface area, the effect of corrosion is considered to be more severe for FRS than other reinforcements made of solid steel bars. Sundholm (1987) demonstrated that FRS corrode over their entire length,

and over 58% of their wall thickness can be lost in just one year after installation. Tilman et al. (1984, 1985) and Jolly and Neumeier (1987) investigated the corrosion problem relevant to a single type of FRS in selected mine waters; however, the corrosion behaviour of a range of FRS in varied underground mining environments so far is not fully understood.

The obvious safety problems that may result from corrosion have led both regulatory and industry personnel to raise concerns regarding the longevity of FRS in underground mining environments in Western Australia. In response to these concerns a research project was initiated by DME, with assistance from the mining industry and suppliers of FRS used in Western Australia. The research project was undertaken by chemists and metallurgists from the Chemistry Centre of Western Australia and geotechnical engineers from the Engineering Geology Section of the Geological Survey of Western Australia.

The research project was aimed at investigating the following:

- (a) corrosiveness of underground mining environments in Western Australia;
- (b) the nature and extent of corrosion of FRS;
- (c) the effects of corrosion on the load-bearing capacity of FRS;
- (d) the methods of predicting the potential longevity of FRS in underground mining environments.

This paper presents the results of the investigations carried out as part of this research work.

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Types of friction rock stabilizers

Three types of FRS were available at the commencement of the study. They are known by the proprietary names of Split Set, Cotter Pin, and Swellex, and were supplied by Ingersol Rand, Hardie Drilling Supplies, and Atlas Copco respectively. Plain steel (ungalvanized) and galvanized or coated varieties are available from each type.

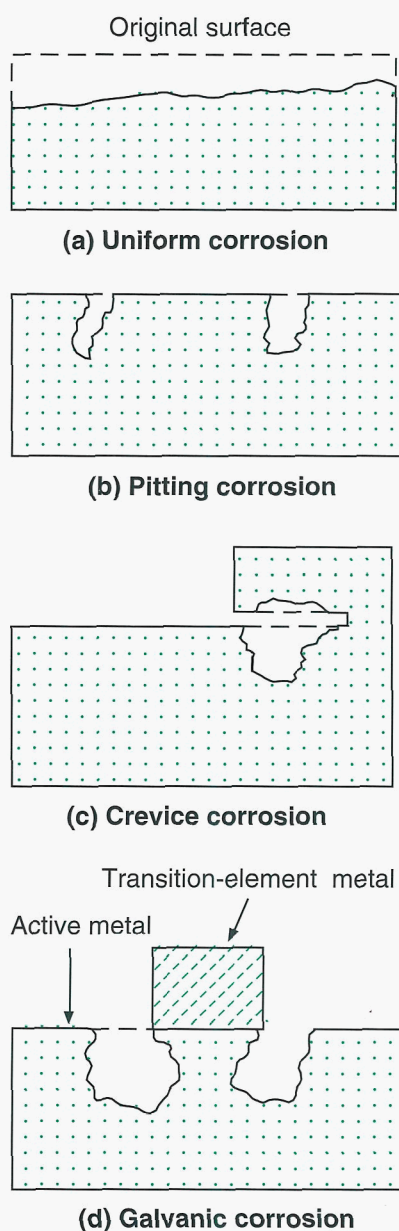
A Split Set is a steel tube of 3 mm nominal wall thickness, with a slot running its full length. The end of the Split Set that is inserted into the rock is tapered, whereas the outer end has a ring flange to hold an end plate. To install, the Split Set is forced into a slightly smaller-diameter hole drilled in the rock. Split Sets are available at various lengths with diameters of 33, 39, and 46 mm.

A Cotter Pin is a steel tube of 2 mm nominal wall thickness with a longitudinal inwards fold along its entire length. The inner end is tapered and the outer end has a welded ring flange to hold an end-plate. The installation process for Cotter Pins is similar to that for Split Sets. Cotter Pins are available at various lengths with diameters of 39 and 46 mm.

A Swellex FRS is a steel tube with a diameter of 41 mm and with a 2 mm nominal wall thickness, that has been reshaped to 25.5 mm diameter by folding longitudinally inwards along its length. Bushes are pressed onto each end and sealed by welding. A valve is fitted to the outer bush to allow injection of water into the Swellex tube. To install, the Swellex tube is inserted into a hole with a diameter less than 41 mm drilled in the rock. The Swellex tube is expanded by injecting water using a high-pressure water pump.

Types of corrosion

Corrosion is defined as a gradual wearing away or alteration of metal by a chemical or electrochemical oxidizing process. The process requires the combined presence of an electrolyte and oxygen. The damage resulting from the oxidizing



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Figure 1. Types of corrosion that may influence the longevity of FRS

process can take various different forms depending on the conditions of the surrounding environment and the quality of the metal itself. Types of corrosion which may destroy FRS are illustrated in Figure 1 and are discussed below.

Uniform corrosion

Uniform or general corrosion is characterized by an even, regular loss of metal from the corroding surface without appreciable

localization of attack (Fig. 1a). FRS which suffer this type of corrosion are radially thinned from inside or outside (or both) depending on the nature of the corrosive environment. The process of metal wastage is uniform around the entire circumference at a relatively linear rate with time.

Localized corrosion

Localized corrosion occurs at discrete, isolated locations on the surface of the metal. Two forms of localized corrosion are common: pitting corrosion and crevice corrosion.

Pitting corrosion (Fig. 1b) is the most common of all types of corrosion in the samples analyzed. Pitting may occur on either surface of the FRS where the surface is metallurgically non-homogeneous or under deposits of foreign matter. Localized variations in the mineralogical conditions of the ground in contact with the surface of the FRS can also create conditions that promote pitting corrosion. Once initiated, pitting corrosion continues until perforation of the FRS results. FRS may become unserviceable because of localized weakening by pitting, even though only a small percentage of the total metal has been lost.

Crevice corrosion (Fig. 1c) is a particular form of pitting corrosion which occurs on confined, closely spaced metal surfaces. In FRS the interface between the collar and the end-plate provides conditions suitable for crevice corrosion. This type of corrosion may lead to the loss of support provided by the end-plate, even though the bulk of the FRS may still be sound.

Galvanic corrosion

Galvanic or bimetallic corrosion (Fig. 1d) occurs when dissimilar metals are in contact in the presence of an electrolyte. The intensity of corrosion resulting from galvanic coupling depends primarily on the difference in solution potential between the metals. Galvanic corrosion of FRS occurs when they are electrically coupled to less reactive metals in the ground such as copper and nickel.

Underground corrosive environments

Corrosion is a chemical or electro-chemical process that requires the presence of an electrolyte and oxygen. In underground mines, water is the most common electrolyte associated with corrosion.

Oxygen is generally available from the air. In well-ventilated areas of an underground mine the oxygen supply is considered to be constant.

The rate of corrosion is accelerated by the acidity and electrical conductivity of the groundwater. Rapid corrosion may take place when the metal is surrounded by water; however, a film of water deposited on the surface of the metal from the moisture in the air also permits appreciable corrosion to take place. The corrosion resulting from moisture in the air can be accelerated by the presence of dust and other impurities, such as sulfur oxide and nitrogen oxide gases.

Mine-water analyses

Groundwater samples were collected from 21 underground

mines in Western Australia. The majority of the samples were 25 L in volume. Up to six samples were collected from some mines where groundwater quality was suspected to be variable within the mine itself. Sample temperature, dissolved oxygen content, and pH were recorded on site.

The groundwater samples were analyzed for Na, K, Ca, Mg, Zn, Mn, Al, Fe, Ni, Cu, P, Si, chloride, sulfate, bicarbonate, and nitrate ions, and pH and total alkalinity. The results of the analyses indicate that only Na, K, Ca, and Mg cations, and chloride and sulfate anions, are present in significant concentrations, with wide variations from site to site. Other ions are present only in comparably small concentrations. More importantly, the results show that there is a wide range in the nature and concentration of dissolved salts in the samples collected. For example, the sodium content, which is indicative of the salinity of the groundwater, ranges from 180 to 99 400 ppm; the combined calcium and magnesium concentration, which is indicative of the hardness, ranges from 80 to 35 400 ppm.

Dissolved-salt content is generally considered to be an indicator of the salt-induced corrosiveness of groundwater; however, a low salt content does not necessarily mean that the environment is less corrosive, as severe corrosion can still take place depending on the mineralogical and atmospheric conditions of the site. Table 1 is a summary of selected chemical analyses of the samples collected in this study.

Rock mineralogy

The majority of rock-forming minerals are relatively chemically inert, and when in contact with steel will have little or no effect on the corrosion of the metal. Nevertheless, some water-soluble minerals such as sulfides, chlorides, and carbonates can significantly influence the corrosion of steel when in contact with it in the presence of aqueous solutions. Water-soluble minerals change the acidity and salinity of water, leading to a change in the corrosiveness of the water. Such minerals (e.g. pyrite) are generally found in orebodies mined by underground methods.

Table 1. Selected chemical analyses of mine waters

Mine no.	Cl ⁻	SO ₄ ²⁻	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺
Parts per million						
1	1 080	360	620	5	110	100
2	1 300	300	670	30	50	180
3	1 520	630	1 020	10	115	100
4	32 500	5 200	16 700	115	580	3 060
5	75 000	1 860	36 300	180	8 000	130
6	347 – 607	390 – 765	180 – 466	11 – 20	38 – 153	36 – 42
7	400 – 2 500	nd	450 – 450	25	175 – 180	85 – 85
8	1 510 – 134 000	320 – 1 470	950 – 72 300	12 – 930	160 – 8 460	90 – 7 080
9	4 450 – 7 010	1 860 – 3 750	2 440 – 2 756	42 – 48	245 – 1 140	450 – 1 440
10	4 660 – 197 000	480 – 4 200	2 750 – 87 600	60 – 1 730	1 060 – 20 900	500 – 14 500
11	9 860 – 13 100	450 – 10 900	55 000 – 71 300	410 – 690	780 – 940	6 070 – 8 470
12	13 000 – 137 000	3 990 – 4 170	7 800 – 7 860	60 – 67	290 – 320	1 320 – 1 380
13	16 500 – 44 800	2 010 – 2 710	8 290 – 15 300	124 – 310	610 – 6 640	1 600 – 3 540
14	22 700 – 29 500	4 920 – 5 970	11 700 – 13 600	120 – 260	380 – 1 560	2 300 – 3 980
15	26 400 – 34 200	4 530 – 5 640	15 900 – 21 090	270 – 390	980 – 1 000	1 640 – 1 730
16	32 300 – 43 000	4 220 – 6 040	16 100 – 19 600	91 – 300	720 – 1 140	3 180 – 3 500
17	32 900 – 81 000	4 950 – 9 120	17 900 – 39 700	160 – 620	1 500 – 2 400	1 920 – 5 700
18	36 500 – 125 000	1 110 – 2 250	19 200 – 63 000	50 – 150	2 000 – 13 000	2 100 – 2 300
19	80 400 – 133 000	2 010 – 19 700	48 490 – 75 500	390 – 870	590 – 5 350	5 100 – 12 300
20	160 000 – 162 000	2 670 – 6 540	79 700 – 84 500	1 080 – 1 200	1 570 – 3 380	8 900 – 9 900
21	168 000 – 185 000	24 300 – 284 000	86 100 – 99 400	1 130 – 1 250	330 – 440	14 800 – 16 800

nd – not determined

The presence of certain transition-element metals that may be otherwise relatively inert in the ground, such as copper and nickel, provide ideal conditions for galvanic or bimetallic corrosion when in contact with steel in the presence of aqueous solutions. The concentration of these metals in underground mines in Western Australia is generally very small (obvious exceptions include nickel and copper mines) but can vary from site to site as well as within a mine. Nonetheless, as galvanic corrosion primarily depends on the difference in solution potential between the metals (or alloys), small concentrations of these metals are sufficient to initiate this type of corrosion. Transition-element metals are commonly present in ore zones, although this depends on the type of ore being mined.

Quantification of corrosion rates

Two approaches were used to quantify the rates of corrosion of FRS. They were:

- (a) assessment of the extent of corrosion of samples of FRS of known history collected from mine sites, and
- (b) laboratory-based experimental corrosion of samples of unused FRS in simulated mining environments using groundwater and rock samples collected from mine sites.

In-mine corrosion of installed friction rock stabilizers

The preferred method of assessing the in-mine corrosion damage is to retrieve installed FRS by overcoring and then measure the extent of corrosion using laboratory techniques. Formal requests were made to all mine operators who use FRS in their underground mines to provide retrieved FRS of known history. Several mining companies expressed interest in overcoring FRS from their underground mines. Three companies agreed to install pairs of FRS at three-monthly intervals at a site set aside for this study and to retrieve them all by overcoring after 12 months from the first installation. Nonetheless, retrieval of FRS by overcoring is yet

to be performed at any of the underground mines in Western Australia.

An alternative approach taken to obtain samples of installed FRS from underground mines was to cut and remove the lower ends of FRS which were protruding from the rock, as a result of re-scaling, small rock falls, or poor installation. This approach was found to be relatively successful. A total of 133 such samples were collected from 12 underground mines. These included samples from three major rock-fall sites where accidents have occurred.

The age of the samples collected ranges from 3 to 77 months. This was estimated by mine site personnel from mine records and from manufacturer's product code stamps on the FRS.

The ground conditions at the sampling sites varied significantly from site to site in terms of lithology and mineralogy. The groundwater conditions ranged from completely dry to wet. In addition, where water was present, the groundwater chemistry differed from mine to mine. Therefore, the samples collected represent a wide range of mining environments; however, as sample collection was largely governed by the accessibility of the sites, they do not necessarily represent the extreme conditions that may be present in underground mines. The 133 samples were all plain steel (ungalvanized) Split Sets. Two samples of galvanized Split Sets were also received separately. This sampling bias is mainly due to the widespread use of Split Sets in underground mines in Western Australia.

All three styles of corrosion described above have been identified from the samples of FRS collected from mine sites. The extent of corrosion differed significantly depending on the type of attack, and any given sample may have suffered more than one type over its length. As a result, neither the area nor the depth of attack was found to be suitable for quantifying the extent of corrosion; therefore, mass loss as a percentage of the original mass was developed as a suitable common measure of the extent of corrosion of field samples.

The samples collected from mine sites were divided into two groups based on FRS length. Group 1 comprises samples with lengths from 500 mm to 1800 mm, whereas Group 2 comprises samples with lengths from 200 to 300 mm.

The samples were analyzed for 'average mass loss'. Three sections were tested from each sample of Group 1, each with a nominal length of 75 mm, and were taken from the two ends and the centre to represent the full length of a sample. The mass loss determined from the three sections was averaged to give a representative mass loss for each sample. For Group 2 samples, mass loss was determined for the entire sample.

Pitting (localized corrosion) was the most common form of corrosion in the samples collected. Pitting results in the localized perforation and weakening of FRS. The extent of localized corrosion may be quantified by estimating the localized mass loss, rather than the average mass loss; therefore, the 'localized mass loss' is defined for the Group 1 samples, which is the maximum value of the mass-loss measurements from the three 75 mm sections of a field sample. For Group 2 samples, localized mass loss could not be determined.

Laboratory-based experimental corrosion

Six laboratory-based corrosion experiments were set up to determine corrosion rates under various simulated mining environments:

1. A static-immersion corrosion test was designed to simulate corrosion under stagnant water or non-changing wet conditions where mining activity decreases or stops.
2. Dynamic corrosion test 1 was designed to simulate an underground mine environment where groundwater with a relatively low dissolved-salt content (less than 1%) is freely flowing over the FRS.
3. Dynamic corrosion test 2 was designed to simulate an underground mine environment where groundwater with a relatively high dissolved-salt

content (approximately 24%) is freely flowing over the FRS.

4. Dynamic corrosion test 3 was designed to simulate an underground environment where water vapour is transported as a fine mist by ventilation, and deposited on the FRS. The dissolved-salt content for this test was approximately 24%.
5. An electrochemical corrosion test was designed to determine the corrosiveness of selected mine water from four mines where the broad spectrum of groundwater qualities is represented. Electrochemical tests were also conducted to determine the effect of pH, salt content, and increased oxygen supply.
6. The salt spray test (ASTM² B117) is a standard test designed to compare the corrosion resistance of the three types of FRS under a continuous salt fog of 5% sodium chloride at 35°C for 500 hours.

Specimens used for laboratory experiments under simulated mining environments were commonly 75 mm in length. In order to be able to compare with in-mine corrosion rates, mass loss was again used as the common measure of corrosion. Measurements obtained from electrochemical tests were converted to mass loss for comparison.

Results of corrosion analyses

In-mine corrosion rates

Figure 2 is a log-log plot of installed age versus average mass loss of samples collected from mine sites. The graph shows that the average mass loss can vary significantly for a given length of time of installation. This large variation is considered to be a function of differing conditions in the mines. Nonetheless, on the basis of data available, ungalvanized FRS can be given upper and lower limits of average mass loss as shown by curves A and B respectively on Figure 2. As a preliminary guideline, the upper limit (curve A) may be used to predict the maximum corrosion damage that may be expected in an underground mine.

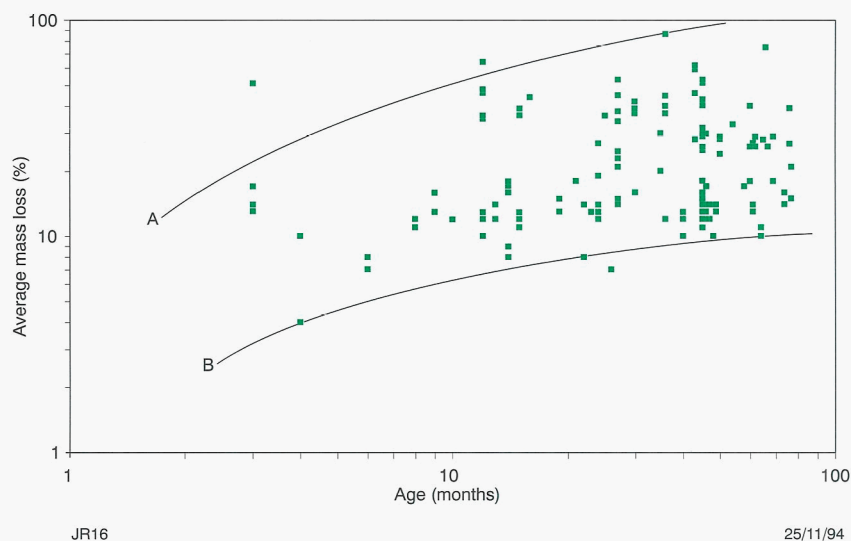


Figure 2. Age versus average mass-loss of samples of FRS collected from mine sites

Figure 3 is a log-log plot of age versus localized mass loss determined from the Group 1 specimens of 75 mm nominal length. This figure shows that more than 10% of local mass loss can be lost within 8 months due to localized corrosion. Moreover, the maximum localized mass loss is up to 80% in just over 10 months.

Effect of rock type on in-mine corrosion

Of the field samples analysed, 55 were collected from a single mine where groundwater quality was

considered to be uniform. Rock type and degree of wetness of each sampling location was recorded for all 55 samples. The samples were recovered from four rock types: basalt, ultramafic rock, porphyry, and massive sulfide. The massive sulfides correspond to the nickel-bearing ore zone; ultramafic rocks and porphyry occur in the footwall and hanging wall to the ore zone; and the surrounding country rock is basalt.

Average mass loss was determined for each of the 55 samples as outlined above. The results of the

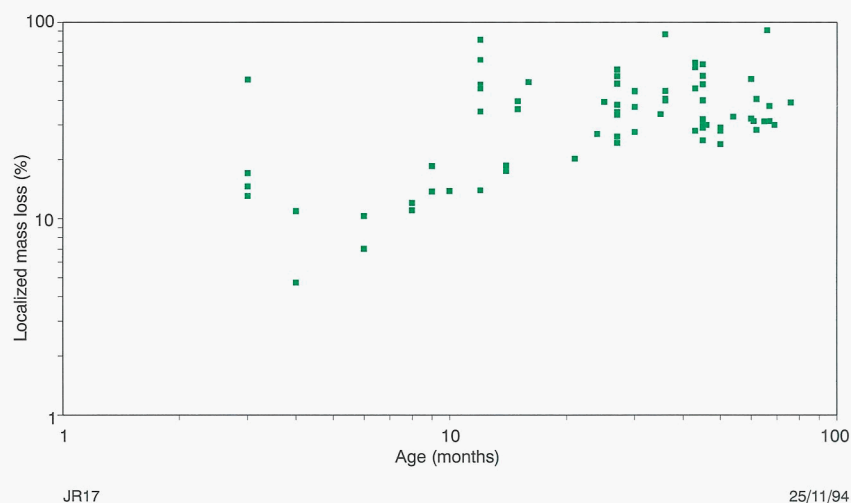


Figure 3. Age versus localized mass-loss of samples of FRS collected from mine sites

² American Society for Testing and Materials.

Table 2. Influence of rock type on rate of corrosion

<i>Rock type</i>	<i>Wetness</i>	<i>Mass loss per month (%)</i>
Basalt	dry	0.2 – 0.6
Basalt	wet	0.3 – 0.8
Basalt	damp	0.3 – 0.7
Ultramafic	dry	0.5 – 1.2
Ultramafic	wet	0.9 – 1.2
Porphyry	dry	0.4 – 1.4
Massive sulfide	dry	0.3 – 1.5

analyses are presented as mass loss per month (corrosion rate) in Table 2. Although a direct correlation between the corrosion rate and the rock type is not possible at this stage, the results suggest that the extent of corrosion may have been influenced by rock type. The lowest minimum and the lowest maximum rates of corrosion were found to be associated with basalt country rock, where soluble minerals and transition-element metal concentrations are significantly low compared to the ore zone. The highest maximum rate of corrosion was associated with massive-sulfide ore zones.

Laboratory experiments

Static immersion tests

Static immersion tests were conducted on samples of Split Set, Cotter Pin, and Swellex FRS. Both galvanized and ungalvanized samples were tested. Water with a chloride content of 66 200 ppm (which is twice the salinity of sea water) was used in these tests. Corrosion rates were determined at 95 and 209 days after the first immersion. The results (Table 3) indicate that the corrosion rate of ungalvanized samples was relatively uniform over the whole time of immersion. In contrast, galvanized samples initially corroded faster. The corrosion rate of galvanized samples at 95 days was 3 to 4 times higher than that of the ungalvanized samples. While a reduction in the rate of corrosion of galvanized samples was clearly evident at 209 days,

rates were still observed to be higher than for ungalvanized samples.

Dynamic tests

Results of the three dynamic tests are also presented in Table 3. The three tests represented free-flowing water with low dissolved salts (less than 1%; Test 1), free-flowing water with high dissolved salts (approximately 24%; Test 2), and mist conditions (Test 3). The results indicate that ungalvanized samples corroded at a faster rate than galvanized samples in the presence of a low concentration of dissolved salts. Under conditions of high salt concentration, galvanized samples corroded faster than ungalvanized samples. This is, however, expected to reverse with time. Further testing is under way to examine long-term trends.

As galvanizing is applied only on the outer surface of Swellex FRS, the experimental procedure is not necessarily applicable to Swellex. The rate of corrosion of galvanized Swellex under the dynamic tests should be treated with caution, as this represents the corrosion of both ungalvanized and galvanized sides of the specimen.

The results of dynamic tests on ungalvanized samples of FRS have shown the following:

- Corrosion rates of all three types of FRS are higher in water with a low concentration of dissolved salts. Under the conditions used for the dynamic tests, a tenfold

difference in the rates of corrosion was observed.

- Corrosion rates were similar for each type of FRS under Dynamic Tests 2 and 3. This indicates that under a high concentration of dissolved salts, both free-flowing water over FRS and moisture deposited on FRS have a similar influence on the rate of corrosion.
- All three types of FRS corroded at similar rates under each of the dynamic test conditions. The rates of corrosion of ungalvanized FRS does not appear to be product-type dependant.

Electrochemical tests

Electrochemical tests were conducted using distilled water with sodium chloride concentrations of 0, 1, 3, 5, and 7%. All three types of ungalvanized FRS were tested. The results of these tests show that the maximum rate of corrosion occurs when the sodium chloride concentration is between 1 and 6%. These results are in agreement with the findings of Borgmann (1937) on the corrosion of cold-rolled steel, where the maximum corrosion rate was at a salt concentration of 2.9% sodium chloride.

Electrochemical tests were also conducted using mine water from four mines. The mine waters have dissolved-salt concentrations of 1.2, 4.8, 5.7, and 6.4%. The major components of dissolved salts in the four mine-water types are chlorides,

Table 3. Results of laboratory corrosion tests

<i>Test</i>	<i>Corrosion rate (% mass loss per month)</i>					
	<i>Split Set</i>		<i>Cotter Pin</i>		<i>Swellex</i>	
	<i>Plain</i>	<i>Galvanized</i>	<i>Plain</i>	<i>Galvanized</i>	<i>Plain</i>	<i>Galvanized</i>
Static	0.2	0.9 → 0.5	0.4	0.8 → 0.5	0.2	0.6 → 0.4
Dynamic 1	3.0	0.1	4.0	0.2	3.5	(a) 1.5
Dynamic 2	0.3	0.5	0.35	1.0	0.4	1.0
Dynamic 3	0.3	0.1	0.5	0.1	0.3	0.3
ASTM B117	11.0	9.0	11.0	9.0	10.0	8.0

Note: Rate of corrosion is calculated over the full time of immersion (209 days). Two rates are given for samples for which corrosion rates differed at 95 days compared with 209 days: the first is at 95 days and the second at 209 days.

(a) The experimental procedure is not necessarily applicable to Swellex because galvanizing is applied only on the outer surface.

sulfates, and bicarbonates. The concentrations of individual salt types differ from mine to mine, and do not directly represent the total salt concentration. The results of these tests have shown similar rates of corrosion for all three types of ungalvanized FRS. Galvanized samples were not included in the electrochemical tests reported here owing to sample preparation difficulties to suit the available apparatus. Galvanized samples are to be tested as part of further studies.

Salt spray tests

The results of the Salt Spray Test (ASTM B117) are also presented in Table 3. These results show that the rates of corrosion in water with a 5% sodium chloride salt concentration at 35°C are significantly higher than those determined from the three dynamic tests and the static immersion tests. The high rates of corrosion are considered to be due to the 10°C increase in temperature (compared with 25°C for dynamic tests) and the near-optimum salt concentration for high-corrosion effects. Although the corrosion rates are higher, all three types of ungalvanized FRS corroded at similar rates under ASTM B117 test conditions. Galvanized FRS corroded at marginally slower rates than ungalvanized FRS. Again rates were similar for all three types.

Reduction in tensile strength

Average mass-loss measurements of corroded field samples

Laboratory tensile tests were performed to determine the ultimate tensile load at failure for corroded samples collected from mine sites. The reduction in ultimate tensile strength was calculated as a percentage of the original ultimate tensile strength before corrosion. Prior to the tensile load testing, average mass loss was determined for corroded samples. A plot of mass loss versus reduction in ultimate tensile strength is shown in Figure 4.

A regression analysis of this data suggests that a linear relationship between average mass loss and reduction in ultimate tensile strength can be expressed as follows:

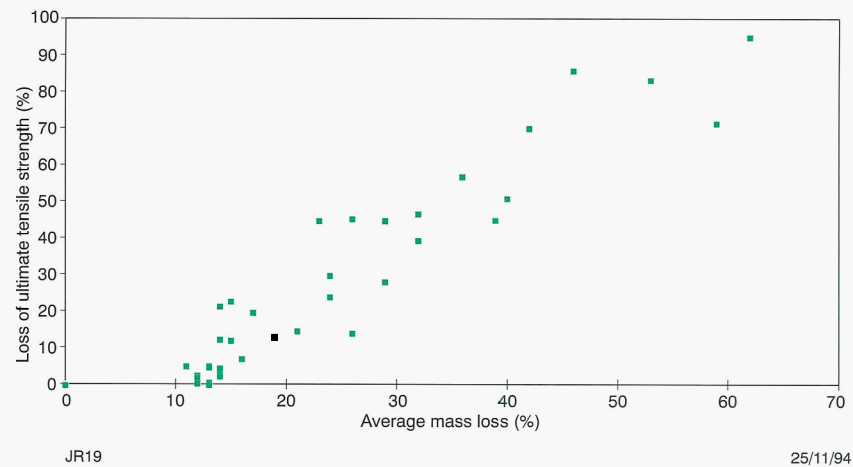


Figure 4. Average mass-loss versus reduction in ultimate tensile strength

$L = 1.8M - 15.8$
where: L = loss of ultimate tensile strength (%),
 M = average mass loss (%) resulting from corrosion.
Note that this relationship is applicable only when the average mass loss is greater than 10%.

Samples with simulated localized mass loss
Tensile tests were also performed to simulate the effect of localized mass loss of FRS resulting from localized corrosion. Localized mass loss was simulated by drilling several holes, 10 to 15 mm in diameter, across new samples. A plot of localized

mass loss versus reduction in ultimate tensile strength is shown in Figure 5.
A regression analysis of this data shows that an approximate linear relationship between localized mass loss and reduction in ultimate tensile strength can be expressed as follows:

$L = 1.4M + 20.5$
where: L = loss of ultimate tensile strength (%),
 M = localized mass loss (%) resulting from pitting-type corrosion.

This relationship indicates that a 10% loss in localized mass results in about 30% reduction in ultimate tensile strength.

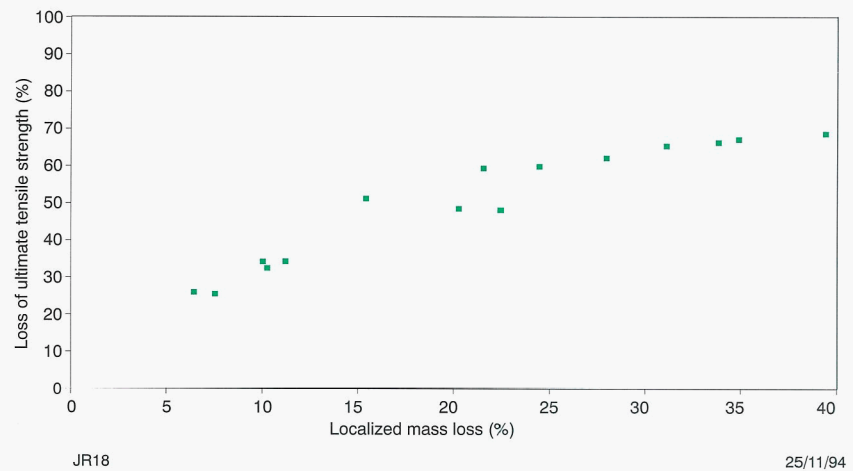


Figure 5. Localized mass-loss versus reduction in ultimate tensile strength

Discussion

This study has established that the quality of groundwater in underground mines in Western Australia is highly variable. The groundwater quality is variable even within single mines, possibly because of the use of water in mines from sources other than the mine itself. As a result, the corrosiveness of underground mining environments is extremely variable from site to site. This is evident from Figure 2.

An important outcome of the project is that for the first time in Western Australia operators and regulators will be able to quantitatively assess the extent and significance of corrosion of randomly collected samples of FRS.

One possible limitation of the study is that the samples were mostly collected from the protruding ends of Split Sets, which may not necessarily represent the conditions acting inside the ground; however, the maximum rate of mass loss recorded (81% in 11 months) was determined from a rock-fall site from a sample which was fully embedded in the ground before the failure.

Analyses of corroded samples have shown that three types of corrosion can damage the FRS in underground mining environments. They are uniform corrosion, localized corrosion, and galvanic corrosion. A linear relationship exists between average mass loss and the ultimate tensile strength. A second relationship also exists between simulated localized mass loss and the ultimate tensile strength. If the mass loss for a FRS can be predicted, then the loss of ultimate tensile strength in an underground mine can be predicted. This has ramifications for the safety of workers due to the progressive loss in holding power of the installed reinforcement.

It is important to note that the maximum initial load-bearing capacity or reinforcing effect available is governed by the maximum frictional resistance along the interface between the drillhole wall and the stabilizer itself. This aspect has not been studied as part of the present investigations. Sundholm (1987) observed that the residual holding force of FRS significantly decreases with time. Sundholm interpreted that the

reduction in holding force was partly due to initial surface corrosion, which smooths down the surface roughness of the stabilizer; and corrosion products, which diminish the sliding friction between the stabilizer and the drillhole wall. In contrast, Ingersoll-Rand (1980) claim that initial surface corrosion increases the holding force. This aspect of FRS is still to be addressed in detail.

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The Collie Coalfield: a starting point for Permian Gondwana correlation in a transtension extensional basin

by G. Le Blanc Smith and J. Backhouse

Abstract

A sequence from Asselian to approximately Ufimian is preserved in the Collie Basin by post-depositional extensional faulting. It is proposed that many Indian and Antarctic Permian basins result from the same style of extensional tectonics and contain similar Permian sequences. The Collie Basin sequence contains ten palynological zones that are extrapolated into the Perth and Carnarvon Basins. Tentative correlations are made with comparable Gondwanan coalfields in India and southern Africa, based on published palynomorph range charts, and allow speculation on coeval depositional and palaeoclimatic regimes.

KEYWORDS: Collie Basin, Permian, palynological correlation, Gondwana, coal, transtension extension tectonics, Western Australia.

The Collie Basin (Figs 1 and 2), southwestern Australia, is an outlying relict of a once much larger Permian epicratonic sag basin. It contains a typical Permian sequence of basal diamictite (up to 30 m thick), overlain by up to 300 m of coal-capped periglacial deltaic and fluvial sedimentary rocks (Sequence P1) and 900 m of coal-bearing alluvial siliciclastic rocks (Sequences P2 and P3; Fig. 3; Le Blanc Smith, 1993). The strata are preserved in a post-depositional, fault-bounded extensional structure within the Archaean crystalline basement as a consequence of right-lateral shear in a transtensional setting (Figs 2 and 4). A similar genesis is envisaged for many Permian coalfields, particularly those of peninsular India and possibly Antarctica.

In the Collie Basin northwesterly striking, steeply dipping, normal-slip faults are dominant, and display differential displacement, stepping, and instances of scissoring in response to weak folding. Rare, small-displacement reverse faults strike to the northeast. Strata generally dip to the southwest and contain up to 74 m of coal in 60 principal coal seams between 0.5 and 13 m thick. They are overlain by a thin veneer of horizontal Cretaceous deposits. Vitrinite-reflectance data from the Collie Basin presented by Sappal (1986) indicate a maximum coal-burial depth of nearly 8 km (Le Blanc Smith, 1993).

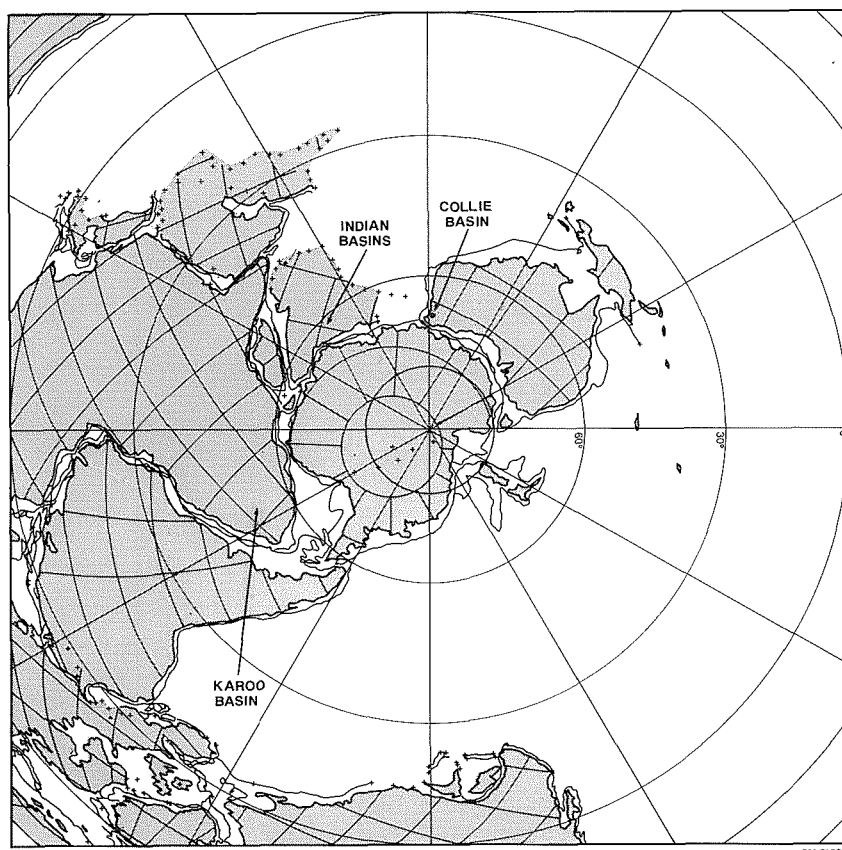


Figure 1. The Collie, Indian, and Karoo Basins located on a polar projection of Early Permian Gondwanaland

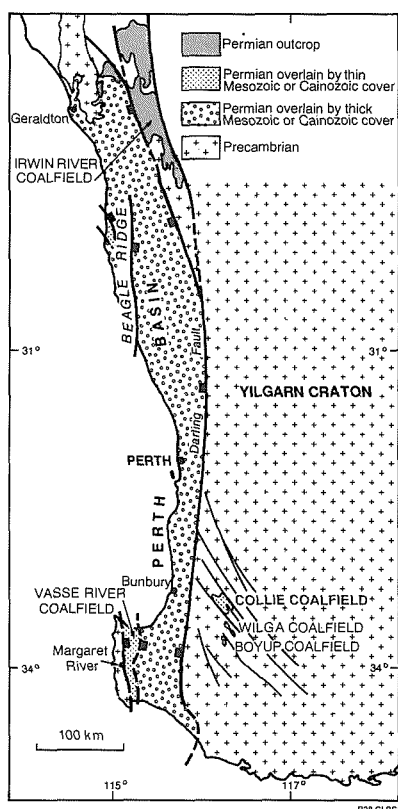


Figure 2. Location of the Collie Coalfield and fault-bounded Permian strata, southwestern Australia

Palynostratigraphy

A number of deep, fully cored boreholes drilled in the Collie Basin have allowed detailed subdivision of the sequence using palynomorphs. Ten palynological zones ranging approximately from the Asselian to the Ufimian were used by Backhouse (1991) for correlation within the basin (Fig. 3). This zonal scheme has been successfully extrapolated from the Collie Basin for over 900 km across a Permian depositional dip section: from the proximal Vasse Coalfield in the southern Perth Basin, northwards through the Irwin River Coalfield, and into the largely marine Carnarvon Basin. Marine faunas in the northern Perth and Carnarvon Basins, recently reviewed by Archbold et al. (1993), provide valuable age control for the palynostratigraphic units.

A suspected lacuna exists within the Collie Group, coincident with the base of the *Didictriletes ericianus*

Zone and a jump in vitrinite reflectance from 0.4 to 0.6%. The sequence in the southern Perth Basin extends 800 m higher than the top of the Collie Group into younger Permian sediments with *Dulhuntyispora parvithola*, which places them in upper Stage 5 of the eastern Australian palynostratigraphic scheme of Kemp et al. (1977) and Price (1983). In the northern Perth Basin, the Wagina Sandstone, also of Late Permian upper Stage 5 age, overlies the marine Carynginia Formation, a unit that on current evidence does not extend above the *Praeolpatites sinuosus* Zone (Backhouse, 1993). The subsurface Permian of the Carnarvon Basin is not fully investigated, but at least 1800 m of largely marine sediments are present in the Kennedy Range area between the base of the *Pseudoreticulatispora pseudoreticulata* Zone and the *Microbaculispora villosa* – *Dulhuntyispora granulata* Zone level. This interval is represented by approximately 600 m of coal-bearing sediments in the Collie Basin. Further north there is evidence for a lacuna in the mid Permian, comparable in age with the missing

section beneath the Wagina Formation in the Perth Basin.

Gondwanan correlation and palaeoclimate

Permian palynofloras are strikingly similar in western Australia and the Gondwanan basins of India and southern Africa to the west. Correlation between these sequences in finer detail may provide evidence for the suspected lacuna below the *D. ericianus* Zone. Some of the Collie palynostratigraphic biohorizons, particularly in the Early Permian, are recognizable in studies on the Karoo sediments of southern Africa by Anderson (1977), Falcon (1975), and Falcon et al. (1984), and confirm that deposition of Sequence-P1 was broadly contemporaneous in southern Africa and western Australia (Fig. 3).

The *P. pseudoreticulata* Zone is equivalent to the construction phase of the periglacial alluvial deltaic platform in western Australia, whereas it equates to the transgressive inundation of equivalent platforms in the northern

SEQUENCE	WESTERN AUSTRALIA COLLIE BASIN LITHOSTRATIGRAPHY Le Blanc Smith, 1993	International Stage/Substage	COLLIE COALFIELD Palynostratigraphic units Backhouse, 1991	EASTERN AUSTRALIA Kemp et al., 1977 Price, 1983	KAROO BASIN Microfloral Zones Anderson, 1977	SOUTH AFRICA KAROO BASIN LITHOSTRATIGRAPHY	INDIAN GONDWANA BASINS LITHOSTRATIGRAPHY
P3	MUJA COAL MEASURES	? Kazanian	<i>P. rugatus</i>	upper Stage 5		BEAUFORT GROUP	RANIGANJ FORMATION
		? Ufimian	<i>D. ericianus</i>	lower Stage 5c	4d	VOLKSRUST	BARREN MEASURES FORMATION
P2	PREMIER COAL MEASURES	? Kungurian	<i>D. granulata</i>	lower Stage 5a	4b	FORMATION	BARAKAR FORMATION
		Baigendzinian	<i>M. villosa</i>	upper Stage 4b	4a		
			Consistent occurrence of <i>P. sinuosus</i>	upper Stage 4a	3c		
	ALLANSON SANDSTONE		<i>P. sinuosus</i>	lower Stage 4	3b		
P1	EWINGTON COAL MEASURES	Aktastinian	<i>M. trisina</i>	Stage 3b	2d	VRYHEID FORMATION	KARHARBARI FORMATION
			<i>S. fusus</i>	Stage 3a	2c		
	WESTRALIA SANDSTONE	Steritamaxian	<i>P. pseudoreticulata</i>		2b		
		Tastubian	<i>P. confluens</i>		2a		
	MOORHEAD FORMATION	? Asselian	Stage 2	Stage 2	1	PIETERMARITZBURG FORMATION	TALCHIR FORMATION
	SHOTT'S FORMATION					DWYKA FORMATION	
	ARCHAEOAN BASEMENT						

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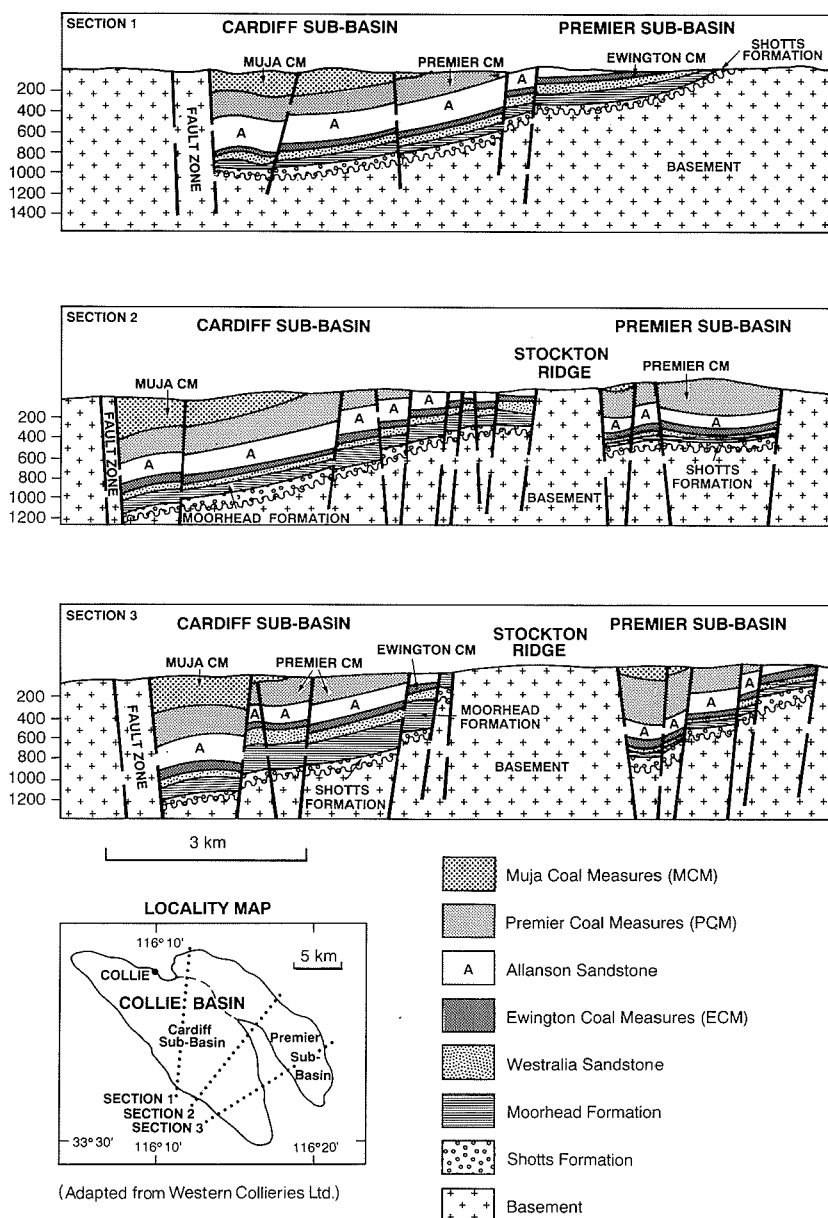
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Figure 3. Provisional correlation of Permian palynostratigraphic zones and rock stratigraphy

Karoo Basin and the accumulation of the Number 1 and 2 Seam coals of the Witbank–Transvaal Coalfield, and probably the Karharbari Formation of India. The *Striatopodocarpites fusus* Zone marks the earliest significant peat accumulation in western Australia in the Ewington Coal Measures of the Collie Basin and the Irwin River Coal Measures of the Perth Basin. The base of this zone correlates with Seam Number 3 of the Witbank–Transvaal Coalfield (Falcon et al., 1984). Further, the *Praeacolatites sinuosus* Zone closely overlies the Ewington and Irwin River Coal Measures, and correlates with palynomorphs of the Number 5 Seam of the Witbank–Transvaal Coalfield.

Provisional broad correlations equate the Ewington Coal Measures (Collie Basin) with the Irwin River Coal Measures (Perth Basin), Karharbari Formation – Lower Barakar Stage (numerous Indian basins), and the Vryheid Formation (Karoo Basin). The palynological sequences of central and eastern Australia can also be broadly correlated with the Collie Basin, but further work is required to establish precise zone boundaries in those areas.

There is a close parallel between the early palaeoenvironments of deposition of southern Africa and western Australia (Le Blanc Smith, 1980a,b,c, 1993; Le Blanc Smith and Eriksson, 1979); however, palynological correlations suggest that the onset of substantial peat accumulation commenced earlier in southern Africa than in western Australia. One inference of this is that the global Permian climatic amelioration probably commenced in the west of Gondwana (southern Africa) and progressed eastwards, through the Indian subcontinent to western Australia and on to eastern Australia.



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Figure 4. Rock stratigraphic and structural sections of the Collie Basin. From Le Blanc Smith (1993)

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Base-metal deposits in the Early Proterozoic Glengarry terrane, Western Australia

by G. Le Blanc Smith, F. Pirajno, D. Nelson, and K. Grey

Abstract

The southeastern terrane of the Glengarry Basin contains chert and stromatolitic carbonate units from both the Glengarry and Earahedy Groups that are unconformably juxtaposed with black carbonaceous argillite along easterly trending faults. Chert breccias and hydraulically fractured laminates occur between stromatolitic units, which are locally silicified. Field observations suggest that the fractured and brecciated horizons were palaeoaquifers, which were contained between relatively impermeable chertified stromatolitic units near the unconformity between the Glengarry and Earahedy sequences. Pervasive silicification resulted in a gradual build-up of fluid pressure and consequent hydraulic fracturing when this pressure exceeded the lithostatic load. The presence of hydrocarbon residues, local base-metal anomalies, and the silicification and brecciation of specific horizons has implications for the genesis of hydrothermal mineral deposition. Metal ores may have precipitated from the overpressured hydrocarbon-rich brines by processes such as hydrocarbon-gas expulsion during thermal maturation of source rocks. Lead-isotope data indicate a model age of 1.65 Ga for the mineralization.

KEYWORDS: Proterozoic, Glengarry, Earahedy, base-metal, carbonate, Mississippi Valley, hydrocarbon, stromatolite, breccia, palaeoaquifer, lead-isotope dating.

The stratigraphy of the Glengarry terrane is being re-examined. It is necessary to establish the stratigraphy of the principal units in order to determine the migration history of metals and hydrocarbons, and their possible subsequent alteration. Two principal stromatolitic chert-dolostone units occur at the base of the Earahedy Group and the underlying Glengarry Group respectively. Grey (1994a) postulates a depositional age older than 1.8 Ga for the Earahedy Group based on comparative biostratigraphic studies. In the south of the Glengarry terrane these units are unconformably juxtaposed, and there appear to be interfaces with black argillite along easterly trending extensional faults. This is significant considering that Mississippi Valley-type (MVT) deposits are commonly close to unconformities of regional extent where fluid migration may be enhanced (Callahan, 1967; Sangster, 1988).

The Glengarry terrane contains a thick sequence of Early Proterozoic sedimentary and volcanic rocks, largely within the Capricorn Orogen between the Yilgarn and Pilbara Cratons (Fig. 1). The area has been mapped, and a preliminary stratigraphy determined, at a scale of 1:250 000 (Elias and Bunting, 1982; Elias et al., 1982; Gee, 1987). The northwestern margin of the Glengarry terrane is in tectonic contact with the Peak Hill and Border tectonostratigraphic terranes (Pirajno et al., this volume) and is preserved in an easterly trending, terraced rift setting over the Yilgarn Craton to the south and east.

The Glengarry terrane

The Glengarry terrane is characterized by a volcano-sedimentary sequence that is relatively undeformed and has undergone low-grade metamorphism (Fig. 1). Significant differences in depositional facies and stratigraphy exist between the Peak Hill and Glengarry terranes, and these will be discussed elsewhere in the course of the new initiative mapping program.

* Capitalized names refer to standard map sheets.

Stromatolite occurrences near Crystal Well

A significant number of microbial-laminated and stromatolite-bearing strata occur within the Glengarry sequence (Gee and Grey, 1993; Grey, 1994b). The stromatolite succession is characterized by diagnostic stromatolite taxa, and specimens from new localities are not only consistent with distributions previously recorded, but also suggest that further refinement of the stratigraphic subdivision is feasible. An intercalation of at least four stromatolitic cherty carbonate units separated by thin, hummocky cross-stratified, calcareous silty sandstone (HCS) occurs in the hills

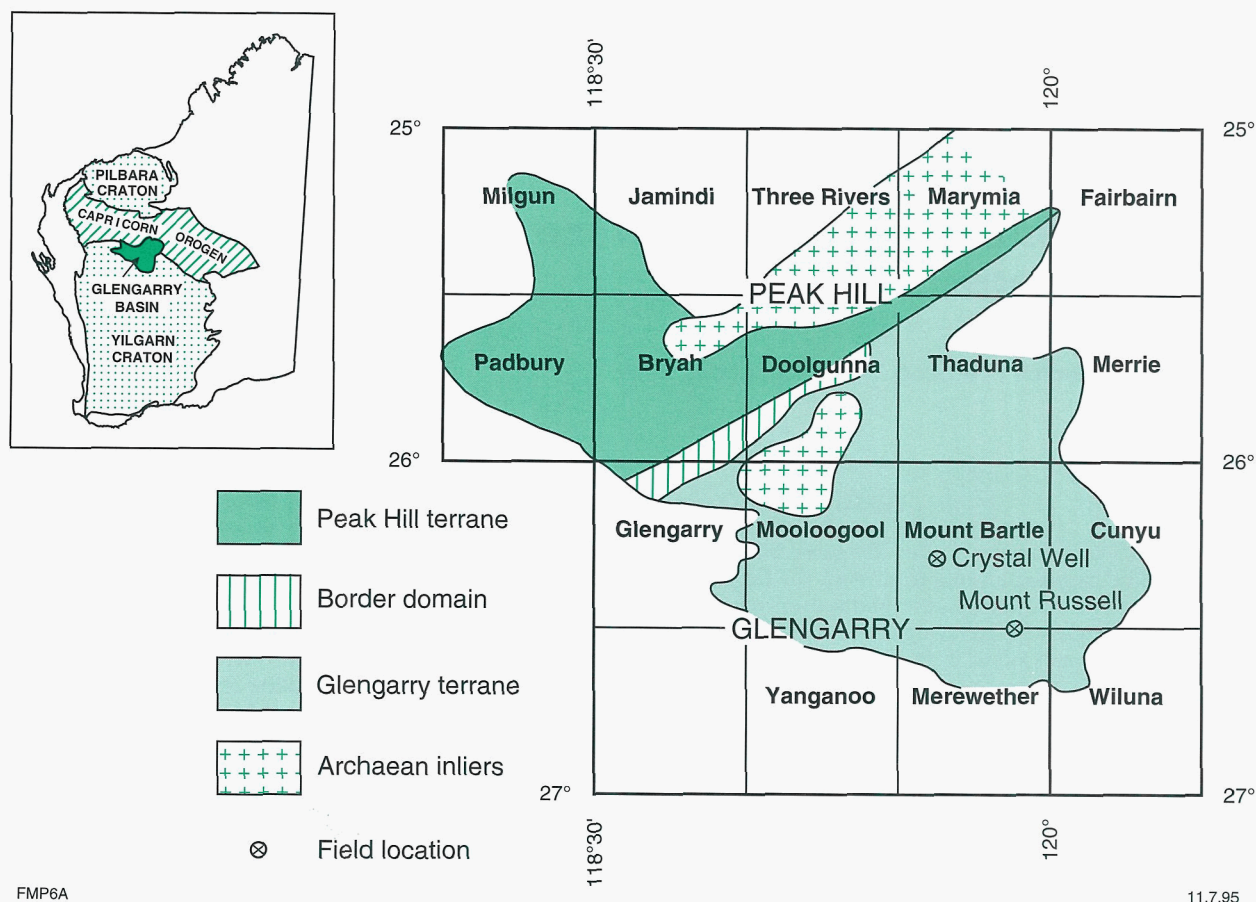


Figure 1. Location map of the area covered by Early Proterozoic Glengarry sequence rocks

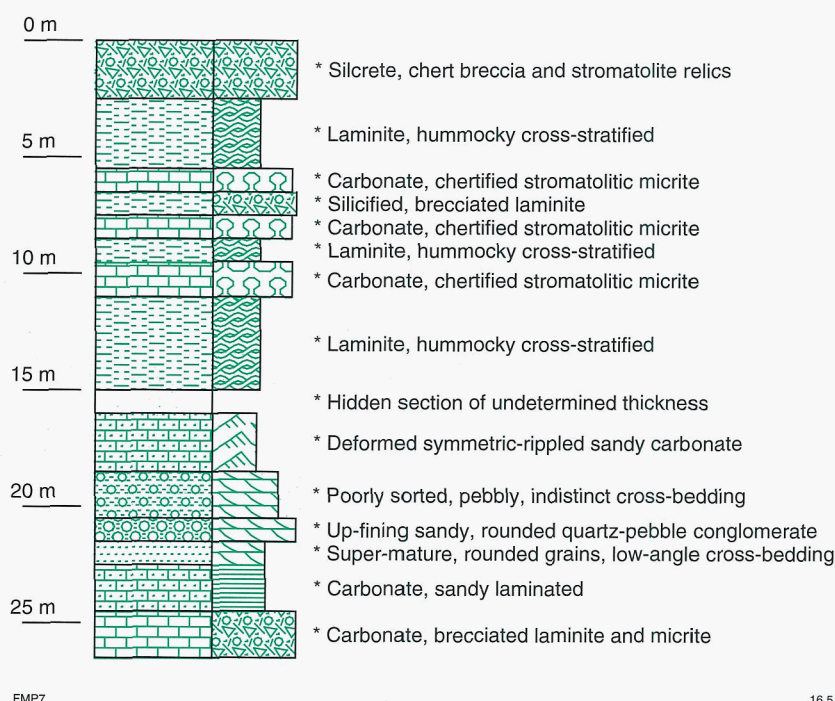


Figure 2. Composite stratigraphic column — Crystal Well area

to the southeast of Crystal Well on Paroo Station (latitude 26°16'37"S, longitude 119°39'02"E); these are underlain by a thin sequence of mature stratified quartz-pebble conglomerate and cross-stratified sandstone, which overlie a carbonate-breccia unit of undetermined thickness. The exposures are limited and weathered, and interpretation of the depositional structures is not conclusive. The siliciclastic units are interpreted as shoreline deposits that prograded onto a carbonate-shelf sequence before being transgressed and reworked by shelf processes. The origin of the underlying carbonate breccia is the subject of current studies. It is possibly a karst surface associated with an unconformity between the Glengarry and Earahedy Groups, but could be a collapse breccia associated with dissolution of evaporite minerals, or debris associated with carbonate reef structures. The overall sequence indicates broad transgression and deepening of the basinal waters.

Chert breccias

Chert and chert–dolostone breccias and hydraulically fractured laminates occur between stromatolitic dolostone units, which are locally silicified. Breccia fragments have small displacements at some localities, and the original laminate morphology can be visualized due to the ‘jigsaw’ nature of the breccias. These units are areally extensive, and field observations suggest that the fractured and brecciated horizons were palaeoaquifers, contained between relatively impermeable stromatolitic units. Pervasive silicification resulted in a gradual build-up of fluid pressure and consequent hydraulic fracturing when this pressure exceeded the lithostatic load. An idealised composite stratigraphic column illustrating these features is shown in Figure 2. The silicification and brecciation of specific horizons has implications for the genesis of hydrothermal sulfide deposition.

Mineralization

Black argillite in the Glengarry sequence is locally anomalous in copper (up to 2800 ppm), zinc, and mercury (Drummond, 1984). Recent exploration activity has located a number of anomalies. Some of these are significant, such as the estimated 220 Mt lead-carbonate and -oxide deposit announced by RGC Exploration in 1993. Cored inter-sections of thick black carbonaceous argillite and chert–carbonate breccia in the southeastern area (Fig. 3) show possible coalified hydrocarbon residues (Drummond, 1984) that were probably sourced from stromatolitic units and black argillite, and subsequently migrated into the carbonate breccia. The formation and migration of petroleum as a consequence of the burial and maturation of organic-rich source rocks are well recorded in the Precambrian (McKirdy and Hahn, 1982), and Proterozoic hydrocarbon accumulations have been reported from Siberia (Meyerhoff, 1980), the McArthur Basin (Jackson et al., 1986), and from the Transvaal Sequence (Roberts et al., 1993). This has implications for the occurrence of MVT and other basin-related base-metal deposits in the Glengarry sedimentary sequence.

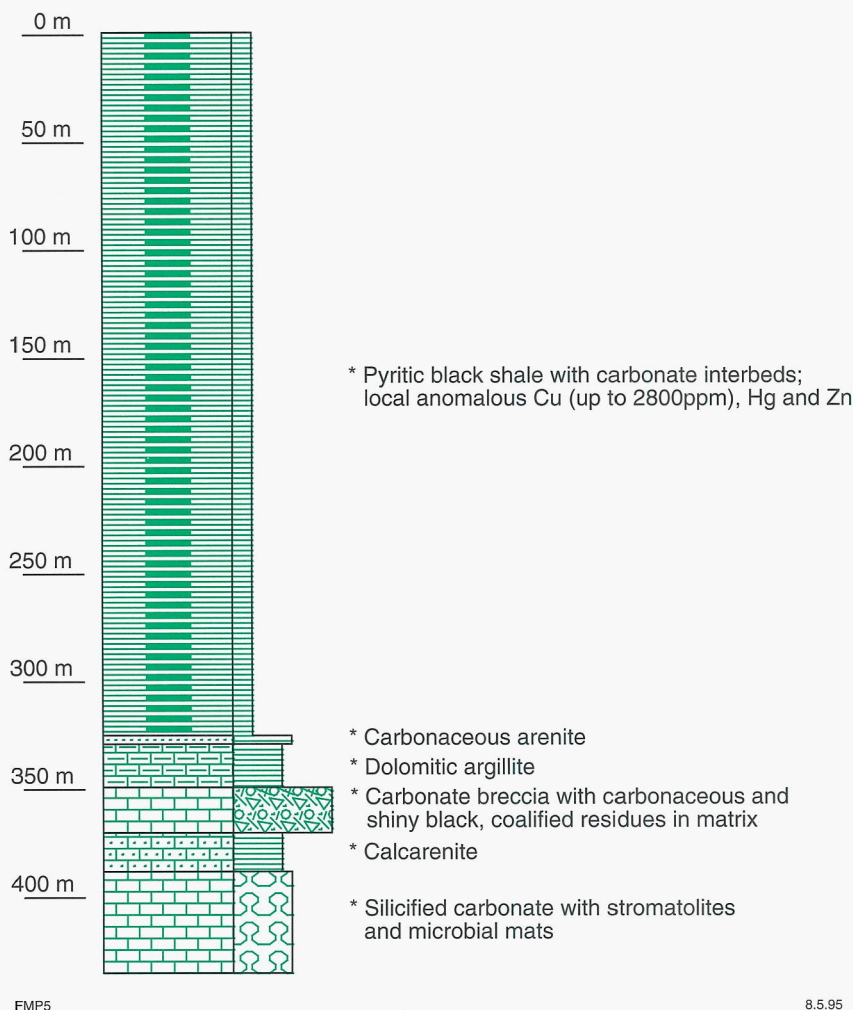


Figure 3. Composite stratigraphic column — Mount Russell area (latitude 26°31'S, longitude 119°51'E)

Coalified hydrocarbon residues in carbonate breccias, possibly similar to those of the Glengarry sequence, are recorded in association with base-metal accumulations from the Transvaal Sequence in South Africa (Wheatley et al., 1986; Roberts et al., 1993), and from the Palaeozoic Lennard Shelf, Canning Basin, northwestern Australia (Eisenlohr et al., 1994). Metal-ore precipitation could have occurred from over-pressured fluids by processes that include the expulsion of hydrocarbon-rich brines, propelled by hydrocarbon gas produced during the thermal maturation of the source rocks. The source of this large amount of lead is unknown; however, it can be speculated that the lead was derived from the feldspars of the feldspathic units in the sedimentary sequence. The derivation of lead from

permeable feldspathic horizons has previously been suggested for MVT deposits (Doe and Delevaux, 1972).

Structural and palaeoenvironmental reconstructions using both surface and subsurface mapping techniques could be used to reconstruct and locate the principal routes of hydrocarbon and metal-bearing brine migration, and the loci of the principal depositional facies (including evaporites, carbonate reefs, shelf sandstones, and marginal-slope facies) that have potential for metals accumulation.

Two samples collected by the Geological Survey of Western Australia were analysed and dated using the Pb–Pb model-age method (Cumming and Richards, 1975). Analytical results are given in

Table 1 and the results of the dating are shown in Figure 4. The lead-isotope data indicate a model age of 1.65 Ga.

Acknowledgments

The authors are grateful to geologists from RGC Exploration Pty Ltd, in particular to Dr David Pascoe, for discussions in the field and access to their core library.

Table 1. Selected whole-rock and trace-element analyses of samples 112725 and 112729, which have a Pb–Pb model age of 1.65 Ga (see Fig. 4)

	(a)112725	112729
	percent	
Fe ₂ O ₃	2.38	0.43
	parts per million	
Ag	43	12
As	7	<4
Au	<10	<10
Ba	442	115
Bi	<4	<4
Cd	<5	<5
Ce	<6	<6
Cr	60	21
Cu	265	95
Ga	293	297
Ge	4	5
La	19	13
Mn	24	54
Mo	3	<2
Nb	<7	<7
Ni	42	15
Pb	431 300	484 600
Rb	50	46
Sb	<4	<4
Sn	<4	<4
Sr	<2	<2
Ta	<5	<5
Te	<6	<6
Th	<2	<2
U	<2	2
V	62	20
Y	<2	<2
Zn	64	32
Zr	220	206

(a) Geological Survey of Western Australia sample number

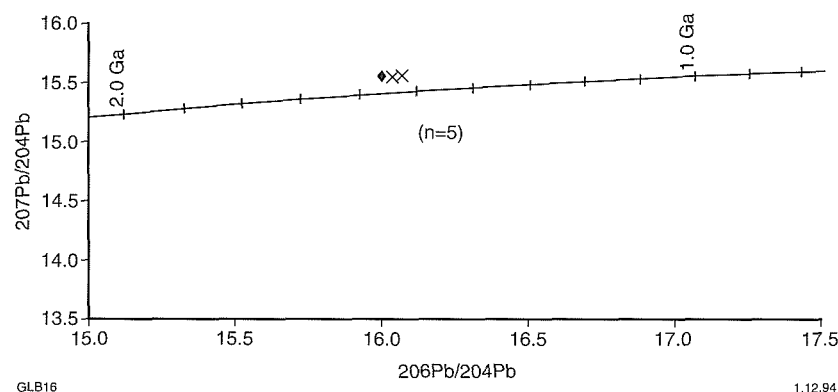


Figure 4. Lead-isotope plot showing the Cumming and Richards (1975) ore lead-isotope evolution curve and the analyses obtained for lead minerals from the Glengarry terrane

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Pillow lavas in the Peak Hill and Glengarry terranes

by F. Pirajno, S. Occhipinti, G. Le Blanc Smith, and N. Adamides

Abstract

Pillow lavas occur in the Peak Hill and Glengarry tectonostratigraphic terranes (previously known as the Glengarry Basin). The lavas in the Peak Hill terrane have been deformed and metamorphosed to greenschist facies. Deformation and metamorphism may have been responsible for the channelling of fluids along shear zones. Gold mineralization is spatially associated with these shear zones. The pillow lavas in the Glengarry terrane underlie a sequence of black shales, are undeformed, and unmetamorphosed.

KEYWORDS: terrane analysis, pillow lavas, metamorphism, gold.

This is a preliminary report on the occurrence of basaltic pillow lavas in the southern areas of the Peak Hill and Glengarry tectonostratigraphic terranes (Fig. 1) of probable Early Proterozoic age. These terranes are part of what was previously known as the Glengarry Basin, which occupies the western portion of the Napperu Province, on the northern margin of the Archaean Yilgarn Craton (Capricorn Orogen; Fig. 1). The structural and tectonic evolution of the Glengarry Basin has been previously studied by Windh (1992) and Gee and Grey (1993).

Field observations integrated with photogeological and satellite-imagery interpretations suggest that the area known as the Glengarry Basin was formed by the amalgamation of at least three distinct tectonostratigraphic terranes. They are here provisionally named the Peak Hill and Glengarry terranes and the Border domain. A tentative and simplified geotectonic overview of the area is shown in Figure 1.

The Peak Hill terrane includes mafic-ultramafic volcanic rocks, and clastic and chemical sedimentary rocks that have been intensely deformed and metamorphosed up to middle greenschist facies. The deformation and metamorphism of this terrane are linked to its collision with a rigid Archaean block (Narryer Complex). The genesis of the epigenetic gold deposits of the Peak Hill terrane may also be related to this collision event.

The Border domain marks a major tectonic discontinuity along which the Glengarry and Peak Hill terranes were juxtaposed. A sedimentary basin was formed along this tectonic boundary, which acted as a depocentre for mass-wasting sourced from the adjacent, uplifted terranes. Structurally controlled gold and copper mineralization is present in this terrane.

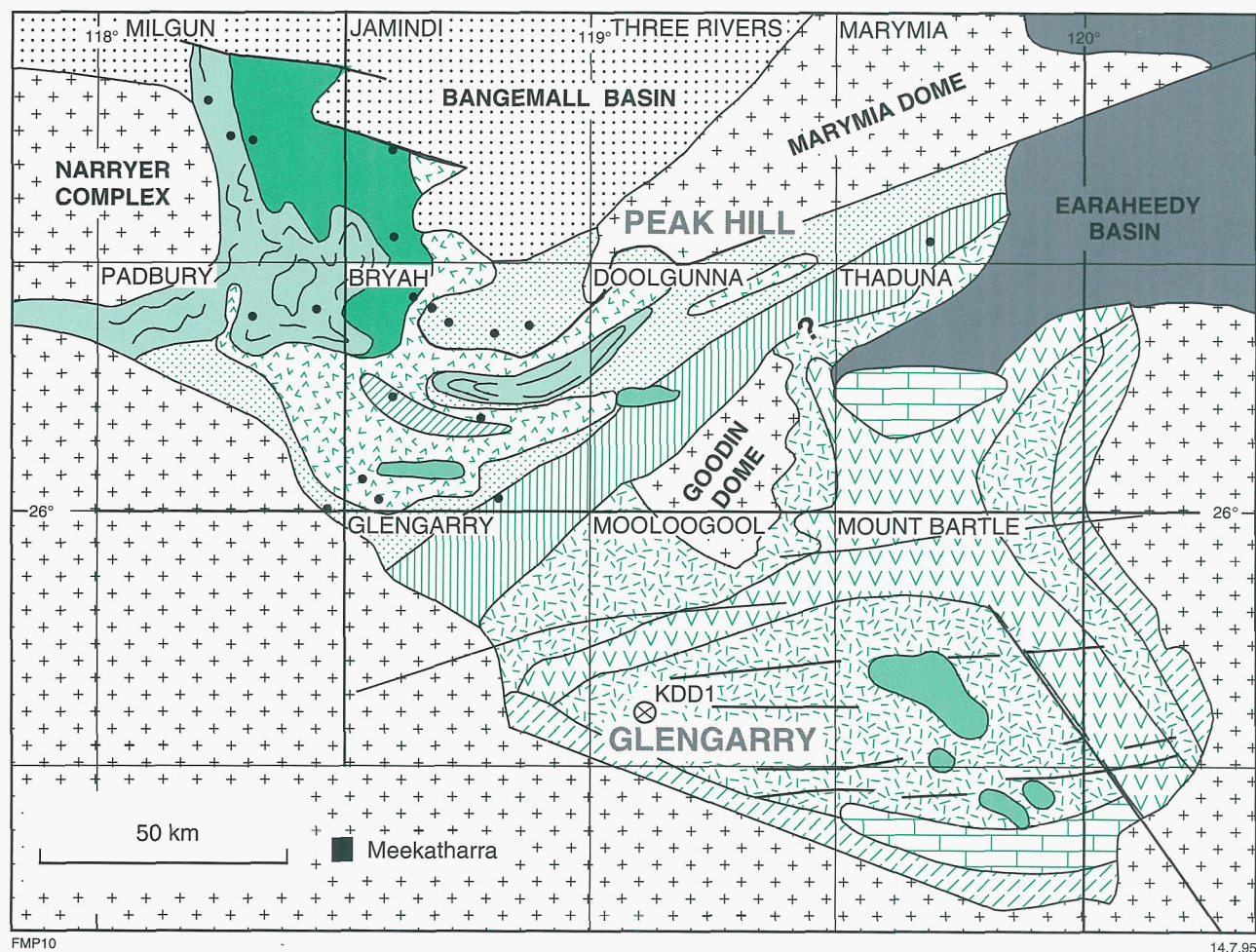
The Glengarry terrane is composed of a volcano-sedimentary sequence (Glengarry Group) deposited in an intracontinental-rift setting. Field work, integrated with core

examination from a number of drillholes, indicates that this terrane was formed during an extensional phase followed by a compressional phase. The former involved a phase of rifting, during which voluminous mafic intrusive and volcanic rocks were emplaced. This was followed by easterly trending listric faulting, with rotation and tilting of the strata towards the north. The compressional phase was characterized by re-activation of the listric faults, uplift, and mass-wasting with deposition of turbidites.

Mafic and ultramafic rocks on PEAK HILL* (1:250 000) have been grouped under the name Narracoota Volcanics (Gee, 1987). They have an estimated thickness of approximately 4000 m, occupy a mid-stratigraphic position in the Glengarry Group (Gee, 1987; Gee and Grey, 1993), and are thought to interfinger with volcanogenic clastic sediments (Thaduna Formation). A geochemical study of the Narracoota Volcanics by Hynes and Gee (1986) led to the conclusion that the volcanics have a general tholeiitic composition and may have originated in a continental-rift setting, although they appear to have a MORB-like signature.

In this paper we describe lavas from an arcuate belt of massive to pervasively deformed and sheared volcanic rocks in the southwest portion of PEAK HILL (Fig. 1). Pillow structures are common, and are recognizable even where they are deformed. We also report on the occurrence of a sequence of flat-lying, basaltic pillow lavas intersected at a depth of 400 m in a

* Capitalized names refer to standard map sheets.



PEAK HILL TERRANE

- Padbury Group
- Labouchere Group
- Clastics
- Narracoota Volcanics and associated sedimentary rocks
- Pillow lavas on BRYAH

BORDER DOMAIN

- Clastics mainly, and olistostromes

GLENGARRY TERRANE

- Turbidites
- Clastics and carbonate sequences
- Mafic volcanics (pillow lavas and sills and dykes?)
- Siliciclastics

- Epigenetic gold
- ⊗ Diamond drillhole
- Fault

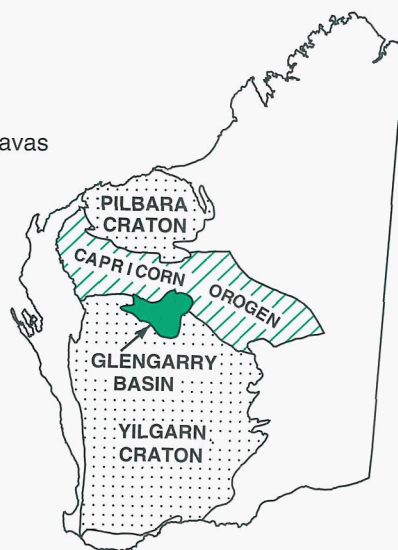


Figure 1. Simplified geotectonic and locality map of the Glengarry Basin showing the location of the 1:100 000 map sheets, the pillow lavas on BRYAH, and the drillhole on MOOLOOGOL. Inset shows the position of the basin within the Capricorn Orogen

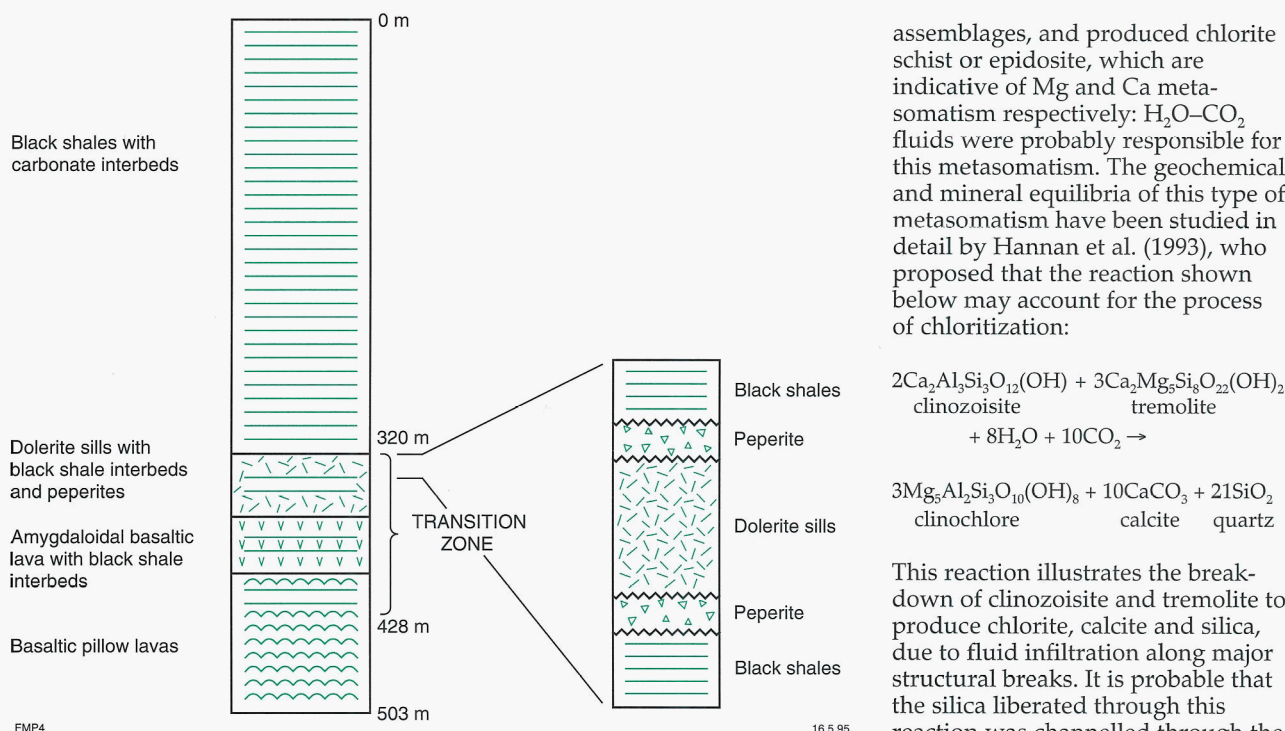


Figure 2. Idealized stratigraphy as deduced from drillhole KDD1. See text for details

diamond drillhole sunk by CRA Exploration in 1985 (Blomley and Cull, 1985). This drillhole is located 20 km east-southeast of the Killara Homestead, on GLENGARRY (1:250 000). The volcano-sedimentary sequence intersected by the drillhole belongs to the Glengarry terrane (Fig. 1).

BRYAH (1:100 000)

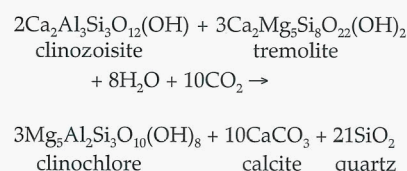
The pillow lavas and associated mafic-ultramafic schist occur in an arcuate belt in the southern part of BRYAH (on PEAK HILL 1:250 000) and are folded into an anticlinal structure (Gee, 1987). The presence of folding has been deduced from the younging directions of the pillows at a number of localities. Detailed geological mapping indicates that this belt of rocks is a major anastomosing shear domain, which contains pod-like outcrops of less-deformed pillow lavas. Dolerite sills have intruded the pillow lavas, and in the southwestern part of BRYAH the pillow lavas are associated with autoclastic and vent breccias.

The dominant schistosity within the shear zone dips steeply towards the

north and south, and strikes approximately east to west. A mineral lineation, defined by aligned chlorite porphyroblasts, has a shallow to moderate plunge towards the east. This indicates that maximum extension during deformation was in an approximately easterly trending direction. Quartz veins within the shear domain also trend approximately east to west. The major deformation event that affected the pillow lavas was probably D_2 , based on overprinting relations in the Robinson Range Syncline. Field observations suggest a left-lateral shear sense.

Massive to weakly deformed mafic volcanic rocks are fine- to medium-grained, with a regional metamorphic assemblage of tremolite-actinolite, albite, clinozoisite, chlorite, titanite, calcite, and quartz. The original igneous components of the rocks have been totally replaced by these minerals during regional greenschist-facies metamorphism. Within the shear domain, metasomatism of greenschist metamorphic assemblages accompanied pervasive deformation. This metasomatism resulted, in some cases, in chlorite- or epidote-dominated

assemblages, and produced chlorite schist or epidosite, which are indicative of Mg and Ca metasomatism respectively: $\text{H}_2\text{O}-\text{CO}_2$ fluids were probably responsible for this metasomatism. The geochemical and mineral equilibria of this type of metasomatism have been studied in detail by Hannan et al. (1993), who proposed that the reaction shown below may account for the process of chloritization:



This reaction illustrates the breakdown of clinozoisite and tremolite to produce chlorite, calcite and silica, due to fluid infiltration along major structural breaks. It is probable that the silica liberated through this reaction was channelled through the shear zone, resulting in zones of extensive silicification and/or quartz veins.

MOOLOOGOO (1:100 000)

Undeformed and unmetamorphosed pillow lavas occur in the southeastern part of MOOLOOGOO (1:100 000), and underlie a sequence of black shales approximately 320 m thick. This volcano-sedimentary sequence was intersected by exploration drilling (diamond drillhole KDD1 at latitude $26^\circ 24' 30''\text{S}$, longitude $119^\circ 08' 30''\text{E}$; Bromley and Cull, 1985; Figs 1 and 2). Between the black shales and the pillow lavas a transition zone, approximately 108 m thick, marks the transition from volcanism to sedimentation. This zone is characterized by intercalated thin beds of black shale, and doleritic sills and amygdaloidal basaltic lavas (Fig. 2). Peperite margins in the contact zones between the igneous material and the sedimentary rocks suggest that the mafic melts intruded wet and unconsolidated sediments. A continuous sequence of basaltic pillow lavas intersected by KDD1 occurs below 428 m from the top of the drillhole (Fig. 2).

The pillow lavas and the overlying shales are thought to have been deposited in a developing rift. They are associated with cogenetic mafic

sills and are part of a thick, little-deformed and unmetamorphosed volcano-sedimentary sequence in the Glengarry terrane (Fig. 1).

Conclusions

The pillow lavas in the Peak Hill and Glengarry terranes indicate the occurrence of subaqueous volcanism, possibly related to incipient phases of rifting. This is supported by the work of Hynes and Gee (1986) who concluded that the Narracoota Volcanics are tholeiitic in composition and were erupted in a continental-rift setting.

The Wembley and Heines Find gold deposits on BRYAH are hosted in discrete shear zones within the arcuate shear domain. It is possible that the mineralization is related to the movement of fluids along these structural breaks. Detailed studies are needed to characterize the nature of the pillow lavas, their significance in terms of the geodynamic evolution of the Peak Hill and Glengarry terranes, and their possible role in ore genesis.

Acknowledgements

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Tectonic evolution and economic geology of the Paterson Orogen — a major reinterpretation based on detailed geological mapping

by A. H. Hickman and L. Bagas

Abstract

Recent mapping of the RUDALL and BROADHURST 1:100 000 sheets has provided considerably more detailed geological data than was previously available from reconnaissance investigations carried out in 1975–76. The new information has necessitated major reinterpretations of stratigraphy, structure, tectonic evolution, and mineral potential in this central part of the Paterson Orogen.

The oldest component of the orogen, the Rudall Complex, contains a foreland basin-type clastic succession divisible into five formations. The Pilbara Craton, which flanks and underlies the western side of the Paterson Orogen, collided with a plate of uncertain character (continental or oceanic) moving from the northeast, some time after 1780 and before 1500 Ma. As a result, the sedimentary succession was thrust and overfolded from the northeast and east, metamorphosed to amphibolite facies, and extensively intruded by sheets of granite–granodiorite. Plate convergence continued spasmodically until about 1250 Ma, and was accompanied by late-stage, relatively minor felsic magmatism.

The Yeneena Group, which unconformably overlies the Rudall Complex, is a sandstone–shale–carbonate assemblage that was deposited between about 1100 and 850 Ma. Its depositional environments were regionally variable, and lateral stratigraphic relationships outside the RUDALL–BROADHURST area are still being examined. In the Broadhurst Range – Rudall River region fluvial–deltaic deposition commenced in a northwesterly trending strike-slip basin system, with terrigenous supply coming from the southwest. The syndepositional strike-slip and oblique faults indicate broadly northeast–southwest compression, and the strike-slip regime is interpreted as a post-collisional response to continued plate convergence.

Infilling of the Broadhurst Range basin system was followed by widening of the Yeneena Basin and extensive carbonate deposition (Isdell Formation). At this stage, the basin deepened to the northeast, and only in the Telfer district are higher stratigraphic units now preserved. Transpressional upright folding and high-angle thrusting between about 900 and 700 Ma resulted in the main northwest-trending fold system (D₄) of the Paterson Orogeny.

Mineralization, mainly involving gold, copper (locally with lead and zinc), and uranium is chiefly syn- to post-Yeneena Group in age. Outside the Telfer area (still to be mapped at 1:100 000), most significant deposits and geochemical anomalies occur on, or in close proximity to, northwest to north-northwest striking faults. These structures are interpreted as syndepositional strike-slip or oblique faults, reactivated during D₄.

KEYWORDS: Paterson Orogen, Proterozoic, Rudall Complex, Yeneena Group, tectonic evolution, plate tectonics, geological structures, stratigraphy, mineralization, thrust faults, strike-slip basin.

As discussed by Blockley and de la Hunty (1975), geological knowledge of the Paterson Orogen (referred to as a 'province' until 1990) was extremely limited prior to reconnaissance mapping at a scale of 1:250 000 by the Geological Survey of Western Australia between 1974 and 1976 (Chin et al., 1980, 1982). The conclusions reached from that work were first reported by Williams et al. (1976), and later expanded, using additional information, by Williams and Myers (1990). The main conclusions were:

- (i) the Paterson Orogen consists of the Rudall Complex (igneous and sedimentary rocks metamorphosed to amphibolite facies) unconformably overlain by the Yeneena Group (clastic and carbonate rocks), which in turn is unconformably overlain by the Karara Formation (clastic and carbonate rocks);
- (ii) the Rudall Complex has a long and complex history of multiple deformation and metamorphism, but contains two distinguishable units: older banded orthogneiss and paragneiss, and younger quartzite and schist;
- (iii) the stratigraphic succession of the Yeneena Group is regionally variable due to deposition in three zones of differing palaeogeographic, tectonic, metamorphic, and igneous history.

Geological mapping of BROADHURST* and RUDALL (1:100 000) in 1989–92 has established that although the 1974–76 reconnaissance mapping was successful in identifying the

* Capitalized names refer to standard map sheets.

main stratigraphic features of the Yeneena Group, it was insufficiently detailed to adequately describe: (a) the geology of the Rudall Complex and, (b) the overall structural geology of the Paterson Orogen. Likewise, very little information relevant to the economic geology of the region and future mineral potential was provided.

Background information

Before describing the tectonic evolution of the central part of the

Paterson Orogen, it is necessary to briefly review present knowledge of the stratigraphy and structure of BROADHURST and RUDALL (Figs 1 and 2).

Table 1 summarizes the Proterozoic stratigraphy of the BROADHURST–RUDALL area, but does not represent the stratigraphy of the entire orogen because of regional stratigraphic variations. Preliminary data from CONNAUGHTON (Bagas and Smithies, in prep.) reveal additional stratigraphic units in the Rudall Complex, and the Yeneena Group successions of the McKay Range,

western THROSSELL, and the Telfer area are known to differ from that of the Broadhurst Ranges (Table 1).

Table 2 outlines the recognized episodes of deformation and metamorphism in the area. It should be noted, however, that D_2 deformation was not a single event, but probably involved spasmodic thrusting and folding over c. 100–200 million years. The complexity of D_2 is illustrated by the presence of distinct tectono-stratigraphic domains on RUDALL (Fig. 3). These domains are thrust-bounded slices of interfolded paragneiss and orthogneiss, which together form a 40 km-wide imbricate zone. Stacking and contact relationships indicate that north-eastern domains have overridden domains to the southwest.

Tectonic evolution

Rudall Complex

The first recognizable stage in the evolution of the Rudall Complex involved the deposition of a siliciclastic succession, approximately 5000 m thick, encompassing units from the Larry Formation through to the Butler Creek Formation (Table 1), probably prior to about 1780 Ma. The succession indicates shoreline–shelf–slope environments in a subsiding foreland basin. The turbiditic Butler Creek Formation thickens eastwards, and the relatively shallow-water sand deposits of the Fingoon Quartzite become thinner to the northeast, implying the presence of a continent to the west during their accumulation. The local occurrence of a large amount of quartzofeldspathic sandstone in the Yandagooge Formation of northeastern RUDALL, indicates a source of feldspar-rich detritus to the northeast. Palaeocurrent evidence has been destroyed, and complex deformation on a regional scale makes palaeogeographic reconstructions difficult. Nevertheless, the features are consistent with shallow-water deposition in a foreland basin on the eastern margin of a continent.

The lowest part of the Poynton Formation consists of well-sorted quartz sands and minor pebble beds, which comprise a

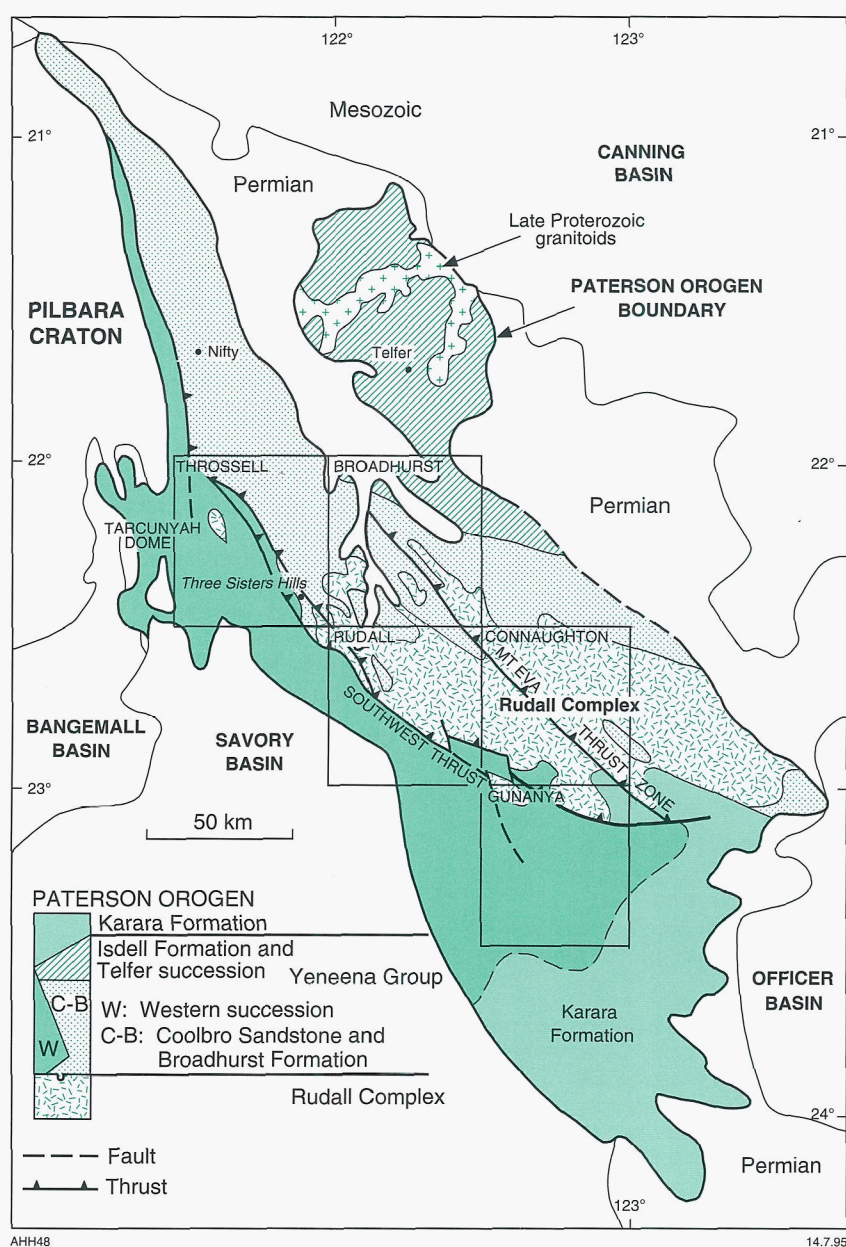
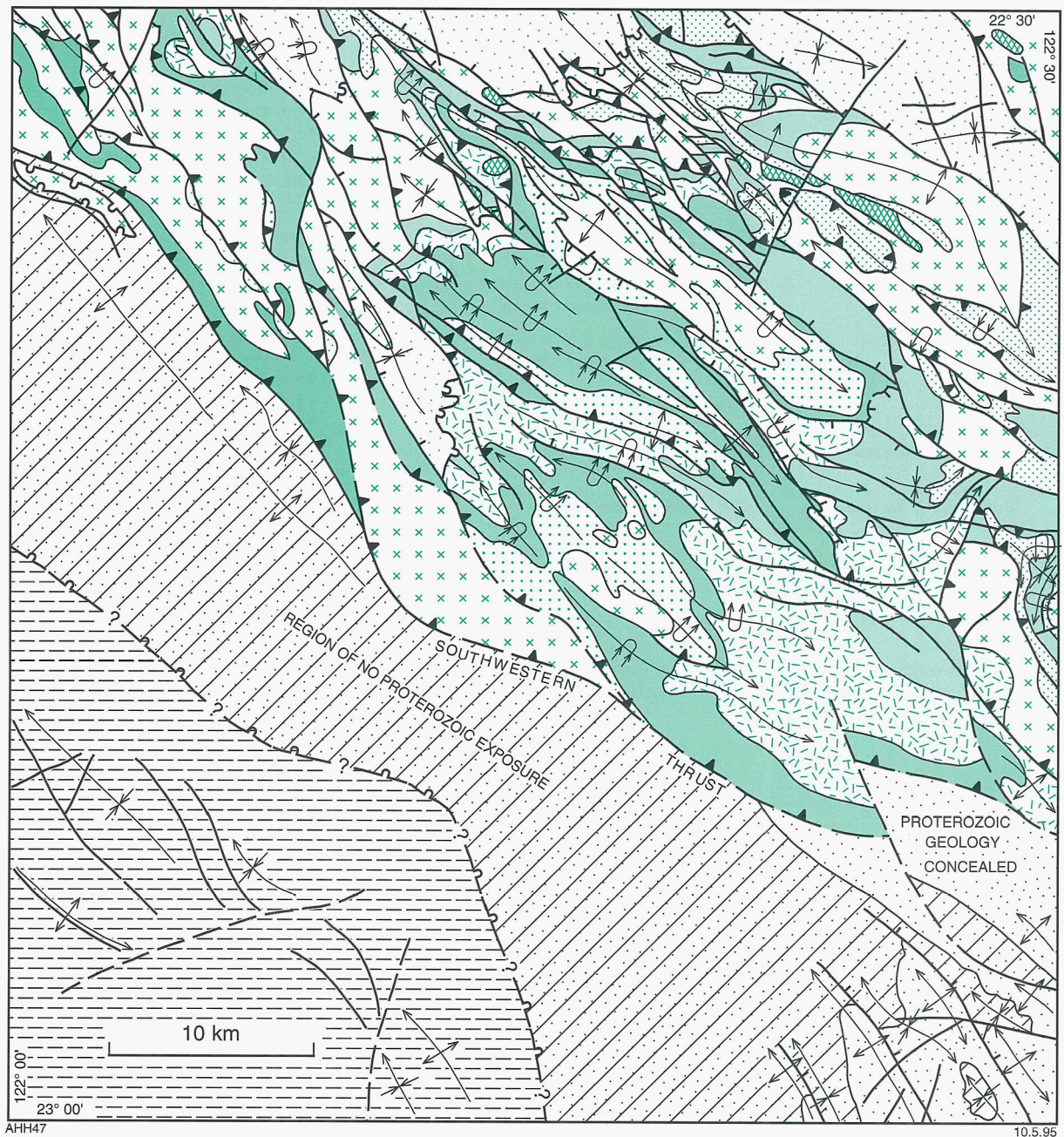


Figure 1. Location of mapped and partly mapped 1:100 000 sheets in the Paterson Orogen



Savory Group



Yeneena Group

Siltstone, carbonate,
sandstone

Sandstone, minor siltstone

Rudall Complex



Peridotite



Orthogneiss

Unassigned meta-
sedimentary rocks

Poynton Formation



Butler Creek Formation



Yandagooge Formation



Fingoon Quartzite



Larry Formation



Anticline



Syncline



Anticline, overturned



Syncline, overturned



Thrust fault



Lag fault



Fault



Unconformity

Figure 2. Simplified geological map of RUDALL, showing major structures and Proterozoic stratigraphy

Table 1. Proterozoic stratigraphy of BROADHURST and RUDALL, excluding the McKay Range succession (Yeneena Group)

	Stratigraphic unit	Thickness (m)	Lithology
YENEENA GROUP	Isdell Formation	>1 000	Limestone, dolostone, calcareous siltstone, and minor shale
	Choorun Formation	<2 000	Sandstone, siltstone, shale, conglomerate, and minor dolostone
	Broadhurst Formation	0 – 2 000	Shale, greywacke, sandstone, and minor carbonate rocks
	Coolbro Sandstone	0 – 4 000	Sandstone, minor siltstone, shale, and local basal conglomerate
~~~~~unconformity~~~~~			
RUDALL COMPLEX	Poynton Formation	>1 000	Quartzite, psammitic gneiss, quartz-muscovite schist, minor BIF
	Butler Creek Formation	>1 000	Banded paragneiss, minor quartzite, quartz-biotite schist
	Yandagooge Formation	1 500	Pelitic to semi-pelitic schist, minor quartzite, and BIF
	Fingoon Quartzite	1 500	Quartzite, minor quartz-muscovite schist
	Larry Formation	>1 000	Psammitic gneiss, minor muscovitic quartzite

shallow-shelf facies quite distinct from the underlying turbidites of the Butler Creek Formation. This abrupt change is not associated with an angular unconformity, but a disconformity could be present. The Poynton Formation is thicker towards the east, but its stratigraphic top is not preserved, and thickness variations could be due entirely to a combination of thrusting and granitoid intrusion. Altered fine-grained units at some localities include metamorphosed felsic volcanic rocks or felsic volcanogenic sedimentary rocks. This indicates prior or contemporaneous felsic volcanism, but there are no volcanic remnants of a magmatic arc in the Rudall Complex. If such an arc existed it must have been situated to the east or northeast of RUDALL.

The most striking geological feature of the Rudall Complex is the widespread intrusive and structural interleaving of meta-sedimentary rocks and orthogneiss. Examination of the map reveals that, although detailed relationships are complex, two valid generalizations can be made:

- (i) lithologically layered and xenolithic orthogneiss is almost entirely restricted to the western margin of the Rudall Complex, and
- (ii) the K-feldspar-augen orthogneiss is mainly confined to sheets within the Yandagooge Formation – Butler Creek Formation section of the stratigraphic column.

This establishes that the lithologically layered orthogneiss occurs in the lowermost structural levels of the complex, whereas the K-feldspar orthogneiss has been preferentially emplaced at a higher structural level, probably along thrusts or shear zones.

The origin of the granitoids in the Rudall Complex is a subject requiring specialized geochemical investigation. As yet there have been no such studies in the region, and evidence is restricted to that from field observations. There is currently no evidence that any of the granitic orthogneisses represent up-thrusted Archaean or Early Proterozoic basement. Therefore, all are assumed to bear an intrusive

relationship to the sedimentary succession, and most are probably genetically related to the orogenic belt. The Rudall Complex contains features consistent with a plate-tectonic regime, and its granitoids could be interpreted in terms of either magmatic arc or fold-thrust belt environments.

The western zone of lithologically layered orthogneiss with numerous enclaves of paragneiss, paraschist, and mafic-ultramafic rocks is intruded by the relatively homogeneous K-feldspar-augen orthogneiss. On RUDALL the layered orthogneiss contains both  $S_1$  and  $S_2$ , but only  $S_2$  has been recognized in the K-feldspar orthogneiss. Providing this is not merely a consequence of the general homogeneity of the latter (making  $S_1$ – $S_2$  distinction difficult), it can be inferred that the  $D_1$  event (sub-horizontal thrusting) occurred prior to crystallization of the K-feldspar orthogneiss protoliths. Thus,  $D_1$  could have led to partial melting, and the intrusion of sheets of the K-feldspar granitoids into the layered orthogneiss and the metasedimentary succession.

The stratigraphic succession of the Rudall Complex on RUDALL contains no mafic volcanic rocks, but sheared serpentized peridotite, associated with pelitic schist and turbiditic metasediments, occurs in three west-northwesterly trending zones. The assemblage is lithologically similar to compressed and attenuated ophiolitic units in many orogenic belts, such as the Cordilleran belt of western North America and the Himalayas (Windley, 1984). From a detailed study of the ultramafic units, Carr (1989) concluded that they represent slices of Proterozoic oceanic crust. On structural evidence it seems that rocks of the Rudall ultramafic zones originated northeast of RUDALL, and the assemblage is one which could have formed in a marginal basin environment. Such an environment could have been adjacent to the postulated northeastern volcanic-arc system.

The deformation and metamorphism assigned to  $D_2$ – $M_2$  indicate major collisional forces were in effect, probably, from the very limited isotopic data, sometime between 1750 and 1500 Ma. Overfolding and thrusting from the northeast and east were produced

by an advancing plate (no remnants of this have yet been identified, but may be concealed beneath the Canning Basin). The extent of deformation suggests either continent–continent collision (Himalayan-style), or continent – oceanic crust collision in which the oceanic crust contained non-subductable accretionary terranes (Cordilleran-style). In the Sylvania Dome area, 250 km west-southwest of RUDALL, Tyler (1991) suggested a 2000–1600 Ma event of continent–continent collision occurred, producing north-northeast-directed thrusting against the southern margin of the Pilbara Craton. Therefore, it appears that the Early Proterozoic successions on the eastern and southern margins of the Pilbara Craton were sandwiched between two obliquely converging plates.

There is substantial isotopic evidence for an important metamorphic and felsic magmatic event during 1250–1100 Ma. Felsic intrusions have been dated at  $1247 \pm 5$  Ma (crystallization age),  $1132 \pm 21$  Ma (?metamorphic age),

and c. 1080 Ma. On the south-eastern margin of the Pilbara Craton, sheared Archaean granitoids at Lookout Rocks provide Rb–Sr biotite ages of 1226 and 1194 Ma (de Laeter et al., 1977). This biotite forms part of a metamorphic foliation that is unconformably overlain by the Yeneena Group (Hickman, 1975; de Laeter et al., 1977). Williams (1992, p. 81) recorded tight, overturned, northwesterly trending folds in the c. 1300 Ma Manganese Subgroup of the Saltbush Range area, 70 km west of RUDALL, and these structures pre-date the unconformably overlying Yeneena Group (Williams, I. R., 1994, pers. comm.). The axial planes of the folds dip northeastward, indicating that the c. 1250 Ma event, like  $D_2$ , involved movement towards the southwest.

The c. 1250 Ma magmatic and metamorphic event may have been caused by raised isotherms associated with uplift and rapid erosion as the Pilbara and eastern plates moved closer together. Further thrusting probably occurred,

but this would now be difficult to distinguish from earlier parallel thrusting ( $D_2$ ).

### Yeneena Group

The Yeneena Group unconformably overlies the Pilbara Craton (Archaean), the Rudall Complex (c. 2000–1200 Ma), and the Manganese Subgroup (c. 1300 Ma) of the Bangemall Group. It is unconformably overlain by the Savory Group (840–600 Ma; Williams, 1992), and is intruded by the Mount Crofton Granite (c. 620 Ma; Nelson, D., 1993, unpublished data). A considerable amount of largely unpublished isotopic data (Pb–Pb, K–Ar, and U–Pb; Hickman and Bagas, in prep.) indicate that hydrothermal events occurred between 900 and 700 Ma. In summary, present evidence, though by no means conclusive, indicates that deposition of the Yeneena Group took place sometime between 1100 and 850 Ma, and that the main episode of deformation ( $D_4$ ), with accompanying hydrothermal activity, occurred between 900 and 700 Ma.

Table 2. Summary of deformation episodes on RUDALL and BROADHURST

Episode	Major structures	Minor structures	Metamorphism and magmatism
$D_1$ : Regional layer-parallel shear, direction unknown	None identified	$S_1$ : Penetrative layer-parallel schistosity; alignment of mica, quartz, and feldspar	$M_1$ : Low pressure, mid-amphibolite facies conditions (not recognized on RUDALL 1:100 000); local melting; granitoid intrusion
$D_2$ : SW- and W-directed thrusting and overfolding	Tight to isoclinal $F_2$ folds (axes trend WNW to N and are overturned towards SSW); $D_2$ thrust zones	$F_2$ : Isoclinal folds $S_2$ : Schistosity due to alignment of mica and quartz $L_2$ : Stretching lineation within $S_2$	$M_2$ : Medium-pressure amphibolite facies; some melting of pelitic rocks
$D_3$ : Local W- or NW-directed isoclinal–recumbent folding	$F_3$ recumbent folds in Yeneena Group; axes E–W to NE–SW	Local faulting and quartz veining of the Rudall Complex – Yeneena Group unconformity	None identified
$D_4$ : Regional deformation in response to SW-directed compression	Upright, tight to isoclinal $F_4$ folding about NW-trending axes; strike-slip fault system	$S_4$ : Axial-surface cleavage inclined steeply NE $L_4$ : Stretching lineations plunge down-dip on $S_4$	$M_4$ : lower greenschist facies; locally intense cataclasis and dynamic recrystallization
$D_5$ : Local deformation; ?NE-directed stress release after $D_4$	None identified	Open, recumbent $F_5$ crenulations; $S_5$ strike-slip cleavage	None identified
$D_6$ : Brittle deformation in response to NNE–SSW compression	ENE and N-striking near vertical strike-slip faults	$S_6$ : Strain-slip cleavage, axial to conjugate kink bands, deforming $S_4$	None identified



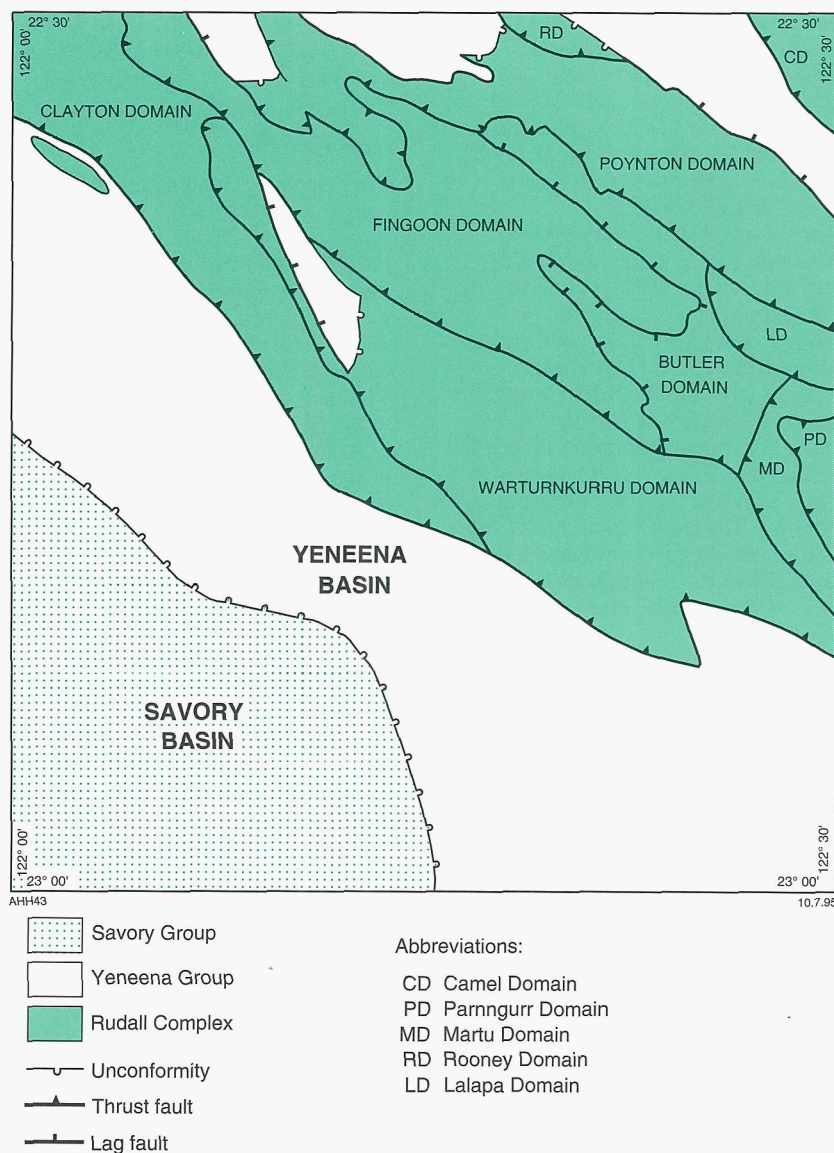


Figure 3. Major tectonostratigraphic units on Rudall

In comparison with the geology of the Rudall Complex, that of the Yeneena Group is relatively simple. Structural modification is mainly confined to upright folding, and associated high-angle faults generally involve displacements of no more than 2–3 km. Metamorphic grade is low, and the succession is not fragmented by ubiquitous granitoid sheets. In fact, granitoid–pegmatite intrusion is absent, except in the northern part of the Paterson Orogen around Telfer.

Despite these differences, the Yeneena Group does have two

important features in common with the Rudall Complex:

- (i) The overall lithological succession is that of a continental margin. For the Yeneena Group, the interpretation that a continental landmass lay to the southwest is supported by abundant palaeocurrent data, and by lateral facies changes.
- (ii) Deformation ( $D_4$ ) included northeast–southwest compression, upright folding and thrusting from the

northeast, and total crustal shortening by many kilometres.

These similarities suggest that the evolution of the Yeneena Basin marked a later stage in the progressive northeast–southwest convergence responsible for the Rudall Complex. Plate convergence was significantly retarded after the major collision during  $D_2$  (in much the same way as collision reduced convergence of the Indian and Eurasian plates during evolution of the Himalayan orogenic belt; Windley, 1984). Plate collision impeded further subduction with the result that continued crustal shortening was mainly accommodated by strike-slip faulting. The Yeneena Basin developed as a strike-slip basin or, more probably, as a series of such basins.

On sedimentological grounds the sandstone–shale–carbonate succession of the Yeneena Group could be either a continental-margin succession or part of an intra-continental basin. The source of clastic detritus lay to the southwest and west, and the overall deepening of the basin was to the northeast. The succession has a basal conglomerate in most areas, and this commonly fills channels cut into the underlying basement. This is true not only along the present western and southwestern boundaries of the Yeneena Basin, but also in the Broadhurst Range, at least 50 km into the basin. Basal conglomerate is thin (commonly less than 10 m thick), and conglomerate is absent from the overlying fluvio-deltaic clastics of the Coolbro Sandstone. Thus, deposition in that part of the Yeneena Basin covered by Broadhurst and Rudall commenced in a continental environment of stream channels and alluvial fans, and progressed, probably due to subsidence, to a deltaic – shallow-shelf environment.

The Coolbro Sandstone is absent from the 'Western Zone' (Williams, 1990), but reaches a thickness of at least 4000 m only 5–10 km into the adjacent Broadhurst Range area. In the Broadhurst–Rudall area the boundary between these two zones of the Yeneena Group coincides with the Southwestern Thrust. A common feature of ensialic sedimentary basins is that normal growth faults (actively controlling deposition) can subsequently be



reactivated with reverse movement during the tectonism responsible for basin closure (Mitchell and Reading, 1986). Thus, the southwestern margin of the Broadhurst Range basin was probably fault-controlled.

Palaeocurrent analysis of the Coolbro Sandstone on BROADHURST (Hickman and Clarke, 1993) revealed relatively uniform northeasterly to northerly currents flowed across the entire 1500 km² of outcrop. This flow regime continues onto northern RUDALL, except that in the east the currents were almost entirely northerly. These patterns are consistent with sediment supply from a continent to the southwest.

The Broadhurst Formation conformably overlies the Coolbro Sandstone, and has broadly the same regional distribution; it appears to be absent from the Western Zone succession. However, unlike the Coolbro Sandstone, this dominantly pelitic formation is most thickly developed in the eastern part of the Broadhurst Range. Instability during the early stages of deposition is indicated by graded turbidites, slump folding, and local conglomeratic sandstone units (Hickman and Clarke, 1993). Shale and intercalated carbonates of the Broadhurst Formation are generally carbonaceous and include stratabound sulfides. Anoxic deposition of black muds and sulfidic grey carbonates indicates a pelagic environment into which periodic turbidity currents carried mixed sand and mud from the basin margin.

Along its eastern boundary the Coolbro Sandstone – Broadhurst Formation succession is exposed only in the Mount Isdell area, where it is faulted against the Isdell Formation. Aeromagnetic data indicate that southeast and northwest from Mount Isdell the boundary is a structural discordance (either a fault or an angular unconformity).

The northwesterly-trending D₄ and D₆ faults of the Paterson Orogen exhibit both strike-slip and down-dip movement. The faults are curved and anastomosing, and break the area into lenticular, northwesterly elongated blocks. This type of pattern is characteristic of strike-slip regimes (Mitchell and Reading, 1986). In the Broadhurst Range – Rudall River area the

curvatures and convergent relationships of the Southwestern Thrust and the Mount Isdell magnetic lineament would be consistent with strike-slip faults towards the northwestern end of a strike-slip basin (dextral movement).

The Western Zone succession is composed of shallow-water facies whereas the Broadhurst Formation is dominantly pelagic. The Western Zone includes shallow-water stromatolitic and microbially banded carbonates, reddish-brown siltstone and shale (commonly ripple-marked), rhythmically layered sandstone–siltstone–shale units, and local evaporates (halite pseudomorphs; Williams, I. R., 1994, pers. comm.). Black sulfidic shale and turbidites have not been recorded from the Western Zone. Differences between the two successions indicate that the Western Zone is a shallow-water, near-shore assemblage (marine or lacustrine), whereas the Broadhurst Formation is a deeper water facies to the northeast. In the RUDALL area the change from shallow- to relatively deep-water sedimentation occurs across the line of the Southwestern Thrust. The postulated growth fault along or just to the west of this line must have become submerged when deposition of the Coolbro Sandstone ceased. It is probably significant that the highest beds of the Coolbro Sandstone exhibit slump folding indicative of basin subsidence.

The Isdell Formation is of major importance in the Yeneena Group, but its stratigraphy and regional correlations are still poorly understood. In the type area around Mount Isdell (BROADHURST) the formation is chiefly composed of dark grey, sulfidic dolomitic limestone and dolostone, with subordinate silty pale grey-cream carbonate and shale. No stromatolites have been found, and the facies appears to be relatively deep-water in nature; however, in the Western Zone of THROSSELL, and on the northeastern part of BALFOUR DOWNS (1:250 000), Williams (1989, 1990) described the formation as a shallow-water assemblage of stromatolitic carbonate, clastic dolostone, sandstone and conglomerate, and dolostone containing scours and erosion channels filled by sandstone and conglomerate. If present correlations (Williams, 1990) are correct, the

Isdell Formation passes from a near-shore, shallow-water unit in the west to a deeper water, partly anoxic carbonate unit in the east.

Deformation of the Yeneena Group occurred mainly during D₄, and produced northwest- and southeast-plunging, tight to isoclinal, overturned folds, with axial planes dipping steeply northeast. Most fold limbs are sheared and partly replaced by high-angle faults (thrusts and lags). Where fault planes are exposed they generally show more than one linear fabric, testifying to reactivation, usually during D₆. D₄ movement appears to have been down-dip, with lineations generally plunging between 50° north-northeast and 50° east. The folds themselves are arranged en echelon, and are here considered to be transpressional in origin. Such folds could be produced within a northwesterly trending strike-slip fault system, under either dextral or sinistral movement. In either situation, the maximum compressive stress was directed along an approximately southwesterly trend (± approximately 30°). Thus, the direction of crustal shortening during D₄ was similar to that during D₂. D₆ deformation involved north-northeasterly trending compression, with the dominant set of dextral strike-slip faults striking northwest to north, and a complementary set of sinistral faults trending east-northeast.

### Mineral potential

Interpretations of depositional and tectonic settings contribute to the assessment of the mineral potential of a region, because particular types of mineral deposits are associated with specific geological environments. Table 3 summarizes the tectonic evolution of RUDALL, and suggests the types of mineralization which might be present.

The Paterson Orogen has proven potential for gold, copper–lead–zinc, and uranium mineralization. Additionally, mineral exploration and the recent mapping and accompanying geochemical investigations have indicated significant prospectivity for lead–zinc, molybdenum, bismuth, and possibly tungsten, nickel, chromium, and platinum-group element (PGE) mineralization.

Table 3. Summary of Proterozoic tectonic evolution on RUDALL, with theoretical metallogenic implications

	<i>Phase</i>	<i>Environment</i>	<i>Unit/feature</i>	<i>Structure</i>	<i>Potential mineralization</i>
STRIKE-SLIP REGIME	D ₆ late strike-slip	Brittle deformation	Quartz veins	Strike-slip faults and transpressional folds	Epigenetic Au in quartz veins
	Clastic deposition	Foreland basin	Savory Group		
	Erosion	Fold-thrust belt (inactive)	Unconformity		
	D ₄ SW-directed movement and basin closure	Dominantly transpressional fold-thrust belt	Silicified shear zones	Upright to overturned, tight to isoclinal NW-trending folds and NE-inclined thrusts	Epigenetic Au in quartz veins; hypothermal base metals
	Stable carbonate shelf	NE-deepening shelf, gradual subsidence	Isdell Formation		Mississippi Valley-type, carbonate-hosted Pb-Zn (most potential in shallow-water facies)
	?Regional basin amalgamation	?Marine transgression	?Unconformity		
	Basin subsidence and enlargement to include Western Zone shelf	Western Zone: supratidal to shallow-water, locally fluvatile-deltaic; Broadhurst basin: rapid subsidence and pelagic deposition	Broadhurst Formation, Choorun Formation, Waters Formation, Gunanya Sandstone	Syndepositional NNW to WNW trending faults, dominantly dextral strike-slip but with accompanying vertical movement producing growth faults; slump-folding from basin margin	Near-shore facies: Sabkha-type Cu-Pb-Zn, Copper-belt-type Cu-Co Distal facies: McArthur River-type Fe-Pb-Zn
	Development of Broadhurst Range strike-slip basin	Dominantly transtensional basin, elongate NW-SE and deepening NE	Coolbro Sandstone		Unconformity-related vein-style U (with associated Cu, Pb, Bi, PGE, and Au) on, or close to, faults
	Deep erosion	Inactive fold-thrust belt	Unconformity		
SUBDUCTION REGIME	Retarded convergence	Post-collisional deformation; crustal thickening and melting	Microgranite, aplite, and pegmatite	Local NW-trending folds	U-enrichment in granitoids
	D ₂ collision, SW-directed	Fold-thrust belt	?Syncollisional granitoids	Nappes, and NE- to E-inclined stacked thrust sheets	Greisen-related Sn-W, with Cu, Mo, and Li movement
	Widespread granitoid intrusion	Late- to post-D ₁ partial melting (crustal thickening), or subduction-related magmatic arc	K-feldspar-augen orthogneiss protoliths	Sill-form granitoid sheets, associated dykes, pegmatite, and veins	Pegmatite minerals; granitoid emplacement-related hydrothermal Au
	Clastic deposition, local volcanism	Rifted shelf; adjacent volcanic arc	Poynton Formation		Sandstone: stratabound U Shale-BIF: sedimentary-exhalative massive sulfides
	D ₁ subhorizontal tectonic interleaving	?Thin-skinned thrusting along fold-thrust belt margin	Lithologically layered orthogneiss	Layer-parallel shear zones	Tectonically emplaced and mobilized pre-existing deposits
	Granitoid intrusion	?Partial melting beneath rifted basin	Granitoid protoliths for lithologically layered orthogneiss	Sill-form granitoid sheets	Greisen-related Sn-W, etc. (but probably too fragmented to be economic)
	Clastic deposition, mafic-felsic volcanic rocks in areas to NE or E	Subsiding foreland basin with shore-line, shelf and slope environments; probable rifting; adjacent volcanic arc and marginal basin	Larry Formation, Fingoon Quartzite, Yandagooge Formation, and Butler Creek Formation		a) Shelf sand and mud: stratabound sandstone-type U b) Carbonaceous mud and BIF: sedimentary-exhalative massive sulfides c) Ultramafic-mafic: serpentinite-hosted Cr, Ni, or PGE; metabasalt-hosted Cyprus-style Cu-Fe

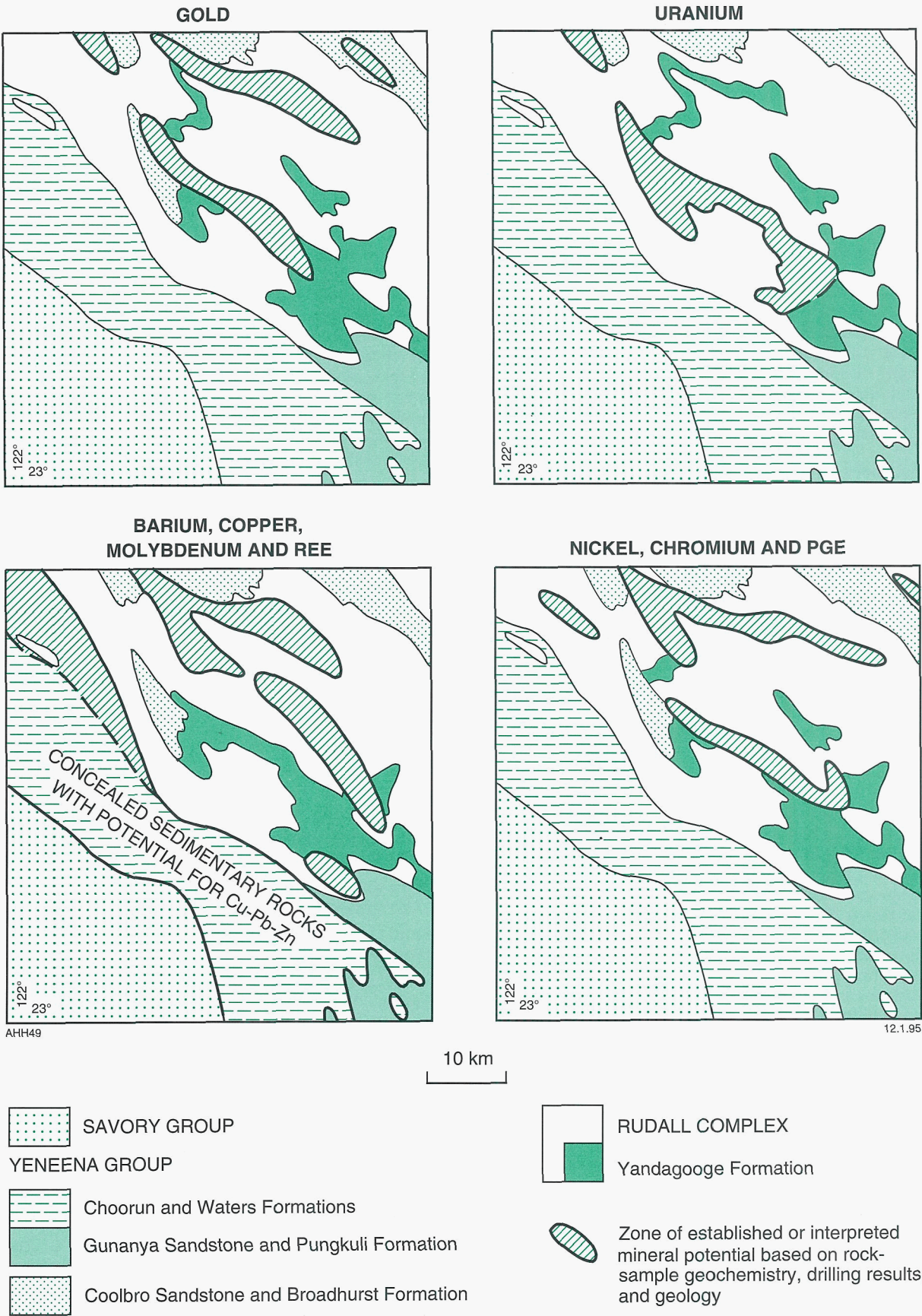


Figure 4. Summary of main zones of known and interpreted mineral potential on RUDALL

Figure 4 shows zones of mineral potential on RUDALL. Three northwesterly striking zones encompass all known significant gold anomalies. The central and southern zones coincide with D₄ faults in the Yandagoo Formation, and the central zone also encompasses mineralization of the Butler Creek and Poynton Formations.

Most of the gold mineralization is hosted by D₄ faults. The currently known deposits therefore appear to be syn- or post-D₄ in age, although because D₄ faults commonly coincide with D₂ faults, and probably also with growth faults formed during deposition of the Yeneena Group, the original age of gold mineralization is uncertain.

The northern zone of gold mineralization is confined to a shale-siltstone member of the Coolbro Sandstone and, if the mineralization is epigenetic, it clearly must be post-Yeneena Group in age; however, because gold mineralization is here associated with pyritic sediments, it could be syngenetic.

Uranium mineralization on RUDALL is confined to a relatively narrow northwesterly striking belt along the southwestern boundary of the Fingoon Domain. This belt is essentially a D₄ graben, and may have been a down-faulted block during deposition of the Coolbro Sandstone. Uranium deposits are hosted by fractures in the Yandagoo Formation, presumably not far below the level of the unconformity at the base of the Coolbro Sandstone. Figure 4 shows that uranium potential declines towards the southeast, based on the interpretation that the Coolbro Sandstone probably wedged out in this direction. Potential for uranium mineralization in the Poynton and Rooney Domains is considered to be low due to an absence of suitable pelitic or carbonate host-rocks close to the basal Coolbro Sandstone unconformity.

Nickel, chromium, and PGE mineralization may be present in the ultramafic rocks of the Rudall Complex, and PGE mineralization could be associated with uranium; however, most of the ultramafic bodies are small and fragmented, and the mineral potential of these

units is therefore considered to be relatively low.

Figure 4 shows four zones with barium-rare-earth element-copper-molybdenum potential. The western zone, in the Clayton Domain, coincides with a belt of major D₄ thrusts and lags, but it is unclear to what extent these have acted as conduits for hydrothermal fluids. The northern zone partly corresponds to the central zone of gold mineralization (discussed above). Other shaded areas on Figure 4 chiefly involve the Yandagoo Formation and the upper Fingoon Quartzite where these units are dislocated by D₄ and D₆ faults. Although copper and molybdenum are commonly

associated with one another, the absence of identified porphyry and the present deep erosion levels make it unlikely that mineralized porphyry-style systems have been preserved.

On RUDALL the Western Zone succession of the Yeneena Group is composed of shallow-water arenites, shale, and carbonate rocks. The succession occupies an area of about 1000 km² (Fig. 4), but is largely concealed and has not yet been explored. Geochemical investigation reveals local copper anomalies, and the belt is clearly prospective for Sabkha-type copper-lead-zinc, and possibly Copperbelt-type copper-cobalt or Mississippi Valley-type carbonate-hosted lead-zinc deposits.

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## Radon-222 content of groundwater in Western Australia

by P. M. Thorpe

### *Abstract*

Radon-222 (radon) is a naturally occurring, inert, radioactive gas of short half-life. It is derived from the decay of radium-226 which in turn originates from uranium-238, both of which are found in trace quantities in all rock-forming minerals. The radon gas released from radium-bearing minerals is either dissolved in groundwater or included within soil air.

There is a potential domestic and occupational health risk associated with the inhalation of radon and its short-lived progeny. However, the extent of the contribution of radon by exsolution from domestic water sources to the radon in air inside houses is uncertain. In Australia the recently proposed draft guideline level for radon in drinking water is 100 Bq/L. A Statewide survey of groundwater radon levels in Water Authority schemes and in other groundwater bores shows that radon levels in untreated groundwater range widely from 0.9 to 233 Bq/L, and average 16.2 Bq/L.

The wide variation in groundwater radon levels is attributed to the type of aquifer. Older, fractured-rock aquifers generally contain higher radon levels than younger sedimentary aquifers with intergranular porosity, which usually contain larger groundwater resources and supply large population centres.

The results of this study suggest that the primary source of radon in groundwater is solid-phase radium-226 contained within aquifer minerals. Radium-226 dissolved in groundwater is unlikely to represent a significant source of radon. This aspect of radon generation is important in that once the radon in the groundwater is separated from the aquifer it will be lost rapidly over a period of days or weeks by both exsolution to air and radioactive decay, and will not regenerate to a significant extent. Specific rock types which have a relatively high radon-producing potential include phosphate nodules that contain uranium, heavy-mineral sands, and fractured igneous rocks. Further research is required to identify aquifer types likely to yield groundwater with high radon levels.

**KEYWORDS:** Ground water, aquifers, radon-222, radium-226, polonium, uranium, ground water management.

Radon-222, hereafter referred to as radon, is the longest-lived isotope of radon and is a naturally occurring inert gas with a half-life of 3.8 days. It is soluble in water and accumulates in groundwater and soil air. It is exsolved from groundwater to the atmosphere when the confining hydrostatic pressure is released. Radon is not ionized in solution, nor does it precipitate in solid phases; it adsorbs onto organic material to a limited extent, especially charcoal.

There is increasing concern for the potential domestic and occupational health risks associated with the inhalation of radon and its short-lived decay products in confined areas, such as dwellings or underground mine galleries. When radon in air is inhaled into the lungs, the radon decay products, chiefly polonium isotopes, adhere to lung tissue. Radon-derived polonium atoms also adhere electrostatically to particulate matter in air, which, when breathed in, may also deposit on lung tissue. The polonium isotopes emit alpha particles, which can cause lung damage and lung-cancer deaths. It is therefore important to investigate the possible contribution of radon exsolved from public water supplies to the overall exposure of the population to radon gas. The ingestion of radon in drinking water is not considered to be a significant risk to health.

This report summarizes the results of a survey of the radon content of groundwater in Western Australia based upon measurements from Water Authority of Western Australia (WAWA) schemes (Thorpe, 1994), and various other production and observation bores. The survey was undertaken jointly by WAWA and the Geological

Survey of Western Australia (GSWA) in 1992, and follows an earlier study in the Perth Metropolitan Area (Thorpe and Davidson, 1991).

### Sources of radon

The parent isotope of radon, radium-226 (half-life of 1620 years), is the fifth member of the uranium-238 decay series and occurs in trace quantities within a variety of rock-forming minerals, in addition to the principal uranium-ore minerals. Uranium and radium are commonly contained in accessory minerals that are common in aquifers, such as monazite, zircon, phosphates, and clay minerals. Uranium is mobile in solution in groundwater under oxidizing conditions, and can be incorporated within secondary mineral deposits. These secondary precipitates coat the surfaces of fractures and mineral grains in a variety of rock types.

Radium-226 is chemically insoluble in water (Michel, 1990); however, its solubility in a groundwater environment is enhanced by the process of alpha recoil. This process involves the recoil effect of the release of an alpha particle from a nucleus, which propels a newly created progeny radio-nuclide with sufficient energy to break chemical bonds. Atoms undergoing radioactive decay on the surface of a mineral grain can eject their progeny directly into the surrounding pore water. In this way, the decay of thorium-230 atoms on mineral-grain surfaces can eject radium-226 atoms into groundwater. This process physically alters the internal crystal structure of minerals containing radioactive isotopes and accelerates their chemical breakdown. This alteration commonly occurs in zircon, which contains traces of uranium and thorium.

Radon is a noble gas and is soluble in water, though not ionized in solution. The solubility of radon in water increases with increasing pressure and decreases with increasing temperature. Numerous studies have shown that radon in groundwater is produced almost entirely from solid-phase radium-226 contained within aquifer minerals, rather than from radium-226 in solution (Wanty and

Gunderson, 1987; Michel, 1990). This is supported by recent work involving detailed radon analysis of groundwater during purge pumping of deep observation bores in the northern Perth Basin (Thorpe, 1994, in prep.).

Below the watertable a state of secular equilibrium develops between the rate of radon production by radium-226 decay and the rate of radon decay. This balance is almost complete after a period of 30 days. The transport of radon by groundwater flow in an aquifer from a zone of high radon production is likely to be minimal because the half-life of radon is short in the unsupported state in terms of rates of groundwater flow. This aspect of the occurrence of radon is important when considering the location of groundwater production bores in areas that contain zones of high radon production.

The physical properties of an aquifer have an important control on the radon content of groundwater. In general, sedimentary-rock aquifers with high intergranular porosity

produce groundwater with lower radon levels than fractured-rock aquifers (Wanty and Gunderson, 1987; Michel, 1990). This difference is attributed to two factors:

- (i) The volumetric ratio between water and rock is substantially lower in fractured-rock aquifers; hence, the radon produced throughout the rock mass is concentrated into a small volume of pore water, producing high radon concentrations.
- (ii) Fractured-rock aquifers, such as granitoids, commonly contain higher concentrations of uranium-bearing minerals (Michel, 1990).

Exceptions to the above are karst limestones and highly lithified sandstones, which behave as fractured-rock aquifers with a low primary permeability and high secondary permeability. Radon levels in karst limestones are likely to be low due to the rapid rate of groundwater flow through the rock mass. This rapid rate of flow, following a high recharge event,

**Table 1. Summary of radon-222 concentrations in groundwater in Western Australia**

Region	Type	Number of samples	Radon (Bq/L)		
			Average	1σ	Range
North West	Source	15	35.4	58.9	1.8 – 233
	Retic.	13	13.8	21.2	<0.8 – 83.9
Mid West	Source	28	24.4	40.5	0.9 – 220
	Retic.	22	9.8	9.7	0.7 – 36.3
Central	Source	11	22.7	19.7	1.6 – 64.7
	Retic.	9	9.4	9.1	1.2 – 27.0
Goldfields	Source	4	15.6	15.4	2.8 – 41.8
	Retic.	4	13.3	14.9	2.5 – 39.1
Perth					
Unconfined aquifer	Source	67	8.3	10.8	1.7 – 81.2
Confined aquifer	Source	25	11.8	5.8	4.1 – 31.9
	Retic.	6	1.6	0.4	0.9 – 2.0
Great Southern	Source	6	31.2	18.3	3.1 – 53.8
	Retic.	4	3.0	1.6	1.2 – 5.6
South West	Source	20	14.9	7.6	5.2 – 38.4
	Retic.	12	5.8	7.3	1.1 – 24.4
Overall	Source	176	16.2	27.0	0.9 – 233
	Retic.	70	9.0	12.7	0.7 – 83.9

Retic. : post-treatment sample from the reticulation  
1 $\sigma$  : population standard deviation

may not give sufficient time for secular equilibrium to be achieved between the rock mass and adjacent groundwater.

High radon levels are likely to be found in sedimentary-rock aquifers that contain secondary uranium-rich carbonate cement, heavy minerals, or phosphatic material. Localized high radon-producing zones, associated with uranium mineralization, are likely to be found in all rock types.

## Sampling and analysis

### Sampling

Groundwater samples for analysis were collected by air-free pumping of bores. The bores were purged of the groundwater standing in the bore casing immediately prior to sampling (otherwise anomalously low radon levels will be recorded; Thorpe, in prep.). Radon gas is rapidly lost by exsolution, so a simple sampling technique was developed to prevent radon loss (Thorpe, 1994). Radon measurements were performed in the GSWA Isotope Hydrogeology Laboratory within two days of field collection and were corrected for radioactive decay to the time of field collection (Thorpe, 1994). About 80% of the samples were retained for three months after the initial analysis for remeasurement to assess whether radon was being regenerated from radium-226 in solution. The measurements showed no detectable increase in activity above that of laboratory background samples. This indicates that most of the radon initially present in the groundwater samples was produced by the decay of solid-phase radium-226 in the aquifer. The remeasurement-emanation technique can only detect radium-226 concentrations greater than about 5 Bq/L. These tests therefore do not indicate that dissolved radium-226 is entirely absent in all of the groundwater sources sampled or that gross alpha radiation and radium-226 activities in the sources are below the draft National Health and Medical Research Council (NHMRC) guideline levels of 0.1 and 0.5 Bq/L respectively.

In the Perth Metropolitan Area, samples were collected from all of the production bores in the confined

aquifers and from a selection of bores within the unconfined aquifer. Post-treatment samples were also collected. In country areas, each aquifer used in a town water supply scheme was sampled. Generally one bore within each aquifer was sampled together with the treated reticulated water. Some rural schemes were not included, although similar aquifer types were sampled elsewhere.

## Results

Overall radon concentrations in production and observation bores

(Table 1) from the sampling site locations shown in Figures 1 and 2 vary considerably from 0.9 to 233 Bq/L, and average  $16.2 \pm 27.0$  ( $1\sigma$ ) Bq/L (Thorpe, 1994). This variation in concentration is similar to that observed by the major groundwater surveys conducted in the United States of America (Longtin, 1990; Dixon et al., 1991).

Radon levels in groundwater in the confined and unconfined aquifers in the Perth Metropolitan Area (Perth Basin) average  $11.8 \pm 5.8$  and  $10.8 \pm 8.3$  Bq/L respectively and range from 1.7 to 81.2 Bq/L. Radon levels in country-scheme sources average

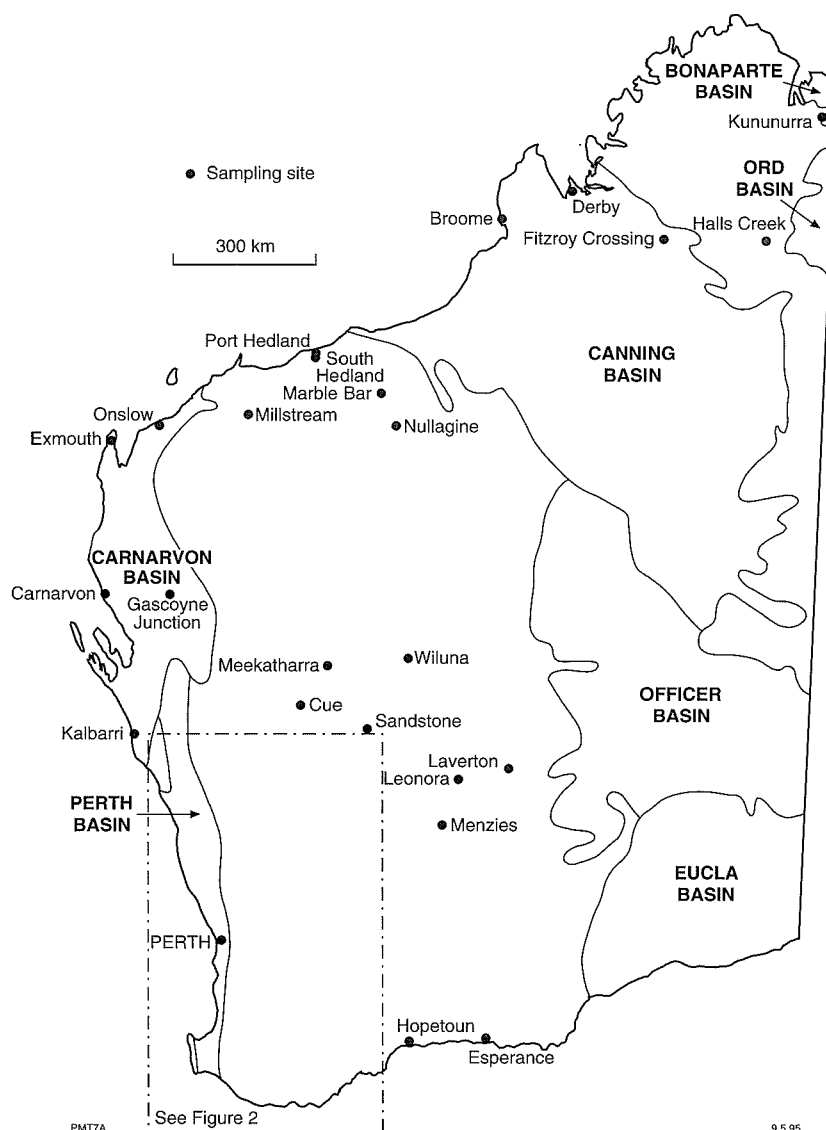


Figure 1. Location of radon sampling sites in Western Australia

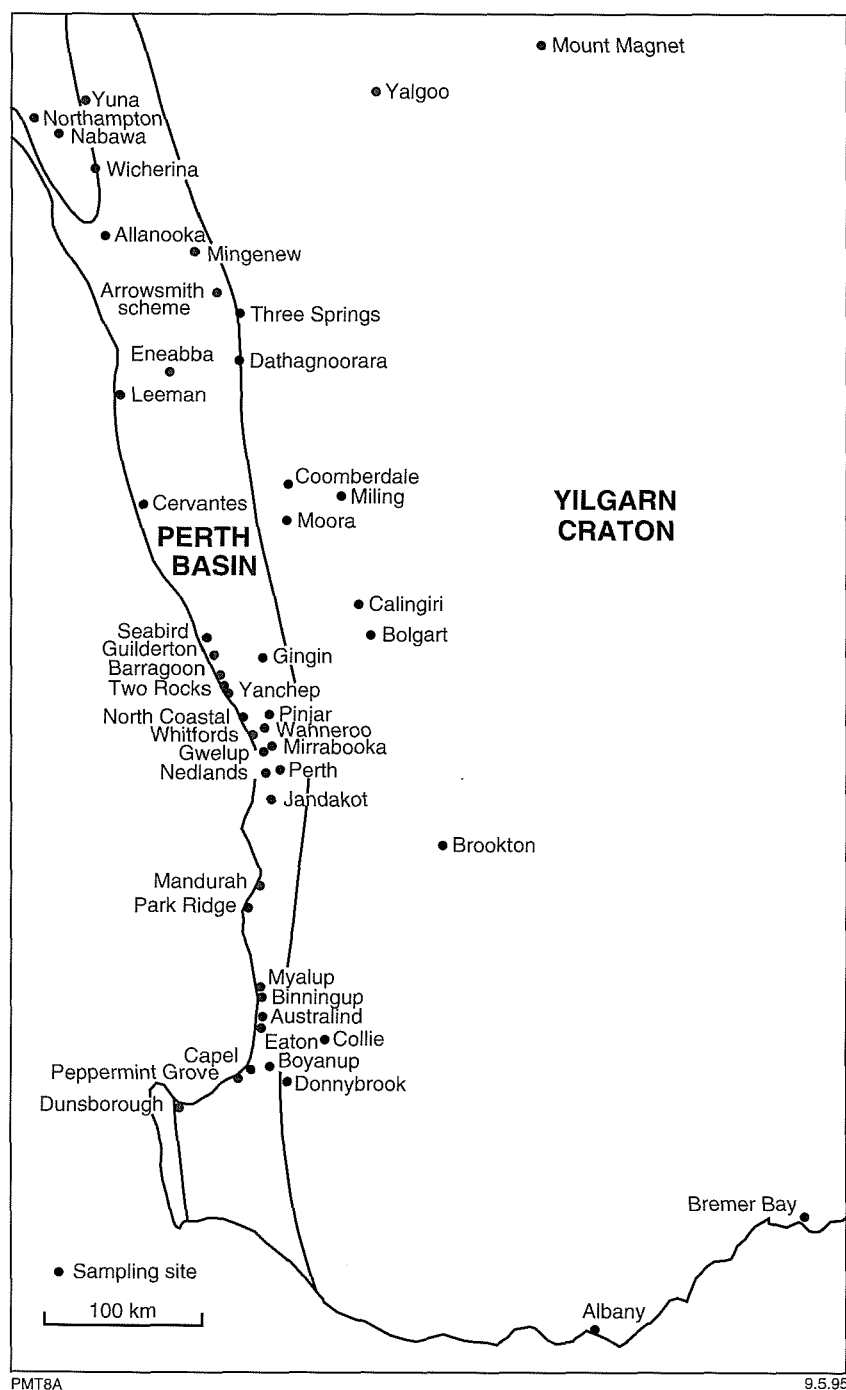


Figure 2. Location of radon sampling sites in southwestern Western Australia

24.0 ± 36.2 Bq/L and range widely from 0.9 Bq/L at Exmouth to 233 Bq/L at Halls Creek.

#### Country areas

In general, higher groundwater radon levels are associated with fractured-rock aquifers. The

highest radon concentrations were found in bores screened within fractured Proterozoic limestone and sandstone at Halls Creek (233 Bq/L) and fractured granite and dolerite at Northampton (220 Bq/L). High levels were also observed at Coomberdale (64.7 Bq/L) in Proterozoic chert, at Hopetoun (52.2 Bq/L) in

weathered granite, at Yuna and Kalbarri (51.7 and 31.5 Bq/L) in jointed Silurian sandstone aquifers, and at Menzies and Marble Bar (41.8 and 41.5 Bq/L) in fractured basalt.

Moderate concentrations were measured at Gingin within the aquifer in the Leederville Formation in the Perth Basin (22.7 Bq/L), particularly at shallow depth, and in aquifers within the Tertiary Plantagenet Group.

Lower groundwater-radon levels are generally associated with sedimentary rock aquifers, which have intergranular porosity. The lowest levels were measured at Millstream (1.8 Bq/L) in Tertiary calcrete; at Hopetoun (3.1 Bq/L) in Quaternary Tamala Limestone; in aquifers within the Mesozoic and younger sediments in the Perth Basin; and within shallow alluvial aquifers overlying basement rocks on the Yilgarn Craton. At Laverton, in the Goldfields, the Telegraph Shaft source has a relatively low radon concentration of 8.3 Bq/L, considering it is located in a fractured-rock aquifer. The Telegraph Shaft draws water from a network of flooded mine galleries and sumps, and radon levels are likely to be low due to a combination of loss by exsolution of radon from groundwater drainage into the air space underground; and loss by radioactive decay in the large volume of water stored in the sumps. Low and relatively uniform radon concentrations were measured at Collie in samples collected from Permian confined sand aquifers (8.8–13.8 Bq/L) located between major coal seams within the Collieburn and Cardiff Members.

#### Perth Metropolitan Area

The results from the Perth Metropolitan Area cover all of the confined- and most of the unconfined-aquifer production bores both within and outside the major groundwater schemes. Results are also included from observation bores constructed for studies of the unconfined aquifer at Whitfords, Nedlands, and Barragoon, and for the proposed North Coastal scheme. Post-treatment samples were collected at the groundwater treatment plants.



Overall, radon concentrations in the operational production bores were low, averaging  $10.0 \pm 6.1$  Bq/L, and ranged from 1.9 Bq/L at Two Rocks in the unconfined Quaternary aquifer to 31.9 Bq/L at Mirrabooka in the confined Leederville Formation. Radon concentrations in the unconfined aquifers, were slightly lower on average than those in the confined aquifers, possibly due to a higher proportion of clays and heavy minerals in the latter.

The radon concentration in the Nedlands observation bores in the unconfined aquifer are low, averaging  $6.0 \pm 2.6$  Bq/L. Similar low levels exist in the North Coastal scheme, Whitfords, and Barragoon bores. These bores are located within the unconfined aquifer which comprises Quaternary Tamala Limestone and Tertiary Ascot Limestone. Moderate radon concentrations (up to 81.2 Bq/L) were measured in the Tertiary Ascot Limestone at Whitfords and in the North Coastal scheme at specific depths where phosphatic nodules were abundant in the strata, adjacent to the bore screen. Analysis of a sample of phosphorated bone fragments from the Ascot Limestone showed the presence of significant concentrations of uranium (265 ppm). The phosphate nodules within the Ascot Limestone are probably derived from the Molecap Greensand (Coolyena Group). The distribution of uranium within the phosphate-nodule beds is unknown, and its effect upon radon levels in the unconfined aquifers is therefore uncertain.

Post-treatment samples contain low radon concentrations, except those from Halls Creek and Nullagine where, possibly, detention times are short in the treatment process and aeration is minimal. In addition, a number of schemes have post-treatment levels similar to or higher than the selected source bores. This probably results from short detention time, minimal aeration,

and the influence of supplies from other source bores. At Collie, groundwater drainage in the mine sumps has a low radon content due to radon loss by both exsolution through pressure release and radioactive decay during detention. Artificial ventilation of the mine galleries will continually remove the radon in the air that has come from groundwater drainage.

In the Perth Metropolitan Area, samples of the reticulated groundwater from the schemes have a very low radon content (averaging  $1.6 \pm 0.4$  Bq/L), which indicates that the primary spray-aeration treatment for iron and hydrogen sulfide is effective in removing about 95 % of the dissolved radon in the source water.

### Conclusions

Levels of radioactive radon-222 gas in public groundwater sources in Western Australia are low on average, though highly variable. Of the 69 WAWA schemes surveyed, only two have source (production

bore) radon levels exceeding the draft NHMRC guideline level for drinking water of 100 Bq/L. Post-treatment samples collected from the schemes all contain radon levels below the draft NHMRC guideline level. The survey results show that simple spray aeration in the treatment process is a very effective and low-cost means of reducing groundwater radon levels.

Variations in groundwater radon levels are controlled by local hydrogeological factors including the type and mineral composition of the aquifer. The main source of radon in groundwater is considered to be traces of radium-226 within the aquifer matrix. Generally, fractured-rock aquifers give rise to higher groundwater-radon levels than sedimentary-rock aquifers with intergranular porosity; however, evidence from this study indicates that sedimentary-rock aquifers that contain accumulations of uranium-bearing phosphate nodules and heavy-mineral sands are likely to impart higher than average radon levels to groundwater.

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## Newly recognized Eocene sediments in the Beaufort River Palaeochannel

by J. D. Waterhouse, D. P. Commander, C. Prangley, and J. Backhouse

### Abstract

An Eocene palaeochannel has been identified for the first time on the western margin of the Yilgarn Craton. The 'Beaufort Palaeochannel' and its tributary have been traced for at least 60 km, from Quongering Pool, 25 km north-northeast of Kojonup, to Haddleton Springs, 60 km west-northwest of Kojonup. The palaeodrainage system probably discharged across the Darling Fault into the Perth Basin and was the precursor to either the Preston or Collie River.

The palaeochannel sediments comprise up to 65 m of sands, silts, and clays. They reflect initial deposition by a meandering riverine system, followed by development of lacustrine conditions as tilting of the Yilgarn Craton reduced the gradient for surface flow along the palaeoriver.

The sediments yield a rich spore-pollen assemblage of late-Middle to Late Eocene age, with no evidence for any marine affinities.

The relationship between the low-level palaeochannel sediments and the Kojonup Sandstone, which is at a higher elevation on a nearby modern drainage divide, is not certain. The Kojonup Sandstone may reflect coeval deposition in tributaries to the main palaeoriver. Alternatively, it may have been deposited prior to a period of rapid uplift and dissection within the Eocene, although the lack of widespread Eocene sedimentation in the Perth Basin makes this explanation less likely.

**KEYWORDS:** Yilgarn, Eocene, palaeochannel, sediment, Beaufort River.

An Eocene palaeochannel has been identified for the first time on the western margin of the Yilgarn Craton. Previously, Eocene sediments were known from the eastern and southern Yilgarn Craton (Balme and Churchill, 1959; Hos, 1975; Hocking and Cockbain, 1991; Kern and Commander, 1993), but the age of sediments in palaeodrainages that drained towards the west was uncertain. In the Blackwood River catchment (Fig. 1), and to the north, probable Eocene plant fossils in arenaceous sediments have been identified at a

few localities on or near drainage divides (Wilde and Backhouse, 1977; Hill and Merrifield, 1993). Recent drilling has confirmed the presence of Eocene sediments in the newly defined palaeochannel (which drained to the west) of the westerly flowing Beaufort Palaeoriver. It is located to the west of the Meckering Line (Mulcahy, 1973), where Tertiary palaeodrainages have not previously been recognized (van de Graaff et al., 1977; Morgan, 1993) and where only one Eocene age has been reported (Hill and Merrifield, 1993).

This paper records the occurrence of these sediments and discusses their geological relationships. The recognition of Eocene palaeochannels in the southwestern Yilgarn Craton is important for the identification of low-salinity groundwater resources, which may occur where palaeochannels are not coincident with present saline drainages, such as at Dardadine near Darkan, to the north of the Beaufort River (Wharton, P. H., 1990, written comm.).

### Previous work

Sediments described from many palaeochannels elsewhere in the western part of the Yilgarn Craton (Laws, 1993; Salama et al., 1993) have not been dated due to lack of suitable material. Eocene palaeochannel sediments in the western Yilgarn Craton were previously known from Darkin Swamp, 65 km east-southeast of Perth (Hill and Merrifield, 1993). The nearest definitely Eocene palaeochannels are just north of the Stirling Ranges (Appleyard, in prep.), adjacent to the Bremer Basin.

In 1992, R. J. George collected samples of cuttings from an exploration drillhole described by Muggeridge (1981) near Duranillin. These were determined to be Eocene in age and their geology and geomorphological position suggested that they were part of a palaeochannel system, as indicated on the geological map of Western Australia (Myers and Hocking, 1988).

In February 1994, groundwater exploration drilling programs were carried out to investigate both the

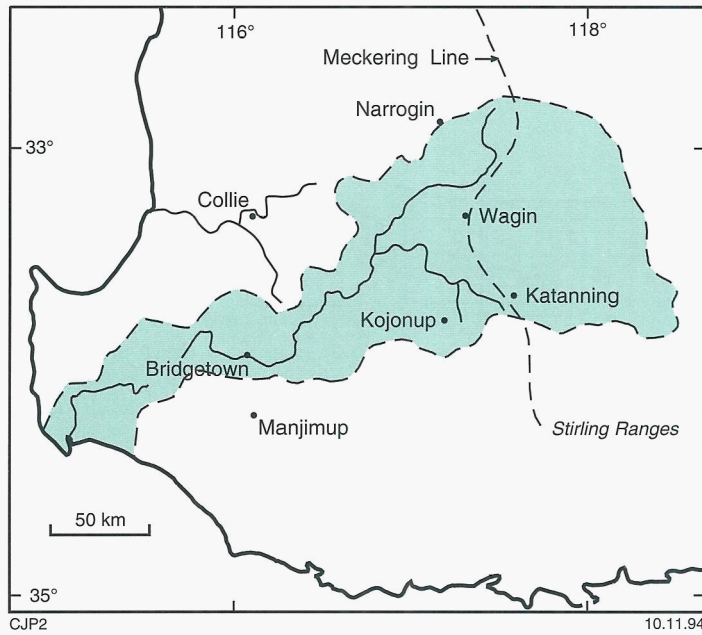


Figure 1.  
Blackwood  
River catchment

### Geological and geomorphological setting

The study area is located within the southwestern portion of the Yilgarn Craton, where the bedrock mainly consists of Archaean granitic rocks. The area lies within the Darling Plateau, in the 'Narrogin semi-stripped etch plain' subdivision of Finkl and Churchward (1973). The highest points in the landscape are Archaean rocks at an elevation of about 360 m.

A number of post-Permian sedimentary units which overlie bedrock in the southwest Yilgarn Craton, including Bremer Basin sediments, have been described by Finkl and Fairbridge (1979) and Backhouse and Wilson (1989). Those for which firm dates have been established are Cretaceous or Tertiary in age.

palaeochannel near Lake Towerrinning, and sediments in the Boscabel area where the occurrence of low-salinity groundwater was known from a 48 m-deep artesian borehole. The two areas are now recognized to be part of the same palaeochannel system (Fig. 2), and by the location and size of the

palaeovalley it is inferred to be the former course of the Beaufort River. The palaeochannel has been recognized over a length of some 60 km, with a markedly different orientation to the modern drainage patterns in the Towerrinning area. The sediments it contains are Eocene in age.

Isolated remnants of the Kojonup Sandstone (which is of assumed, but unconfirmed, Eocene age, and fluvial in origin) are preserved on drainage divides at the southern margin of the Blackwood catchment (Wilde and Backhouse, 1977) at an elevation of about 320 m. These exposures are located within 20–30 km of the study area.

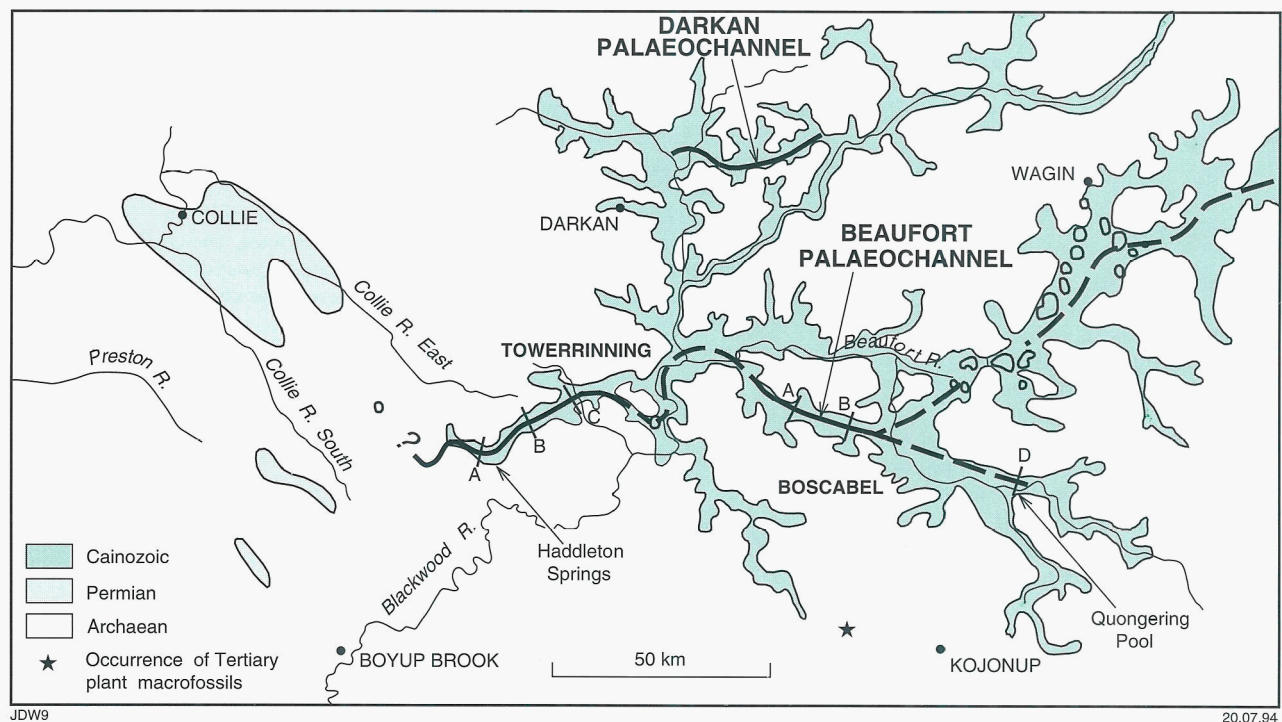


Figure 2. Location of the Beaufort Palaeochannel



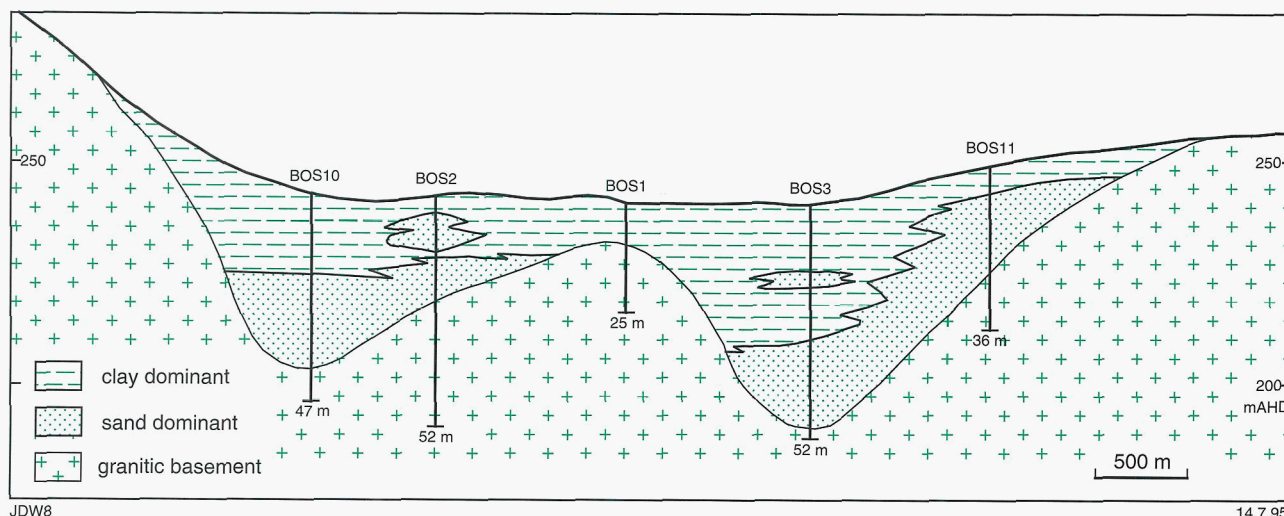


Figure 3. Geological cross section across the Beaufort Palaeochannel

The Beaufort Palaeochannel, where recognized over its length, occurs low in the landscape within a discontinuous valley. In places, the modern drainages cross this palaeovalley, making its continuity less obvious; however, its course can be traced once these overprinting features have been recognized. In comparison with the known outcrops of Kojonup Sandstone, the valley floor where the Beaufort Palaeochannel is present ranges in elevation from 220–260 m (Fig. 3), with the base of the sediments as much as 60–70 m lower. The palaeochannel sediments are thus consistently 100–150 m lower than the nearest known outcrop of Kojonup Sandstone.

### Stratigraphy

The sediments in the palaeochannel can be divided into two units. The lower unit consists of interbedded sands, clayey sands, and clays, which are all carbonaceous in places. The upper unit, where present, is dominantly composed of clay and silt, with lesser amounts of sand. The lower unit is commonly dark brown and grey, and is oxidized in places to yellow and red, whereas the upper unit is typically pale grey to white.

The sediments in the lower portion of the palaeochannel occupy a relatively narrow channel that is 200–500 m wide. They overlie weathered Archaean bedrock. In

places, the overlying clay extends over a wider area to the flanks of the palaeovalley (Figs 3 and 4). White clay, presumably weathered, can be seen close to the surface along parts of the course of the palaeochannel in excavated farm dams. Its characteristically massive appearance distinguishes it from exposures of deeply weathered basement rock, in which some remnant igneous or metamorphic textures are preserved.

At most locations the sequence includes a wide range of interbedded sediments without a consistent upper clay unit. The multiple layers of differing sedimentary materials show little apparent correlation from borehole to borehole, which typically are spaced at 400–500 m intervals along the transects. This is interpreted to reflect deposition by a meandering river system with an associated wide range of depositional

environments within the palaeovalley. Later, more uniform lacustrine conditions may have prevailed throughout the system, with subsequent erosion of some of the areas where lacustrine clay was deposited. Alternatively, a system of separate lakes may have developed along the palaeovalley as gradients decreased, in a similar way to the chains of lakes presently occupying the palaeodrainage east of the Meckering Line (Fig. 1).

On Towerinning Transect C (Fig. 2), the lacustrine clay is well developed and overlain by a second fluvial sand sequence with an overlying less well-developed clay. The deeper sands, in the earlier-formed fluvial sequence, are subrounded to rounded, typical of those elsewhere in the palaeochannel, and are believed to have been transported along it. However, the shallower sand is

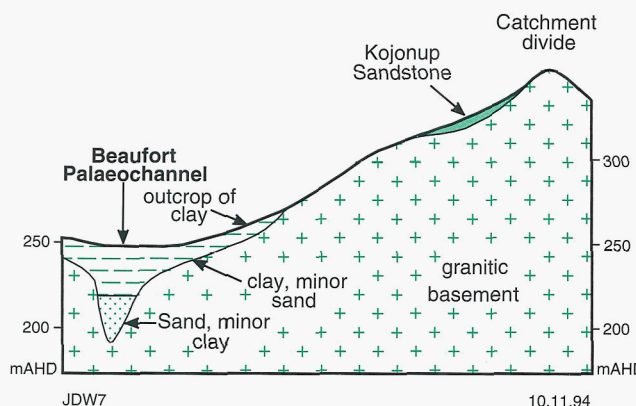


Figure 4. Relationship of Tertiary units in and around the Beaufort Palaeochannel



remarkably angular and appears to have been derived locally. The upper fluvial/lacustrine sequence, with its angular sands, may reflect local rather than regional conditions along the palaeodrainage.

## Palynology

Carbonaceous material from depths of 12 to 42.5 m, representing almost the entire palaeochannel sequence, contained rich and diverse spore and pollen assemblages. The assemblages are dominated by *Haloragacidites harrisii*, *Nothofagidites* spp., bisaccate gymnosperm pollen, and a diverse range of proteaceous pollen. Marine indicators have not been recorded from any samples examined to date.

The spore–pollen assemblages belong in the Middle or Upper *Nothofagidites asperus* Zone of Partridge (1976) and Stover and Partridge (1982), with a possible late-Middle to Late Eocene age. Broadly similar Eocene spore–pollen assemblages are recorded from the Bremer Basin (Hos, 1975; Stover and Partridge, 1982) and from the western margin of the Eucla Basin (Milne, 1988).

## Geological evolution

The sedimentary sequence in the Boscabel–Towerrinning area provides a record of early Tertiary geological events in the southwest Yilgarn Craton.

Prior to the Eocene epoch, flat-lying sediments of the Cretaceous Nakina Formation (Backhouse and Wilson, 1989) were deposited, overlying Permian strata. These are preserved in the Collie, Boyup, and probably Wilga Basins. Their elevation and attitude indicate that the present Darling Plateau was in existence at that time. The absence of extensive deposits of clastic sediments younger than Early Cretaceous in the southern Perth Basin suggests an absence of significant erosion from the southern Darling Plateau, although local erosional events associated with the Avon Palaeoriver in the Perth area correspond with the deposition of the Kings Park Formation during the Paleocene.

The palaeochannel trends westwards from Towerrinning, suggesting that the Beaufort Palaeoriver discharged across the Darling Scarp in the vicinity either of the present Collie River, which occupies a deep valley through the Darling Scarp, or the Preston River, which contains a substantial thickness of sediments that are as yet undated (Commander, 1993).

The relationship of the palaeochannel sediments with the more elevated Kojonup Sandstone is intriguing. If the Kojonup Sandstone represents an earlier deposit on a landscape that was subsequently rapidly dissected by uplift associated with continental breakup along the margin of the craton, substantial evidence of sedimentation in the Perth Basin might be expected; however, it is more likely that the Kojonup Sandstone represents deposits that were formed by tributaries coeval with the basal sediments in the main valley.

Further uplift from the west is likely to have reduced the gradient sufficiently enough for fluvial

sedimentation along the drainage to cease, with lacustrine conditions developing instead. Subsequent tilting to the south (Cope, 1975) has resulted in drainage diversion and capture, and the modern Blackwood River has cut through Archaean bedrock south of Lake Towerrinning to behead the ancestral Beaufort River. The palaeochannel west of Towerrinning has also been cut by Darlinup and Haddleton Creeks, both of which are southerly flowing tributaries of the Blackwood River.

The palynomorph assemblages indicate that Eocene marine influences do not appear to extend into the Blackwood catchment, and are restricted to the area south of the Ravensthorpe Ramp (Hocking and Cockbain, 1991).

Deep weathering and lateritization of the Archaean bedrock and exposed Kojonup Sandstone appears to post-date the deposition of the palaeochannel sediments. This is consistent with development of laterite on a dissected surface as postulated by Playford (1954) and Prider (1966).

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# U–Pb zircon dating of Archaean greenstones from the Eastern Goldfields

by D. R. Nelson, C. P. Swager, A. L. Ahmat¹, and R. H. Smithies

## Abstract

U–Pb zircon dates for eight felsic rocks from the Eastern Goldfields are reported. Felsic volcanic and volcanoclastic rocks from five localities within three tectonostratigraphic domains were deposited during 2673–2684 Ma. A dacite interleaved with komatiitic rocks of the Kalgoorlie Terrane has been dated at  $2709 \pm 11$  Ma and a felsic tuff interleaved with ultramafic rocks of the Bulong Complex of the Gindalbie Terrane was deposited at  $2705 \pm 4$  Ma. A felsic porphyry, previously believed to be a felsic volcanic unit near the base of the Kalgoorlie Terrane stratigraphy, was intruded at  $2658 \pm 6$  Ma. The new geochronological data suggest that the stratigraphic complexity observed within mapped tectonostratigraphic domains and terranes of the Eastern Goldfields greenstones is at least in part due to the rapid and localized deposition of felsic volcanic rocks in and adjacent to isolated volcanic centres in a highly active tectonic environment.

The new data indicate that the Eastern Goldfields greenstones formed at the same time as similar greenstones of the Abitibi Subprovince of Canada, and that at least some of the major tectonic episodes, including episodes of granitoid intrusion, were also contemporaneous.

**KEYWORDS:** Eastern Goldfields, greenstone, uranium–lead–zircon dating, geochronology, Archaean.

Over the last ten years, a team of geologists from the Geological Survey of Western Australia (GSWA) has been mapping the geology of the Eastern Goldfields region of the Archaean Yilgarn Craton. The results of this painstaking mapping work are now becoming available. The detailed 1:100 000 geological maps and 1:250 000 interpretative terrane maps arising from this work (the Kalgoorlie interpretative map was released in 1990 (Swager *et al.*, 1990) and the Kurnalpi interpretative terrane map is due to be released soon) reveal the complex relationships between adjacent greenstone

belts and granitoid rocks in the Eastern Goldfields, and provide an excellent basis for the investigation of the processes by which Archaean granite–greenstone terranes formed.

The mapping of the Eastern Goldfields greenstones has delineated a series of fault-bounded tectonostratigraphic domains (Swager, 1993; Fig. 1). Within each of these domains, a relatively coherent regional stratigraphy can be established. Where it can be demonstrated that adjacent domains share a common geological history, these domains can be united into a terrane; however, it is not always

possible to confidently establish stratigraphic relationships between adjacent domains based solely on field evidence. In order to understand how these domains were assembled and to investigate relationships between adjacent greenstone domains, and between greenstones and granitoids, GSWA geoscientists are undertaking a comprehensive program of U–Pb zircon dating in the Eastern Goldfields using the Perth Consortium Sensitive High-Resolution Ion Microprobe (SHRIMP).

The Perth SHRIMP was commissioned by the Minister for Mines, the Hon. George Cash, in December 1993. Located at Curtin University of Technology, the instrument is operated by staff from Curtin, the University of Western Australia, and the GSWA. The SHRIMP is used to determine the age of a rock by measuring the change in abundance, due to radioactive decay, of elements occurring within zones 30 microns in diameter in individual mineral grains.

The Eastern Goldfields dating program is currently in its early stages, with only eight of the anticipated 25 dates completed. Nevertheless, these preliminary results provide insight into the formation of the granite–greenstone terranes of the Eastern Goldfields.

## The Kalgoorlie Terrane

Within the Eastern Goldfields greenstones, the six westernmost tectonostratigraphic domains (Bullabulling, Coolgardie, Ora Banda, Kambalda, Boorara, and Parker Domains) are believed to

¹ Now at Ashton Mining Limited, 24 Outram Street, West Perth, Western Australia. 6005.

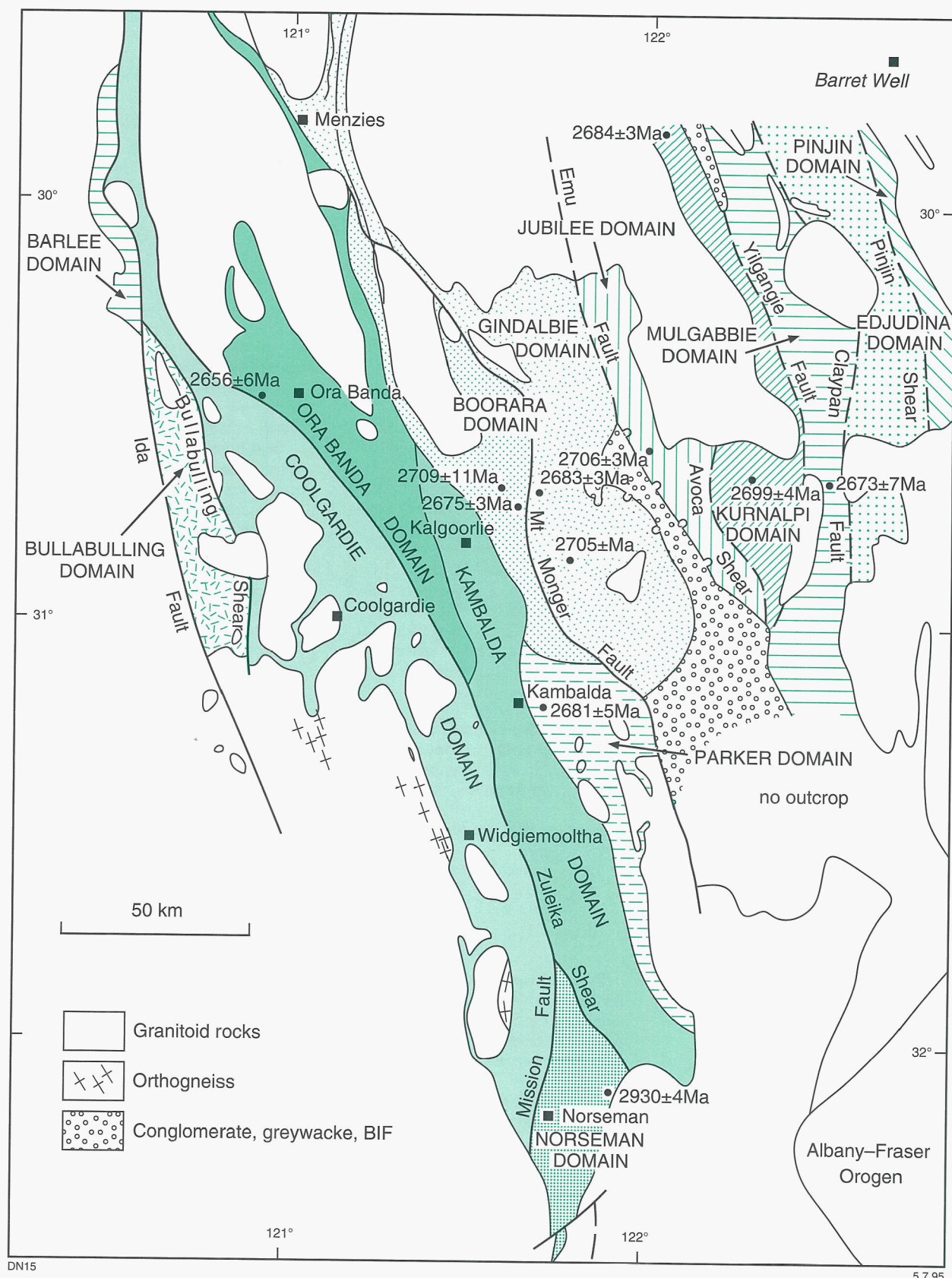


Figure 1. Regional geological map (based on figure 1 of Swager, 1993) of the Eastern Goldfields granite–greenstone terranes, showing tectonostratigraphic domains and their bounding faults. Geochronology sampling sites are also shown



contain parts of a single, relatively simple stratigraphic sequence, and have been grouped into the Kalgoorlie Terrane (Swager et al., 1990; Fig. 1). In general terms, the Kalgoorlie Terrane stratigraphy consists of a lower basalt unit, an overlying unit dominated by ultramafic (komatiitic) and mafic flows, an upper basalt unit, and an uppermost felsic volcanic and volcanoclastic unit, commonly referred to as the Black Flag Group. Claoué-Long et al. (1988) dated a volcanogenic sedimentary rock overlying the ultramafic unit near Kambalda at  $2692 \pm 4$  Ma (all errors given are at 95% confidence).

Three samples from the Kalgoorlie Terrane have been dated so far as part of the GSWA study. The depositional age of a felsic volcanic rock from the Black Flag Group in the Parker Domain was determined to be  $2681 \pm 5$  Ma. A thick dacitic flow within the komatiite unit in the Boorara Domain was dated at  $2709 \pm 11$  Ma. These preliminary data provide support for the concept, developed entirely from field observations, of a relatively simple general stratigraphic sequence for the entire Kalgoorlie Terrane, but it is also apparent that the inferred simple stratigraphic succession has been disrupted in places by the localized eruption of felsic volcanic rocks from isolated vents, both during and after the eruption of the komatiitic lavas. These two new dates indicate that deposition of the komatiite and Black Flag units of the Kalgoorlie Terrane stratigraphy occurred over a period of at least 12 million years.

A felsic schist within the Ora Banda Domain, previously thought to represent a deformed felsic volcanic unit near the base of the Kalgoorlie Terrane stratigraphy, was dated at  $2658 \pm 6$  Ma. This unit is now interpreted to represent an intrusive porphyry associated with the Siberia Monzogranite.

### *The eastern terranes*

The eastern terranes contain diverse and complex stratigraphic sequences that predominantly consist of basaltic and ultramafic units, and proximal felsic volcanoclastic units. The structural complexity and lateral discontinuity in the

stratigraphies of these terranes make lithostratigraphic correlation between them difficult or impossible. It has therefore been necessary to rely largely on precise, high-quality geochronological data in order to establish the relationships between the various stratigraphic units of these terranes.

The Gindalbie Terrane, located adjacent to the Boorara Domain of the Kalgoorlie Terrane, contains one of the most complex structural-stratigraphic sequences of any terrane in the Eastern Goldfields. In general terms, the lower part of the structural-stratigraphic column is dominated by a calc-alkaline association. This is structurally overlain by komatiitic flows of the Bulong Complex. A bimodal basalt-rhyolite sequence overlies the Bulong Complex, the contact between which is faulted.

U-Pb zircon dating has indicated a depositional age of  $2705 \pm 4$  Ma for a felsic tuff interleaved with ultramafic rocks in the lower part of the Bulong Complex. This date is within error of the date of  $2709 \pm 11$  Ma obtained for a dacite interleaved with the komatiite unit from the Boorara Domain, and is consistent with the minimum age of  $2692 \pm 4$  Ma obtained by Claoué-Long et al. (1988) for the Kapai Slate, which overlies the komatiite unit in the Kambalda Domain. The ultramafic rocks of the Bulong Complex may therefore be correlated with the komatiite unit of the Kalgoorlie Terrane. A date of  $2683 \pm 3$  Ma was also obtained for a felsic tuff from the upper unit of the Gindalbie Terrane. Parts of the upper unit of the Gindalbie Terrane may therefore also be correlated with the Black Flag Group of the Kalgoorlie Terrane.

Rocks of the lower calc-alkaline association of the Gindalbie Terrane have yet to be reliably dated. However, should future geochronological investigations confirm that they predate the Bulong Complex, they may be stratigraphically equivalent to the substantial felsic duplexes underlying the Kalgoorlie Terrane stratigraphy, as inferred from the 1991 Australian Geological Survey Organisation (AGSO) seismic traverse (Goleby et al., 1993).

A quartz-feldspar volcanic breccia containing black aphanitic clasts,

sampled near the Mount Monger Fault, was dated at  $2675 \pm 3$  Ma. Its close proximity to the Mount Monger Fault, a major terrane-boundary fault, makes the stratigraphic relations of this sample uncertain. The geochemical characteristics of this sample more closely resemble those of the felsic volcanic rocks of the Gindalbie Terrane than those of the Black Flag Group of the Kalgoorlie Terrane, and the sample is here tentatively assigned to the Gindalbie Terrane.

A date of  $2684 \pm 3$  Ma has been obtained from a thin rhyodacite unit at the base of a basalt sequence from the Kurnalpi Terrane, located further to the east of the Gindalbie Terrane. Within the Mulgabbie Terrane, near the eastern margin of the exposed greenstones, a dacite separating basalt from an andesitic-basaltic sequence was dated at  $2673 \pm 7$  Ma. Despite the complex and diverse lithostratigraphic successions of these terranes, which is evident from field mapping, the geochronological data indicate that all of the terranes from which dates have so far been obtained contain similar felsic volcanoclastic lithologies that were deposited synchronously at c. 2680 Ma.

### *Deposition of the Eastern Goldfields greenstone successions*

The field and geochronological data collected so far indicate that the stratigraphic complexity observed within the domains and terranes of the Eastern Goldfields greenstones is at least in part due to the rapid and localized deposition of felsic volcanic rocks close to isolated volcanic centres. Four of the five dates obtained on felsic volcanic rocks from the eastern terranes agree within their assigned analytical uncertainty (the exception being the date of  $2705 \pm 4$  Ma from the felsic tuff within the Bulong Complex of the Gindalbie Terrane), yet the stratigraphic associations of each of these dated felsic volcanic rocks is unique. The felsic volcanic rocks of the eastern terranes are commonly closely associated, or interleaved, with basaltic rocks, whereas within the Kalgoorlie Terrane basaltic volcanic rocks are rarely found interleaved with felsic

volcanic rocks of the Black Flag Group. Lithologically similar felsic volcanoclastic rocks were probably erupted from a number of distinct volcanic centres within the Eastern Goldfields greenstone successions, within a geologically narrow time interval of approximately 15 million years.

Emplacement ages of 2690–2680 Ma for early (pre-D₂) granitoids from the Eastern Goldfields (e.g. Hill et al., 1992) are similar to those obtained for the felsic volcanic rocks. Geochemical and Nd-isotope data suggest that the early granitoids and felsic volcanic rocks were probably at least partly derived from similar sources and may have been cogenetic. It is therefore apparent that the greenstone successions were deposited during emplacement of at least some of the early granitoids, in a tectonically active environment.

### *Where is the basement to the greenstones?*

Multiply deformed monzogranite to granodiorite gneisses are exposed at localities near the western, southern, and eastern margins of the Eastern Goldfields Province greenstones. These gneisses typically preserve upper amphibolite facies mineral assemblages and are characterized by low zircon abundances. Preliminary data obtained on one complex orthogneiss sample, from the Pioneer Dome about 35 km north-northwest of Norseman, indicate the presence of complex zircon age populations, with zircons as old as c. 3300 Ma. It appears likely that these complex gneisses (which are quite different from the comparatively simply deformed granitoids and orthogneisses occurring near major faults along the margins of the greenstones, and in the region to the west and north of Leonora) may represent reworked older crustal basement onto which the greenstones were deposited. Further dating is underway on other examples of the gneisses in order to investigate this possibility. The gneisses may also have provided the source rocks from which the granitoids and felsic volcanic rocks were derived.

### *Formation of the Eastern Goldfields granite–greenstone terranes*

The following evolutionary model of the formation of the Eastern Goldfields granite–greenstone terranes is consistent with the available field and geochronological evidence. At c. 2710–2690 Ma, asymmetric rifting, mainly by north-trending normal faulting of pre-existing granitic and gneissic crust, resulted in the development of a series of adjacent basins into which predominantly basaltic and ultramafic volcanic rocks were deposited. Felsic volcanoclastic rocks were also erupted from a few isolated volcanic centres at the same time as the ultramafic volcanism. At c. 2685 Ma, felsic volcanoclastic rocks were erupted from numerous volcanic centres and early (pre-D₂) granitoids were emplaced mainly as thick sheets into the base of the greenstone sequences. This igneous activity may have been a consequence of heating of the base of the crust during crustal thinning. This was followed at c. 2670–2665 Ma by regional (D₂) compression, involving reactivation of early structures. Additional episodes of granitoid emplacement have been identified at c. 2665–2660 Ma and c. 2630–2600 Ma (Hill et al., 1992).

Tectonic models advocating the involvement of mantle plumes (e.g. Hill et al., 1992) cannot account for the compressional regime responsible for D₂ structures, and the volcanic rocks lack many of the diagnostic geochemical features found in the volcanic rocks of modern subduction zones. Furthermore, the field and geochronological data obtained so far also do not support currently popular tectonic models for the formation of the Eastern Goldfields granite–greenstone terranes by lateral accretion of ‘exotic’ terranes or by accretion of a series of separate island arcs, although it is possible that future work further to the west and east of the Eastern Goldfields greenstones may identify such terranes or arcs. On present evidence a continental margin back-arc basin setting offers the closest modern analogy of the tectonic setting for the formation of the Eastern Goldfields granite–greenstone terranes. The Kalgoorlie

greenstones were probably deposited within a series of narrow back-arc rift basins formed along a continental margin and above an active subduction zone, which was located further to the east of the rift basins.

### *Global correlation of late Archaean granite–greenstone terranes*

The availability of precise geochronological data enables the age of formation of late Archaean granite–greenstone terranes throughout the world to be compared. The new geochronological data obtained as part of this study indicate that greenstones of the Eastern Goldfields of Western Australia formed contemporaneously with similar greenstones of the Abitibi Subprovince of Canada, and that at least some of the major tectonic episodes, such as the major compression events recognized in both provinces and the episodes of granitoid intrusion, were also contemporaneous (Corfu, 1993, recently summarized geochronological data from the Abitibi Subprovince). Models for the formation of late Archaean granite–greenstone terranes must now account for these remarkable similarities.

It is possible that the late Archaean granite–greenstone terranes formed during a major, perhaps global, catastrophic magmatic episode that occurred approximately 2740–2675 million years ago. Campbell and Griffiths (1990) have argued that disturbances at the core–mantle boundary may produce plumes more than 2000 km in diameter near the Earth’s surface, and cause catastrophic episodes of voluminous magmatism. Evidence for the eruption of substantial volumes of volcanic rocks during the late Archaean is also found in a number of other Archaean cratons (e.g. the 2765–2685 Ma Fortescue Group flood basalts of the Pilbara Craton and 2715–2700 Ma basaltic rocks of the Ventersdorp Supergroup of the Kaapvaal Craton). However, as briefly mentioned above, such mantle-plume models cannot account for some aspects of the geology of many late Archaean granite–greenstone terranes.

Reliable geochronological data from throughout the Yilgarn Craton are sparse, but those which are available, in addition to those from the Superior Province of Canada, suggest that these cratons may once have been part of a single continent. It is conceivable that the Eastern Goldfields and Abitibi granite–greenstone terranes are dispersed remnants of what may once have been a single granite–greenstone

‘superterrane’, formed during a major late Archaean subduction and/or collision event, which occurred along the margin of a united Yilgarn–Superior Craton. The comprehensive mapping program and geochronological investigations of the Eastern Goldfields granite–greenstone terranes currently underway will enable these and other hypotheses to be examined.

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## Onshore northern Perth Basin gravity project

by R. P. Iasky

### Abstract

A series of gravity surveys have been conducted along seismic lines in the onshore northern Perth Basin. The data collected were combined with data from the Australian National Gravity Database, which is maintained by the Australian Geological Survey Organisation, and were processed to produce images. The images were manipulated to highlight structural features and provide new insights into the structural evolution of the area.

The gravity images of the onshore northern Perth Basin were analysed for lineaments and four major trends were identified: north-northwesterly, easterly, northeasterly to east-northeasterly, and northwesterly. These trends on the gravity maps correlate directly with faults and lineaments that have been mapped using seismic and magnetic data. The most intense structural fabric occurs along the north-northwest trend within the Darling–Urella Fault System. The easterly trend is in the northern part of the Perth Basin, near the southern extension of the Northampton Complex, suggesting that faulting related to this trend is a result of the interaction of pre-existing basement terranes. The northeast trend is interpreted as antithetic strike-slip faulting, and the northwest trend corresponds to transfer faults that are also observed on aeromagnetic maps. Both northeast- and northwest-trending sets of faults were developed during the separation of Greater India from Australia, in the Early Cretaceous.

**KEYWORDS:** Perth Basin, gravity, Bouguer anomaly maps, lineaments, structural evolution.

Potential-field data have been used in the petroleum industry to analyse subsurface geological structures since the 1920s, but the seismic-reflection method has predominated throughout the history of exploration because the resultant reflections can be correlated directly to geologic strata (Nettleton, 1971). In the 1990s, there has been a revival in the use of aeromagnetic methods in petroleum exploration because technological advances in computing, satellite navigation, and instrumentation have improved the resolution of smaller anomalies. The

new data have enabled the identification of small anomalies that relate to structures within the sedimentary strata, whereas, in the past, potential-field data were mainly used for identification of broad, basement-related features. Mapping the gravity field, especially onshore, has not been as popular as the use of aeromagnetic methods because airborne gravity surveying is inaccurate and ground surveying is logistically more difficult to conduct. This has resulted in sparse coverage of the area and poor resolution of small anomalies.

In the last decade, potential-field data have been displayed as images similar to those produced with satellite spectral data, and this has improved interpretation because it is easier to visualize trends and lineaments on these images. Gravity anomalies are produced when horizontal and vertical density differences occur in sedimentary and basement lithologies. Unlike magnetic anomalies, gravity anomalies are not affected by surface cultural effects and surficial magnetic rocks and sediments. Processed gravity images show lineaments caused by faulting; intra-basement structural and lithological changes; and, possibly, intra-sedimentary variations in density. Gravity surveys represent a relatively low-cost method of addressing local and regional structural problems. Depending on the amount of coverage, gravity surveys can provide a powerful complementary dataset to seismic and magnetic data, which can be used to analyse subsurface geological structures.

A regional study of the onshore northern Perth Basin between latitudes 29°S and 31°S (Fig. 1), which has just been completed (Mory and Iasky, in prep.), uses integrated well, outcrop, seismic, aeromagnetic, and gravity data to review the structure and stratigraphy of this part of the Perth Basin. An opportunity to improve the gravity coverage in the study area, with minimal logistical problems, arose in late 1993 and early 1994, when a number of seismic surveys were to be recorded in the northern Perth Basin. West Australian Petroleum (WAPET) planned to record a two-dimensional and three-dimensional seismic survey over the Strawberry



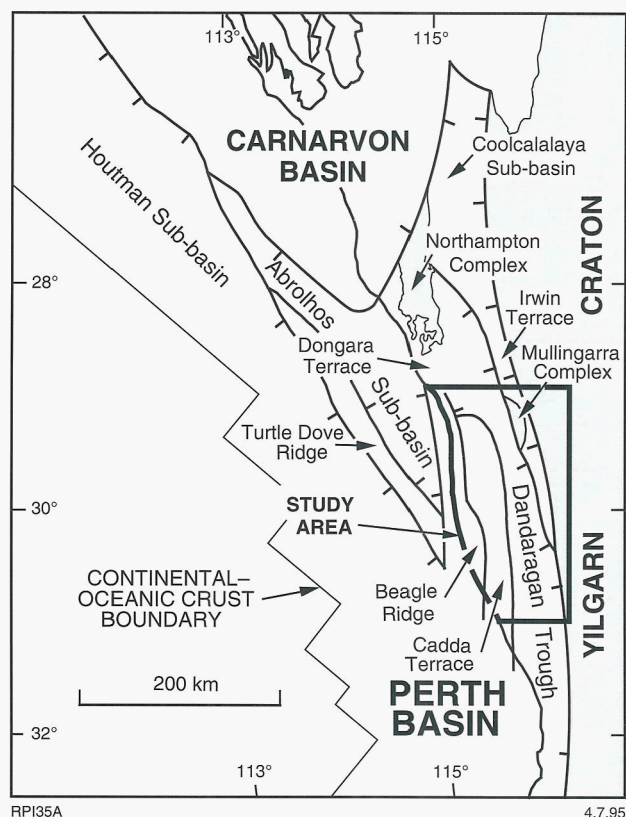


Figure 1. Location of study area in the onshore northern Perth Basin, including tectonic elements

Hill structure and the Dongara field respectively. The three-dimensional survey was an ideal place to record gravity data along a regular grid and achieve a station spacing that is close to that obtained in aeromagnetic surveys. These surveys were followed by two-dimensional surveys by Discovery Petroleum over the Mount Horner field; by Victoria Petroleum to delineate a small structure northwest of Mount Horner; and by Consolidated Gas over the Woodada field. The Geological Survey of Western Australia (GSWA), in cooperation with these companies, proceeded to collect gravity measurements along seismic lines (Fig. 2) where topographic control was being established as part of seismic surveying.

### Data coverage

Data was collected in the onshore northern Perth Basin between latitudes 29°00'S and 31°00'S and longitudes 114°55'E and 116°00'E. Data from a total of 3299 new stations, recorded over

the 1993–94 seismic-survey lines, and 4269 existing gravity stations from the Australian Geological Survey Organisation (AGSO) database were processed to produce images of gravity anomalies over the basin. The northern quarter of the area between latitudes 29°00'S and 29°30'S is the most densely covered (good to average) and contains 4643 stations (61% of all stations). The remaining stations are spread over the southern three-quarters of the study area; the southern half only has regional coverage at a station spacing of 10–12 km.

Five seismic surveys were conducted in the northern Perth Basin from November 1993 to April 1994. At the same time, the GSWA recorded gravity at regular intervals along the seismic lines. In addition, north of latitude 29°30'S, gravity was recorded on regional traverses along farm tracks, bush tracks, and pipelines to infill sparsely covered areas in the basin and to add control across major faults (Fig. 2). The amount and timing of the respective gravity surveys is listed in Table 1.

The recently collected data consist of measurements along seismic lines at a station spacing of 300 to 500 m, and additional regional traverses along main roads and tracks at 500 m spacing. By comparison, the AGSO data consist of: a compilation of data collected by WAPET in the 1960s at 800 m (half a mile) spacing; Bureau of Mineral Resources (BMR) regional data collected at 10–12 km spacing; and a number of other smaller mineral exploration surveys at the eastern boundary of the basin, spaced at 500 to 1000 m. The area of investigation has good coverage over the Dongara and Mount Horner fields, medium coverage over the Woodada field and the Darling Fault, and poor coverage in the rest of the area.

The data were reduced to the 1967 International Gravity Formula, and corrected for latitude, free-air, and Bouguer anomalies to sea-level datum (Wellman et al., 1985). The densities used in the Bouguer correction were 2.00 g/cm³ in the Perth Basin, and 2.67 g/cm³ over crystalline rocks on the Yilgarn Craton and Mullingar Complex. The Bouguer gravity data were grided and filtered using the Intrepid geophysical processing package, and a series of images were produced using the ER-Mapper image-processing software.

### Identification of structural features

The following discussion is based on the identification of structural trends and lineaments observed on the gravity images of the study area. Many images of Bouguer gravity, and first and second derivatives of the gravity field, illuminated from different directions, were produced to identify structural features. While it is beyond the scope of this paper to show all the results, the image on Figure 3 shows the location of major structural features and summarizes the observed lineaments in the onshore northern Perth Basin. The northern part of the study area has a more detailed interpretation because of the higher resolution resulting from better coverage. The position of the lineaments when compared to faults mapped on seismic horizons (Fig. 4) suggests that the majority can be attributed to basement structures.

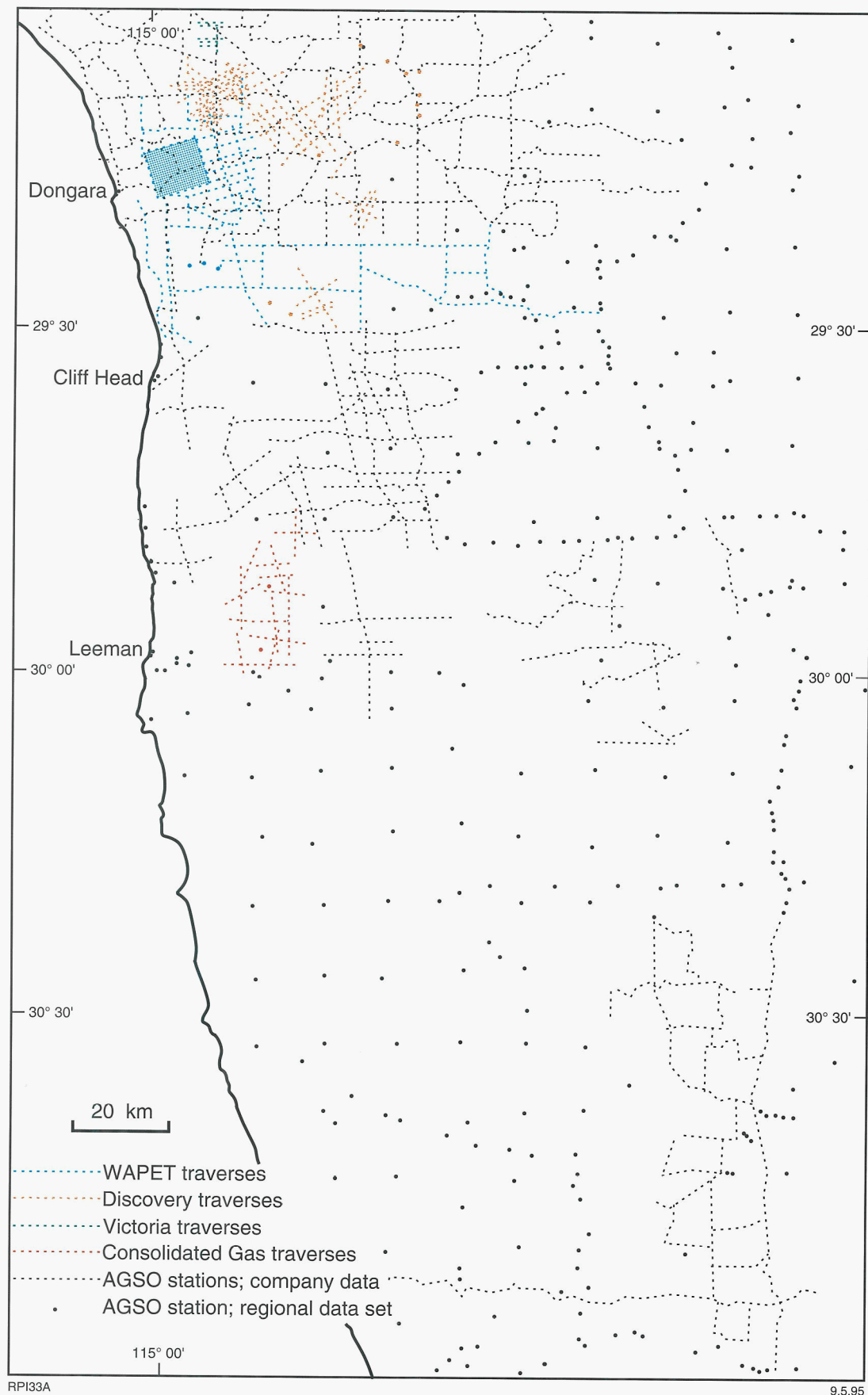


Table 1. Gravity surveys recorded between November 1993 and April 1994

Survey name	Company	Start date	End date	Line kilometres	Station spacing (m)	Number of stations
Regional infill — Dongara–Arrowsmith area	WAPET	22/11/93	14/12/93	382.0	500	703
Strawberry Hill 2D SS	WAPET	15/12/93	04/01/94	114.8	500	223
North Dongara 3D SS	WAPET	05/01/94	05/02/94	469.8	300	815
Mingenew SS	Discovery Petroleum NL	17/02/94	26/03/94	371.8	300, 450	1 161
Tabletop SS	Victoria Petroleum NL	22/02/94	23/02/94	24.5	300	55
Logue SS	Consolidated Gas Pty Ltd	13/04/94	19/04/94	136.0	450	342

SS: Seismic survey

### Northerly to northwesterly striking lineaments

The Darling Fault is apparent as a major north- to north-northwesterly trending feature on the southeastern part of the image, but the anomaly has a considerably reduced amplitude in the north. Between 29°40'S and 30°05'S the throw on the Darling Fault decreases significantly as the throw on the Urella Fault increases. This type of fault geometry and kinematics has been described as a relay ramp (Peacock and Sanderson, 1994). Northeast-trending lineaments displace the Darling Fault in a sinistral sense in several places along its length. The most dominant of these is at approximately at 29°40'S where the throw of the Darling Fault is relayed to the Urella Fault. Both faults appear to continue to the north and south respectively, but their gravity anomaly is considerably smaller. Where the Yilgarn Craton is juxtaposed with the Mullingar Complex, the Darling Fault cannot be clearly identified because of the minimal density contrast. At this point the anomaly representing the Urella Fault increases in width because of the effect of the near-surface rocks of the Mullingar Complex.

The Urella Fault is the major north-northwesterly trending feature in the northeastern part of the image, with the Darling Fault parallel to it on the eastern side. A major splay of the Urella Fault which strikes west at approximately 29°10'S, is interpreted as the intersection with the Allanooka Fault. North of the Allanooka Fault the gravity data show that the throw of the Urella Fault diminishes and that two other smaller splays striking west are present. A high-amplitude lineament parallel to, and to the west of, the Urella Fault is interpreted as the Wicherina Fault to the north of the Allanooka Fault.

The Beagle Fault System is identified by the higher-amplitude anomalies on the western part of the images, bordering the coast. There are several broken lineaments striking north to northwest that probably represent several en echelon faults as mapped with seismic data (Fig. 4). Unfortunately, the data coverage near the coast is poor and the resolution of these lineaments is low.

The Mountain Bridge Fault is represented by a set of lineaments striking north, which have been identified north of approximately 29°30'S, immediately east of the Beagle Fault System (Fig. 3). Another set of near-parallel lineaments, immediately to the east and at the same northing, represents the Beharra Springs Fault as mapped with seismic data.

The lineaments representing these two faults are discontinuous, indicating that the faults may not penetrate basement in places, even though they may be present within the sediments. North of the Allanooka Fault, other larger-amplitude, north-northeasterly striking lineaments appear to be unrelated to these two faults. Both the Mountain Bridge and Beharra Springs Faults appear to be dissected by northeast-striking lineaments.

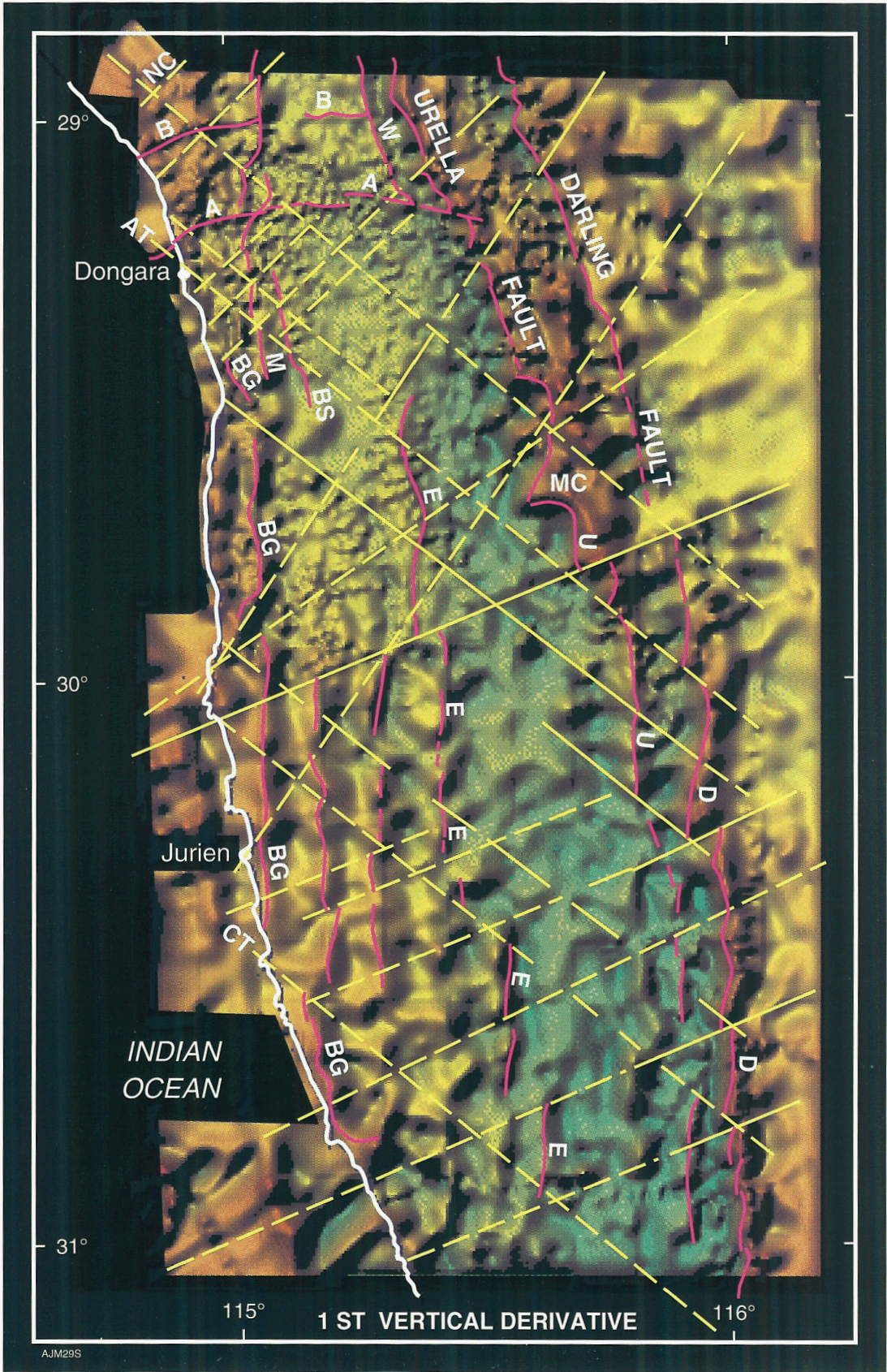
The Eneabba Fault System can be identified in the central part of the image as a series of north-striking lineaments that divide the deeper Dandaragan Trough in the east from the shallower Cadda Terrace to the west. These lineaments extend throughout the length of the image, south of the Allanooka Fault.

### Easterly striking lineaments

At approximately 29°10'S, the Allanooka Fault is well defined on both its western and eastern margins. In the west it is a linear feature that strikes east-northeast, and it diminishes in amplitude towards the east. The high-amplitude, broad anomaly to the northwest of the Allanooka Fault represents the southern extension of the Northampton Complex, and the Allanooka Fault is the southern edge of this high basement block. The fault appears to comprise a

Figure 2. (opposite) Distribution of gravity stations in the study area, indicating the position of new gravity traverses







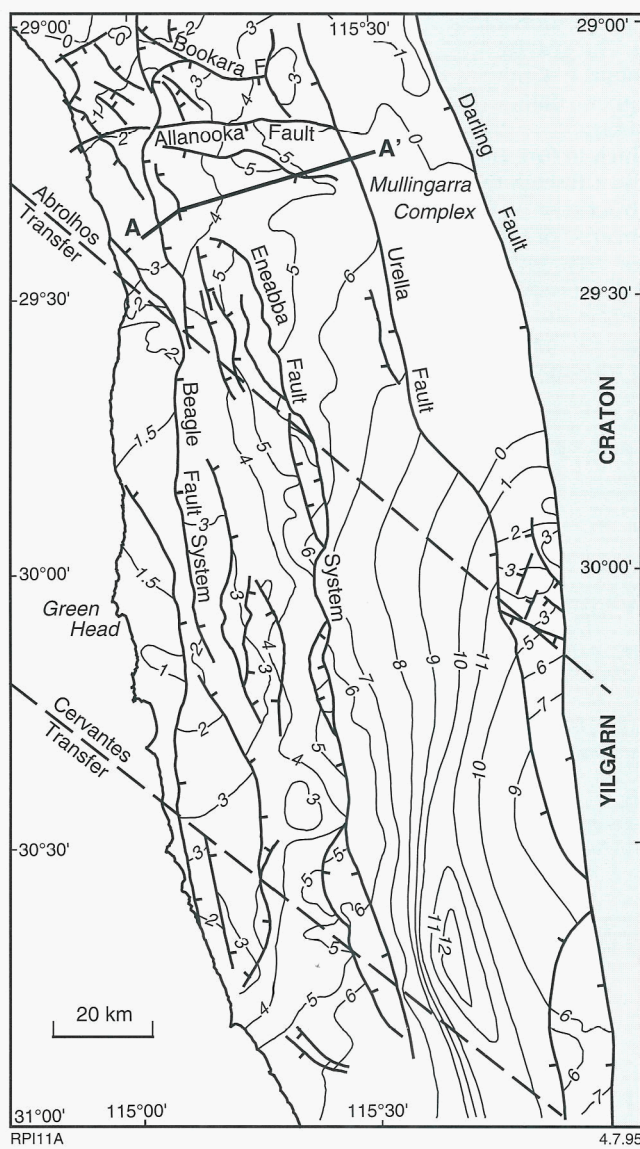


Figure 4.  
Depth to basement  
structure of the  
onshore northern  
Perth Basin,  
interpreted from  
seismic data.  
Contours in  
kilometres below  
Australian Height  
Datum (AHD)

series of east-northeasterly striking lineaments that are not necessarily continuous at basement level.

The Bookara Fault is identified as an east-striking lineament on the northwest part of the image at approximately 29°00'S. It is a high-amplitude lineament in the west where basement is shallower, and its amplitude diminishes to the east as sediment thickens, continuing through to the Wicherina Fault. Two other lineaments, also striking east, are

displayed north of the mapped position of the fault, indicating further, similar, easterly trending faulting to the north.

It is important to note that easterly trending lineaments occur only in the northern part of the study area, adjacent to the southern extension of the Northampton Complex. Mory and Iasky (1994) suggested that the east-striking faults are a direct result of a northerly extension phase in the Permian; however, Harris et al. (in prep.) could not

reproduce these faults in analogue modelling experiments, which indicates that the lineaments are a consequence of pre-existing structures within the two basement terranes of the Yilgarn Craton and the Northampton Complex.

### Northeasterly to east-northeasterly striking lineaments

There are numerous northeasterly trending lineaments striking between 45° and 65°N throughout the image (Fig. 3). These appear to displace northerly trending lineaments in a left-lateral sense, and examples of this displacement occur on the Allanoooka, Darling, and Urella Fault systems. One of the east-northeasterly trending lineaments at the southern edge of the image was identified from seismic mapping and named the Vlaming Transfer by Hall and Kneale (1992). The northeasterly trending lineaments were also identified in the aeromagnetic images, and correspond to strike-slip faults that are antithetic to the northwestern extension phase of tectonism that occurred at continental breakup (Harris, 1994). They were also recognized by Harris et al. (in prep.) in an analogue-modelling experiment. The direction of these lineaments correlates with the direction of dolerite dykes in the Northampton Complex, and it is possible that they represent reactivated basement fractures.

### Northwesterly striking lineaments

Northwesterly striking lineaments (along approximately 300°) correspond to fractures associated with the transfer faulting initiated at breakup, such as the Abrolhos Transfer (Hall and Kneale, 1992; Mory and Iasky, 1994), and appear to displace northerly trending lineaments in a sinistral sense on the images and seismic sections (Fig. 4). These lineaments are more prominent when the gravity image is illuminated from the southwestern direction and, therefore, are not delineated clearly in Figure 3. Although only a few of these lineaments have

Figure 3. (opposite) Image of first derivative of Bouguer gravity (northwest sun illumination), with a summary of interpreted lineaments. The abbreviations used in the diagram are: A — Allanoooka Fault; AT — Abrolhos Transfer; B — Bookara Fault; BG — Beagle Fault System; BS — Beharra Springs Fault; CT — Cervantes Transfer; D — Darling Fault; E — Eneabba Fault System; M — Mountain Bridge Fault; MC — Mullingar Complex; NC — Northampton Complex; U — Urella Fault; W — Wicherina Fault

been identified in gravity images, they are numerous in aeromagnetic images and are spaced between three and six kilometres apart. The analogue modelling performed by Harris et al. (in prep.) showed that pre-existing north-northwest faults acted as transfer faults during the northwest–southeast extension at breakup. This modelling indicates the influence of earlier deformation on the pattern of faulting during subsequent tectonism.

## Conclusions

Gravity images of the onshore northern Perth Basin show that there are four families of lineaments, trending north-northwest, east, northeast, and northwest. The north-northwesterly and easterly trending lineaments correlate directly with faults mapped using seismic data, whereas northeasterly trending lineaments are observed on aeromagnetic maps, and northwesterly trending lineaments are observed on aeromagnetic maps and also implied on seismic maps. The good correlation with other datasets suggests that gravity mapping may be a very attractive, low-cost method of obtaining structural information in sedimentary basins.

Gravity data can be collected along seismic lines at a small additional cost to the seismic program. The resolution of the data, and therefore the degree of interpretation that can

be made, is directly proportional to the station coverage. The gravity mapping, when combined with seismic and aeromagnetic data, provides complementary information with which to formulate structural models. Even though the effect of basement structures dominates images because of the large density contrast between sediments and crystalline rock, smaller anomalies within the sedimentary strata can be identified, given adequate data resolution.

## Acknowledgements

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# Program review

## Program 1.0

### MINERAL RESOURCES MANAGEMENT

1.1.2.1	Advice on changes to mining legislation .....	101
1.1.2.2	Advice for landuse planning .....	102
1.1.2.3	Aboriginal liaison .....	103
1.1.2.4	Resource advice .....	104
1.2.3	Advice on administration of mining legislation .....	105
1.3.2	Geotechnical and rock mechanics advice .....	106
1.5.1	Registration and archives WAMEX .....	108

## Program 2.0

### PETROLEUM RESOURCES MANAGEMENT

2.1.3.1	Advice relating to petroleum resources .....	110
2.5.1	Registration and archives WAPEX .....	111

## Program 3.0

### GEOLOGY AND RESOURCE INFORMATION

3.1.1.1	Yilgarn Craton .....	112
3.1.1.2	Pilbara Craton .....	113
3.1.1.3	King Leopold and Halls Creek Orogens .....	114
3.1.1.4	Paterson Orogen .....	116
3.1.1.5	Pinjarra Orogen .....	118
3.1.1.6	Savory Basin .....	119
3.1.1.8	Basin Studies .....	119
3.1.1.9	Statewide mineralization studies .....	121
3.1.1.10	Regional mineralization studies .....	122
3.1.1.11	Mine mineralization studies .....	123
3.1.1.12	Geology of 1:1 000 000 sheet areas .....	123
3.1.1.13	1:50 000 environmental geology mapping .....	124
3.1.1.14	ROCKMIN .....	125
3.1.1.15	Reconnaissance gravity traverses .....	125
3.1.1.16	Geophysical databases .....	126
3.1.1.17	Regolith .....	126
3.1.3	Airborne geophysical mapping .....	127
3.1.4	Glengarry Basin regional geological mapping .....	129
3.1.5	Eastern Goldfields regional geological mapping .....	132
3.1.6	Regional geochemical and regolith mapping .....	135

3.2.1	Groundwater exploration assessment and mapping .....	136
3.2.2	Advisory services and investigations .....	137
3.2.4	Groundwater exploration .....	139
3.3.1.1	Dams and damsites .....	140
3.3.1.2	Foundation and construction materials .....	141
3.3.1.3	Geotechnical data .....	141
3.3.1.4	Geophysical investigations and advice .....	142

## **Program 6.0**

### **CORPORATE SERVICES**

6.3.3	Library and information services .....	143
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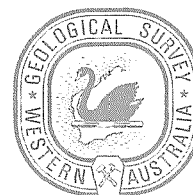
## Program 1.0

# MINERAL RESOURCES MANAGEMENT

### Subcomponent 1.1.2.1

### Advice on changes to mining legislation

**Objectives:** *To provide advice on the effectiveness of the Mining Act and Minerals (Submerged Lands) Act in relation to regulating mineral exploration, and to monitor the possible effects of legislation or other government initiatives on access for exploration.*



The GSWA, as the Government's advisor on mineral exploration, takes an active role in monitoring current legislation to assess its effectiveness in regulating and promoting mineral exploration and, where necessary, to propose changes to improve that effectiveness. While the Western Australian Mining Act is the main vehicle under which exploration is carried out in the State, input is also made to the Commonwealth Offshore Minerals Act, and to drafts of various Agreement Acts covering major resource developments. Other legislation that may affect access for exploration is also scrutinized so that its impact can be assessed and minimized.

#### *Mining Act*

During 1993–94 a number of legislation issues, which have been the subject of papers prepared by GSWA, were addressed by subcommittees of the Mining Industry Liaison Committee (MILC). Amongst these issues were: circumstances that warranted the extension of term of an exploration licence; reporting of exploration activities and results for all mining tenements; release of old exploration data to open file; copyright on exploration reports; trespass during aerial surveys; and the need for a register of aerial photography.

For some exploration licences the Department already accepts that an extension of term is warranted where holders or operators have had restricted access for exploration

during the five year term, because of circumstances beyond their control. But there are other circumstances where it would be in the best interests of the State to extend the period of effective exploration on a licence to allow newly discovered mineralization to be investigated more intensively or to apply revised geoscientific concepts for more vigorous testing of certain areas. It was recommended that the legislation should be amended to specify: the particular circumstances under which applications for extensions could be made; the period for each extension; and the minimum expenditure requirements for each period.

A review of exploration data that had recently been submitted to the Department showed that some operators were not providing full details of their exploration activities on all types of tenements, along with their Form 5 reports. During the review it was realised that, except for exploration licences, the legislation did not provide specifically for the submission of mineral-exploration reports. Amendments were recommended to make it clear in the Act that such reports were required for all tenements where geoscientific activities had been carried out and results obtained. It was further recommended that the Act should provide for penalties to be imposed on tenements where reporting responsibilities had been neglected. In addition it was recommended that the legislation be amended to allow operators to lodge one combined mineral-exploration report for numerous

contiguous tenements that were being worked as one tenement group with a common exploration program — this would provide legal backing for the Department's present practice of consenting to combined reporting.

A large amount of useful exploration data on old projects is still on closed file because a small part of the original project area is still held under title. Changes to the Act have been recommended to allow any exploration reports more than ten years old to be placed on open file, unless a written objection is lodged with the Minister.

The issue of copyright was originally raised by a prominent Perth mining lawyer, who pointed out that the Department's present practice of microfilming statutory reports on cancelled tenements, and making these available for sale to industry, contravened the Commonwealth Copyright Act. Following considerable discussion, recommendations were made for the Act to be amended to require operators to submit their mineral-exploration reports together with an authorization from any copyright holder enabling the Minister to provide copies of these reports for sale when they become eligible for release to open file.

The possibility that operators were liable for trespass when carrying out aerial surveys that encroached upon tenements belonging to third parties was raised at a meeting of Chief Government Geologists in 1990. The matter came into prominence again during 1993

when it became an issue in a legal case in Queensland involving a valuable mineral property. It was therefore recommended that the legislation be amended to provide that the collection of geoscientific data using aerial survey methods over any land, regardless of its ownership, would not constitute unauthorized mining under the Act.

There is a need for a central register of aerial photography to be maintained by the Department, so as to avoid needless repetition of such surveys by different operators. An amendment to the Act was proposed to require operators undertaking aerial photography for the purpose of mineral exploration to provide details to the Minister within twelve months.

Recommendations made by the MILC subcommittees have been submitted to the Parliamentary Counsel for transcription into the appropriate legal format.

### *Offshore Minerals Act*

The former Commonwealth Minerals (Submerged Lands) Act, which came into force in 1990, was based heavily on offshore petroleum legislation. Experience during its first two years of operation highlighted a number of problems specific to mineral exploration. The Act was therefore completely revised and re-enacted as the Offshore Minerals Act, which incorporates many of the changes previously suggested by the Department.

### *Special agreements*

Special Agreement Acts dealt with during the year concerned a new iron-ore development in the Pilbara, and ongoing assessment of coal resources at Collie.

### *Future plans*

Matters still requiring amendments to the Mining Act relate to the compulsory partial surrender of exploration licences; and to revising the Form 5 report (expenditure–activity summary). These matters will be addressed in future submissions to MILC.

*J. G. Blockley*

## **Subcomponent 1.1.2.2 Advice for landuse planning**

**Objectives:** To provide policy and administrative advice to Government concerning land access issues. To provide geological advice on the mineral and petroleum resource implications of proposed nature reserve, national park, and regional management plans for the Department of Conservation and Land Management (CALM). To provide geoscientific advice on landuse studies and urban strategies for the Department of Planning and Urban Development (DPUD) and local authorities. To represent the Department on Government landuse policy-development bodies, and inter-agency technical groups and advisory committees dealing with landuse, coastal, and water catchment issues.



The GSWA provides Government, industry, and the community with current geoscientific advice and assists in resolving landuse conflicts associated with mineral and petroleum exploration and production.

As Government and community approaches to land access evolve, relevant policies and administrative guidelines are developed.

### **Major achievements during 1993–94**

In December 1993, the Government endorsed a comprehensive set of procedures for gaining mineral exploration and mining access to

conservation reserves and other environmentally sensitive areas. A revised set of Guidelines has been printed that summarizes this process.

A policy concerning petroleum exploration in future Marine Conservation Reserves was developed through intensive negotiation between the DME, Industry, CALM, and the Departments of Resources Development and Environmental Protection. This was agreed to by Government in January 1994.

In response to increased concern regarding the activities of the Australian Heritage Commission, the Department has instituted a process of plotting all listed and

interim National Estate natural areas on the public plans and a State-wide digital map of National Estate areas has been prepared.

Resource assessment reports were prepared for proposed extensions to limesand mining in Cockburn Sound and for mineral exploration applications in Karijini National Park, Rudall River National Park, and several Class-A Nature Reserves. Reports were also written on the mineral resources of the proposed Dampier Archipelago National Park and assessments made for extensions to Cape Range, Karijini, Purnululu, and Yanchep National Parks.

A series of submissions were made on wide-ranging topics of

concern to the Department including: the Resource Assessment Commission's report on the coastal zone; the State's study of coastal-zone management; CALM's South Coast and South West Forest Management Plans; and DPUD's Central Coast Study and amendments to the Metropolitan Region Scheme.

Reviews of environmental management in the gold and mineral-sand mining industries were conducted by a subcommittee of the Minerals Environment

Liaison Committee (MELC) and reports are in preparation.

### *Future plans*

Land access and geoscientific advice and policy matters tend to evolve with time and cannot be planned for in detail. However, major activities planned include: the completion of the Cowaramup Environmental Geology GIS report; introduction of the benefits of Environmental Geology mapping to

potential users; and the conducting of resource assessments in relation to marine and terrestrial conservation-reserve proposals. In addition, there will be participation in the development of strategies in relation to the protection of basic raw materials and road-making materials.

Following the Government's announced policy on petroleum activities in marine conservation reserves, policies will be developed concerning mineral exploration and mining in these areas.

W. M. Carr

## Subcomponent 1.1.2.3 Aboriginal liaison

**Objective:** *To minimize conflict between mining and petroleum industries and Aboriginal communities in regard to land access and Aboriginal heritage issues.*

The objective of this subcomponent is achieved through the development of appropriate policies and procedures in regard to Aboriginal issues affecting both the mining and petroleum industries, and a liaison service provided to individual companies and Aboriginal groups. This service is aimed at facilitating communications between parties to prevent conflicts from arising and, if they do, assisting with their resolution.

The liaison function was somewhat neglected during the year due to the absence of the Aboriginal Liaison Officer since early October and his subsequent resignation in early March. The position is expected to be filled early in the new financial year.

Most of the work in the policy area revolved around two major issues: access to Aboriginal reserves and native title.

### *Access to Aboriginal reserves*

Access to Aboriginal reserves has become extremely difficult over the last 20 years, with very little exploration, and no mining

production at all, on reserve land. Following several earlier attempts at improving procedures for the granting of entry permits required under the Aboriginal Affairs Planning Authority Act, it was decided that the problems are much deeper and need fundamental reconsideration of the existing policies.

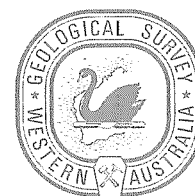
This led to the development of a joint discussion paper by the staff of the GSWA and the Aboriginal Affairs Planning Authority in the early part of the year. The proposal formed a basis for intensive consultations with the major industry groups and the Ngaanyatjarra Council, as a lessee of the most extensive Aboriginal reserve in the State. This reserve is adjacent to the South Australian and Northern Territory borders, and contained the largest number of outstanding applications for mining tenements of all the Aboriginal reserves in the State. Following these discussions a new policy for access to Aboriginal reserves for the mining industry was formulated by DME and subsequently endorsed by Cabinet in December 1993. This enabled the granting of a large majority of outstanding

applications on most reserves in Western Australia by the end of December.

### *Native title*

The native title issue, resulting from the High Court decision in 1992, was the subject of extensive discussions with industry and the State Government during the year. The Court's ruling, recognizing common-law rights of Aboriginal people in regard to land in areas where they had not previously been extinguished, overturned the existing concepts of property rights and created considerable doubt about the validity of other current land interests, including mining titles, and great uncertainty about future dealings with land.

In doubt of validity were primarily tenements granted after the proclamation of the Racial Discrimination Act in October 1975, which could have affected some of the major mining projects operating in the State. In regard to future tenement grants, the situation was equally uncertain due to the lack of knowledge about the existence and



extent of any surviving native title and the nature of the rights it may confer on its holders.

The Government deliberations on the matter culminated in the proclamation of the Land (Titles and Traditional usage) Act on 2 December 1993, accompanied by amendments to the relevant mining and petroleum statutes. The legislation validates titles granted since October 1975, confirms the

Crown ownership of minerals, and replaces any remaining native title by statutory rights of traditional usage equivalent in their extent to the native title they replace. It also establishes procedures for the granting of mining tenements, which take into consideration traditional usage rights in the granting process.

Subsequent to the promulgation of the State laws, the

Commonwealth Government proclaimed the federal Native Title Act which came into operation on 1 January 1994.

Both statutes are currently the subject of a High Court challenge with a decision expected before the end of April 1995.

In the meantime, the granting of mining titles continues under the State laws.

V. Novak

## Subcomponent 1.1.2.4 Resource advice

**Objectives:** To compile and maintain a detailed inventory of the State's identified mineral resources and analyse the information in respect to geology, metallogenic setting, economics, and international commodity markets. To provide high quality and timely information and advice to Government, industry, and the general public on the State's mineral exploration, mineral resources, and project development potential. To maintain a mineral deposits and mines core dataset as a uniform Departmental information base on which other subcomponents of the Program can operate.



Activities under this sub-component are primarily supported through MINEDEX, the mines and mineral deposits information database.

Maintenance of the MINEDEX core of project and site names, plus ownership and other ancillary information, is paramount to the smooth running of various Departmental activities. Accordingly, high priority is placed on keeping these datasets up to date. The first significant audit of the core datasets was embarked upon during the year, and was near completion by the end of the year. Basic information on projects, sites, and ownership, by commodity sectors and locations, is in constant demand by industry, the public, and various Government departments and agencies. These are serviced by printouts or personal enquiry searches. During the year, a mines and mineral deposits gazetteer of Western Australia was produced from MINEDEX core-data in conjunction with the Surveys and Mapping Division.

MINEDEX has been continually evolving since its inception in the late 1980s. System development activities during the past year centred on two areas. The first was the mineral-production and production-forecasts module, for which detailed user specifications have now been defined by the Royalties and Policy Development Division and the GSWA. Progress on program development has been slower than anticipated and introduction of the system will not take place until the 1994-95 year.

The second area of development activity has been in the linkage of MINEDEX with TENGRAPH (the DME's electronic tenement-graphics system). Progress is well advanced to allow all MINEDEX sites to be displayed in TENGRAPH when this latter system goes live to the public in August 1994.

The backlog of resources data capture has largely been alleviated, although a detailed review of statutory exploration reports is still to be undertaken in some commodity sectors. A major audit

of resources in the MINEDEX inventory was undertaken, allowing a publication on the resources inventory to be commenced. This includes State totals of major commodities and various summarized breakdowns where appropriate. Examples of such breakdowns include nickel resources split into laterite and sulfide ores, and various host-rock types; iron ore by stratigraphic unit and grade subdivisions; and heavy-mineral sands by region and strandline. Resources in Western Australia are placed in a world context and related to production. Little progress was made in the production of individual-commodity publications, although extensive advice was given and tabulations circulated on specific mineral-resource enquiries. Industry profiles, primarily concentrating on resources and producers, were prepared for ELC consideration for the gold and heavy-mineral sands sectors.

Quarterly reviews of mineral exploration activity in Western Australia were prepared as advice to



the Minister. These reviews analyse the mineral-expenditure statistics by commodity sector as published by the Australian Bureau of Statistics (ABS) and relate them to known areas of activity and development potential. Mineral exploration activity in the State has shown a gradual but progressive increase in expenditure through the 1990s, and has been led primarily by the gold sector. In response to a number of enquiries, an attempt was made to assess the breakdown between nickel and copper-lead-zinc exploration expenditure. This is not carried out by ABS. The results show quite a variability in exploration effort from year to year for these commodities, but overall indicate a relatively even split between the two groups. Additional information gleaned from the exercise is the distribution of exploration activity by regions of the State.

Outputs from the exploration-monitoring activity include:

- a paper entitled 'Exploration in Western Australia' in the AusIMM Bulletin;

- a paper on mineral exploration, developments and initiatives in Western Australia for an AMF presentation;
- a presentation on the mineral industry of the Kalgoorlie region for a mining geology conference in Kalgoorlie;
- an internal paper on recent gold discoveries and exploration in Western Australia, for the Minister.

Of a more general nature, the publication entitled 'Overview of Minerals and Energy in Western Australia' was updated. Various statistical tabulations and graphs were produced for the Chamber of Mines and Energy, the Economic Research Unit in Sydney in its analysis of the Mabo issue, and a number of other enquiries, notably from Regional Development Authorities (Geraldton and Mid-West, Goldfields-Esperance), the Northern Land Council, and other groups and members of the public.

Various industry overview presentations and MINEDEX

demonstrations were given to delegations of overseas visitors, including those from China, Vietnam, Malaysia, Philippines, Sri Lanka, Kazakhstan, and Bulgaria.

Ad hoc advice on technical issues related to royalties was provided. Most notable issues included definitions of construction materials/basic raw materials, quality and value appraisal of monazites, and processing of manganese ore and iron ore.

The Karpa Springs gold-fraud case drew to a conclusion during the year. Expert technical advice was provided to the police on this matter.

Overall, this subcomponent required timely responses to a wide variety of resource, exploration, and mineral-development issues. The large number of enquiries dictated a significant level of reactive output, to an extent, to the detriment of the specific, defined work program.

W. A. Preston

### Component 1.2.3

#### Advice on administration of mining legislation

**Objectives:** To monitor exploration performance on mining tenements and provide geological advice needed for the administration of the Mining and Mineral (Submerged Lands) Acts.

A basic requirement of a Mining Act is that it provides an equitable system of tenement administration by which prospective ground is not tied up by parties unwilling to explore or otherwise evaluate it. In Western Australia this is achieved through provisions requiring regular reports on expenditure and activities to be lodged with the DME. These can then be used to provide advice on such matters as exemptions from expenditure, exemptions from partial surrender for exploration licences, extensions of term of exploration licences,

grouping of tenements for reporting, and applications for special prospecting licences.

Applications for exploration permits under the Offshore Minerals Act are also examined to ensure that the programs put forward are technically sound, and that the applicants have the necessary financial and technical resources to carry them out.

Annual reports on a number of Agreement Acts are monitored to ensure that they comply with the terms of the Agreement.



#### Mining Act

With the introduction of electronic surveillance of reporting and performance on exploration licences during 1993, it became possible to readily identify operators failing to provide reports on mineral exploration activities. Previously, identification of such operators involved labour-intensive manual searches of files and registers, and could not be undertaken on a routine basis. This facility has improved the Survey's ability to identify operators who do not

appear to be working their tenements satisfactorily, and to translate this into advice to other Divisions of the Department.

Another section of the Mining Act for which geological advice is needed deals with the alienation of Crown land. Proposals to change the status of Crown land to freehold or reserves are examined to ensure that ground with known mineral deposits, or high mineral potential, is not given a status that could impede access for exploration.

During 1993-94, the GSWA dealt with approximately:

- 2550 applications for one-year exemption from expenditure;
- 30 applications for five-year exemption from expenditure;
- 70 applications for exemption from drop-off on Exploration Licences;
- 120 applications for extension of term of Exploration Licences;
- 130 requests to alienate Crown land;
- 370 items relating to project status and combined reporting;
- 9 applications for Special Prospecting Licences.

A rise in the gold price together with encouraging new discoveries, such as Bronzewing and Jundee,

produced a noticeable increase in the level of exploration in 1993-94 and a concomitant rise in new tenement applications. Despite this activity, the number of exemption applications reviewed by the Section increased appreciably. Reasons for this appear to include the transfer of exploration activity to the new 'hot' areas, at the expense of other regions, and the increase in the number of recognized projects, allowing expenditure to be concentrated on specific members of a group of tenements.

The large number of requests for combined reporting status reflected the industry's recognition of the convenience of this mechanism for both preparing reports, and for the rational allocation of exploration funds to a project.

During the year, a start was made on checking reports that provide resource estimates to ensure that adequate supporting information is provided. This will be needed for assessing applications for Retention Licences during 1994-95.

### *Offshore Minerals Act*

In the continuing absence of guiding Regulations for the Commonwealth Offshore Minerals Act, all applications need to be considered carefully to ensure that consistency in expenditure and program requirements is maintained. Bullish statements by one operator in late

1993 led to a sharp increase in interest in the offshore regime, with the result that the number of permits granted, or under application, trebled within a few weeks.

### *Special agreement acts*

Ongoing advice was provided to the Department of Resources Development and the Collie Basin Management Committee on the acceptability of drilling programs carried out under an Agreement Act, and on coal resource matters.

Inspections of the Hope Downs, Marillana Creek and Rhodes Ridge iron-ore projects, together with the Nifty copper operation, were made to gain first-hand information on the progress of these ventures.

### *Future plans*

In 1994-95 it is intended that computer-assisted monitoring of applications for exploration licences will be introduced so as to enable the Department to query programs that appear to be inadequately resourced, technically or financially. Procedures for assessing applications for the Retention Licences will be put in place during the year. Current procedures for assessing exploration permits under the Offshore Minerals Act will be kept under review in the light of the new legislation and accumulated experience.

*J. G. Blockley*

## **Component 1.3.2 Geotechnical and rock mechanics advice**

**Objective:** *To provide high quality and timely advice to the Mining Operations Division on geotechnical and rock mechanics issues relating to operating and abandoned openpit and underground mines in very diverse geological settings.*

The Engineering Geology Section (EGS) provides a wide range of geotechnical and rock mechanics advice to the Mining Operations Division (MOD) of the DME on

geotechnical issues relating to operating and abandoned openpit and underground mines and tailings storages in all parts of the State.

The very diverse range of geological, geotechnical, and groundwater conditions in the mining industry result in a wide variety of ground conditions. The



ground conditions can range from very weak, saturated soil in some near-surface areas, to weak weathered and highly sheared ultramafic openpit wallrocks, to highly stressed, very strong, brittle rock that has a propensity for seismic activity in underground mines at moderate depths.

This challenging range of ground conditions means that ground stability in openpit and underground mines is a very important safety and resource utilization issue. The large number of openpit and underground mines in the State requires a considerable commitment by EGS geologists and engineers to mine-site visits, observations, and discussions with mine operations and technical personnel. A large part of the role of the EGS is to review geotechnical reports produced for mining operations by consultants. The EGS review of such documentation provides an independent assessment of the geotechnical aspects at mine sites. Typically, the types of reports that are reviewed are those that are included with Notices of Intent for new or extended mining operations, or requested by the District Inspectors of Mines for operating or abandoned mines.

The EGS also undertakes research into areas concerning public safety and geotechnical issues associated with operating and abandoned mine sites and tailings disposal, and presents educational courses for industry groups.

### *Openpit mining*

Due to the variability of ground conditions encountered, openpit wall stability is inherently difficult to predict with a high degree of certainty. The economics of openpit mining require that the minimum amount of waste material be removed. Obviously, the use of steeper wall angles reduces the amount of waste removed; however, steeper wall angles usually result in an increased risk of wall failure. A significant number of wall failures have been experienced in openpit mines due to a range of factors including:

- highly weathered soil and soft rock materials;

- adversely oriented geological structures with large continuity;
- low shear-strength materials associated with geological structures or the intact rock mass;
- groundwater pressures;
- inappropriate slope geometry.

Prudent openpit wall design requires that these geotechnical issues be appropriately addressed during the planning and operation of all openpit mines. The advice provided by the EGS to MOD ensures that relevant technical issues are considered by openpit miners to ensure that safety considerations and resource maximization are applied.

Future work by the EGS will be involved with preparing and presenting short courses dealing with geotechnical aspects of openpit mining. These courses will be presented at openpit mine sites for employees involved with ground-stability issues.

### *Underground mining*

Underground mining activity has undergone something of a resurgence recently as a number of openpits reach their limit of economic mining. The exposure of underground employees to rock-fall hazards is a very important safety issue in underground mining where rock falls are the largest single cause of fatalities and reported injuries. The ground-control issues associated with underground mines need to be addressed at a range of scales in the mining operation. Two broad types of ground control are recognized: local-scale ground control, and large-scale ground control.

The EGS has arranged a presentation to the mining industry titled 'Ground Control in the Workplace'. The talk addresses the local-scale ground-control issues in underground mining. This talk has been presented at sixteen mine sites to approximately 650 employees, the majority of whom are members of the underground workforce. The main purpose of the talk is to raise the awareness and discussion of ground-control issues by all people associated with underground

mining operations. The talk covers issues such as:

- why ground control is required;
- factors controlling ground stability;
- examples of ground response;
- barring down;
- ground support.

The talk has been well received and has prompted some very useful discussions and perceptive comments by members of the underground workforce. It is the intention of the EGS to present this talk at all underground mine sites during 1994–95.

The large-scale ground-control issues will be addressed in a separate course run with the Western Australian School of Mines in Kalgoorlie during the second half of 1994 and during 1995.

### *Corrosion of friction rock stabilizers*

Friction rock stabilizers (FRS) are the most commonly used ground reinforcement method in underground mines in Western Australia. Following the installation of FRS, they are exposed to a wide range of groundwater and atmospheric conditions. These conditions may often change with seasonal variations in climate and changes in mine operating activities. FRS corrode with time owing to their interaction with the chemical and physical characteristics of the surrounding environment. Because of their thin-wall steel tube construction, corrosion reduces their integrity and load carrying capacity, which can subsequently lead to unexpected rock falls.

A research project was jointly initiated by EGS, MOD, and the Chemistry Centre of Western Australia and has been progressively investigating the factors controlling the corrosion of FRS in underground mines in Western Australia, and the effects of corrosion on the load-bearing capacity of FRS. The research was completed this year, and Guidelines on the corrosion behaviour of FRS will be published in 1994–95 for

industry use as a result of this research project.

### ***Subsidence above shallow abandoned coal mines***

Subsidence above shallow coal workings has been a recurring problem in the Collie Basin for decades and is still a challenge today. Development of subsidence sink holes due to the presence of shallow workings has been a threat to the continued safe operation of public utilities such as roads or railways, and has halted the development of a town planning project.

In order to minimize the effects of subsidence above shallow workings on future town planning and urban or rural development, research under the auspices of a MERIWA grant was undertaken this year to:

- delineate the location and extent of subsidence;
- investigate the controls on subsidence;
- investigate the most appropriate engineering solutions and

remedial techniques for site rehabilitation.

The results of the research, which will be published during 1994-95, will enable areas with potential for subsidence to be identified.

### ***Tailings storages***

The EGS provides geotechnical advice to the MOD on technical and environmental issues relating to the design, operation, and rehabilitation of tailings storages in Western Australia.

To assist the MOD with their environmental approvals process in the tailings storage area, the EGS reviews geotechnical reports that have been produced on behalf of mining companies, and provides advice on relevant technical issues. These reports are produced for the following general reasons:

- as technical support for Notices of Intent or Works Approval Applications for new or extending mining operations (these include investigation and design data);
- as a compilation of construction quality control data, and a

summary of as-built conditions on the storage facilities;

- as annual audits to examine the management of the facility, and assess the performance of the storage as against the expectations defined in the design documentation, and also to assess the engineering implications of decommissioning proposals;
- after requests by District Inspectors of Mines or Environmental Officers after specific problems have been identified.

Last year, as part of the service to the MOD, the EGS reviewed approximately 108 documents, and visited some 37 sites of tailings storage facilities where 67 individual storages were examined. These site visits have allowed the EGS to assess and discuss particular operations, as well as to disseminate information concerning best industry practice. In addition, officers from the EGS have participated in four workshops on tailings management and rehabilitation for operators and consultants. These workshops have been excellent forums for frank exchanges of ideas and information and have been of benefit to all who attended.

*A. M. Lang and I. H. Lewis*

## **Component 1.5.1**

### **Registration and archives WAMEX**

**Objective:** *To ensure that annual mineral exploration reports for all current tenements are submitted to the Department in compliance with the relevant legislation, and to provide the mineral industry with ready access to historical mineral exploration data in order to encourage efficient and effective mineral exploration and future mineral-resource development.*



WAMEX, the Western Australian Mineral Exploration Index, is a computer-based information system for mineral-exploration reports that are submitted to the Department by the mining industry, in compliance with the reporting requirements of

the Western Australian Mining Act. The system serves three functions by providing:

1. a publicly available reference database for open-file company exploration reports on mining

tenements that have been relinquished;

2. a confidential database for Departmental reference to all company exploration reports on open file (relinquished tenements)



and on closed file (current tenements);

- 3. a Departmental monitoring facility to ensure that mineral-exploration reports for all current tenements are submitted in compliance with the Mining Act.

Information may be retrieved from WAMEX using a number of keywords such as those relating to commodities, exploration methods, location, and companies, for example. These keywords are entered into the system when submitted reports are examined by the Department. A public-access version of WAMEX is available for open-file data searches to be made in the GSWA Library. Output from WAMEX database searches are available, from the public access module in the Library, either as hard-copy printouts or as downloads to disk.

Microfiche copies of reports may also be viewed in the Library at Mineral House and at the Kalgoorlie Regional Office. Reports on microfiche may also be purchased from the First Floor Counter at Mineral House.

During 1993–94 a total of 2849 reports were received in relation to exploration and prospecting activities carried out on 9637 tenements: this compared with the 1992–93 total of 2187 reports received in relation to activities on 7625 tenements. The increased number of reports since 1992–93 has resulted from electronic monitoring procedures that were introduced in May 1993 for exploration licence reports. Gold continues to be the most commonly sought commodity in mineral-exploration reports received, representing 65.6% of the total (Fig. 1). In addition, a total of 984 reports were released on

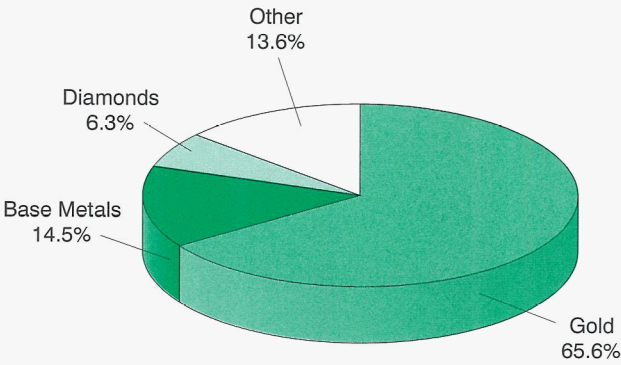


Figure 1. Mineral exploration reports received from July 1993 until June 1994 by commodity type (2849 reports)

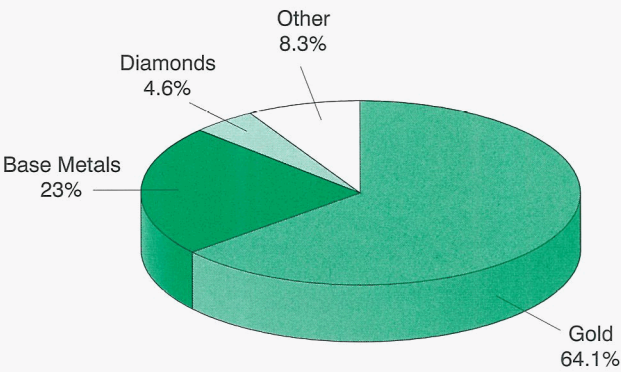


Figure 2. Mineral exploration reports released from July 1993 until June 1994 by commodity type (984 reports)

microfiche to open-file during 1993–94. Again, gold was the most common commodity in released reports, representing 64.1% of the total (Fig. 2).

Highlights for 1993–94

Electronic monitoring of annual reports on exploration licences was introduced on 1 May 1993 and this involved the despatch of computer-generated letters to request overdue reports from certain tenement holders, who had overlooked their reporting obligations.

There was increased monitoring of industry requests to submit

combined statutory reports, to ensure that all operators obtain prior agreement from the Department as to which group of tenements will constitute a reporting unit (or project) before submitting future combined reports.

Monitoring of the contents and standards of annual mineral-exploration reports submitted for exploration licences was also increased, to ensure that activities described in reports substantiate expenditures and activities claimed on Form 5s.

I. Ruddock

## Program 2.0

# PETROLEUM RESOURCES MANAGEMENT

### Subcomponent 2.1.3.1

#### Advice relating to petroleum resources

**Objective:** *To provide high-quality, timely petroleum resources information and policy advice to Government, industry, and the general public in order to ensure long-term social and economic benefits to the community from the responsible development of the State's petroleum resources.*



The GSWA, in conjunction with the Petroleum Division, are the Government's advisers on petroleum exploration. Consequently the GSWA participates in monitoring current legislation in so far as it promotes and regulates petroleum exploration and proposed changes that may improve effectiveness in those objectives. Advice is provided in relation to the Western Australian State Petroleum Acts in both the onshore and offshore areas as well as the Commonwealth Petroleum (Submerged Lands) Act.

Although the Petroleum Division has direct regulator responsibility, the GSWA, through its geoscientific expertise in basin studies, basin evaluation, and environmental geological areas, provides advice relevant to these areas in awarding exploration permits, formulating policy and legislation, and in multiple landuse issues including those concerning marine parks.

The GSWA is also directly responsible for the management, archiving, and administration of both State and Commonwealth petroleum data, reporting requirements of the Act(s) and the

subsequent release of that data to the private sector. Commensurate with the increasingly sophisticated technology, changing exploration practices, and the progressive movement towards computer-based digital data technology, changes to the Regulations and Directions of the Act(s) are proposed to match and complement changing Industry practices and attitudes towards data reporting and release issues.

#### Highlights for 1993–94

In 1993–94, technical-data packages relating to competitive bids for gazetted offshore acreage were reviewed and evaluated during releases of two rounds of Commonwealth offshore areas. Technical packages relating to applications for vacant state acreage were also reviewed and evaluated during three rounds of acreage release. Detailed briefings were provided to Government on marine-park access strategies in relation to the Monte Bello, Ningaloo Reef, Scott Reef, and Shark Bay areas.

The GSWA participated in an extensive industry survey

(questionnaire) seeking comment on a range of petroleum-data management issues. This raised the following major points that are being addressed:

- Additional clarification is needed to define 'basic' and 'interpretative' data.
- All data from relinquished or surrendered acreage should become open-file data immediately.
- Seismic-data submissions relating to 3-D surveys need to be reviewed, and the requirement should be made that all data for 2-D surveys should be submitted in migrated format.
- The State Petroleum Act(s) need to be revised to allow (retrospective) release of interpretative data. Currently only basic data is available for many activities concluded more than 5 years ago.
- The reporting and release requirements relating to reprocessed seismic surveys need to be defined.

A. K. Svalbe

## Component 2.5.1

### Registration and archives WAPEX

**Objective:** To provide access to a computerized petroleum exploration data indexing system to assist in management, administration, storage, and retrieval of the large volumes of exploration data submitted to Government by the petroleum exploration and development industry, and ultimately to release the data as open-file information.



WAPEX, the Western Australian Petroleum Exploration Index, is a computer-based information system for information on permits, wells, surveys, and specialist studies conducted in Western Australia for petroleum exploration. It also registers petroleum exploration data submitted to the Department in compliance with the reporting requirements of the Petroleum Acts. WAPEX aims to encourage petroleum exploration and to ensure that previous activities are not wastefully duplicated. In addition, WAPEX provides essential information for use in studies of Western Australian sedimentary basins. This service is provided through the following processes:

- Monitoring of company compliance with reporting requirements under the State and Commonwealth Petroleum Acts for the Department.
  - Accessioning, capture into the WAPEX database, and archiving of all petroleum exploration data submitted to the Department.
  - Release of information as either basic or interpretative data.
  - Performance of data searches for outstanding data when permits are renewed, surrendered or expire. Performance of searches for available data for release of acreage by the Petroleum Division.
  - Microfilming unedited reports for wells, surveys, and specialist studies for release by contractors.
  - Provision of advice and access to the petroleum industry and the public requiring 'open-file' information on permits, surveys, wells, and other geoscientific data.
- The section provides the following services and products:
- Provision of access to 'open-file' cores, cuttings, palaeontological, and digital data requested by industry under the Department's jurisdiction.
  - Photocopies and microfiche copies of company reports on surveys, wells, and selected geoscientific reports either as edited or unedited versions for release by organizations (Petroleum Information, Advanced Reprographics, and Wiltshire Geological Services) contracted to release this information to industry and the general public.
  - Monthly and quarterly lists of data declared 'open-file'.
  - Quarterly production of Comfiche showing all surveys, wells, and specialist studies conducted in Western Australian acreage, including, if 'open-file', their microform number, or S-file number if released as a hard copy.
  - Quarterly lists of released data for incorporation in the issue of the 'Petroleum tenements map for Western Australia'.
  - Production of the biannual 'Wells drilled for petroleum in Western Australia' map.
  - Provision of advice to industry and the public on the WAPEX database.

During 1993–94, there were 157 active petroleum tenements, which provided the 1284 activities reported to the Petroleum Resources Sub-section (PRSS). These activities were on wells, surveys and permits, and include reports, seismic sections, well logs, magnetic-tape information, maps, and palaeontological data, bringing the total data registered in WAPEX to 382 612 items. Data released to third-party agencies for the exploration industry included 183 edited reports, 196 unedited reports, 230 sets of well logs, and 180 sets of seismic sections.

#### Highlights for 1993–94

- The continued use of Total Quality Management techniques to improve the quality and efficiency of the petroleum-data management processes.
- The completion of the 'WAPEX Procedures Manual', which will act as both a training manual and an explanation of procedures to carry out work responsibilities of each procedure in PRSS.
- The production of a set of three maps entitled 'Wells drilled for petroleum in Western Australia' using digital methods. It will be updated semi-annually on 30 June and 31 December each year, and both hard-copy and digital versions will be made available for purchase.
- Seismic Supply International was awarded the tender for the storage of the Department's State petroleum magnetic-tape archive. The contract will be for an initial period of 3 years.

A. K. Svalbe

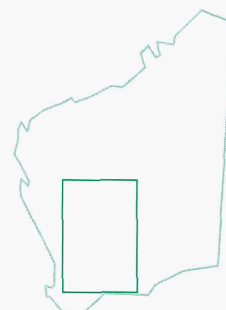
## Program 3.0

# GEOLOGY AND RESOURCE INFORMATION

### Subcomponent 3.1.1.1

### Yilgarn Craton

**Objective:** To increase geoscientific knowledge 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, and remote sensing.



The Yilgarn Craton is a major geological unit that contains substantial mineral deposits. It currently yields all of the State's production of alumina and nickel, most of its gold, and a significant proportion of base metals, tin, and tantalum. It is the focus for more than half the current mineral exploration in Western Australia.

Most GSWA mapping in the Yilgarn Craton is concentrated in the Eastern Goldfields region: subcomponent 3.1.1.1 covers the rest of the region that is less well known. Two areas were investigated during 1993–94: the COCANARUP* and RAVENSTHORPE 1:100 000 sheets and the BYRO 1:250 000 sheet (Fig. 3). Both these areas lie near the tectonically reactivated margins of the Yilgarn Craton. Mineralization styles in these reactivated margins appear to be different from those in the interior of the Craton.

The map sheets in the vicinity of Ravensthorpe were investigated to help resolve potential conflict between CALM and the mining industry in relation to the possible extension of the Fitzgerald River National Park to include part of the Ravensthorpe greenstones.

The remapping of BYRO is part of a broader project to understand the complex geology in a region formerly known as the Western Gneiss Terrane, and to determine

the location and nature of the boundary of the Yilgarn Craton.

#### COCANARUP and RAVENSTHORPE

Mapping and compilation of these 1:100 000 sheets have been completed. This resulted in a dramatic reinterpretation of the stratigraphy and tectonic evolution. The Ravensthorpe greenstone belt comprises two disparate units that were tectonically juxtaposed in late

Archaean time. One unit contains abundant mafic and ultramafic rocks whereas the other unit is dominated by andesitic plutonic and volcanic rocks, and rocks of clastic or volcanoclastic sedimentary origin. Nickel mineralization is restricted to the former unit, whereas most of the gold mineralization is associated with the latter. This new interpretation of the tectonic evolution has further important implications for understanding the genesis of copper–gold

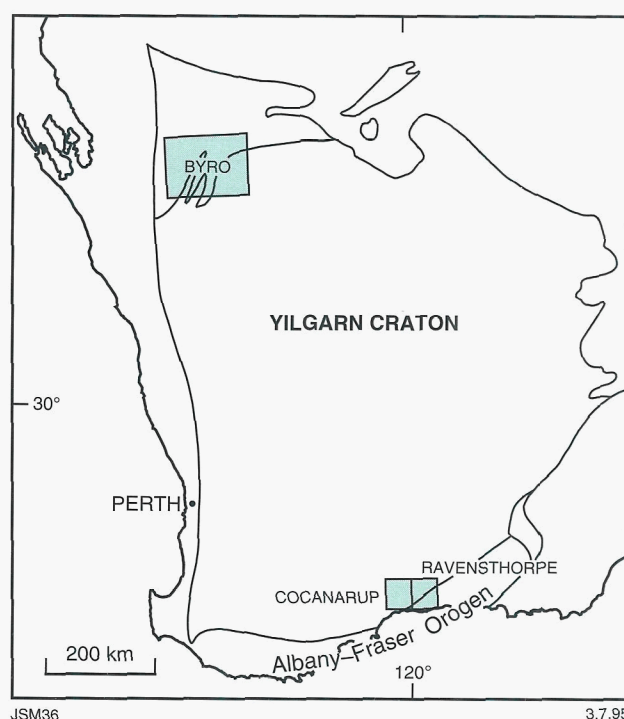


Figure 3.  
Map of the Yilgarn Craton, showing the location of GSWA mapping projects under Subcomponent 3.1.1.1

* Capitalized names refer to standard map sheets.



mineralization. It is expected that these maps will be published together with explanatory notes in 1994–95.

## BYRO

A significant part of BYRO was remapped. This revealed that, contrary to previous interpretations, most of the gneisses were derived from plutonic igneous rocks and not sedimentary rocks, and the gneissose layering reflects intense deformation rather than sedimentary bedding.

The region was previously thought to be devoid of metavolcanic rocks and therefore to differ significantly from the granite–greenstone terranes of the Yilgarn Craton. However, closer inspection indicates that layers of BIF within narrow belts of metasedimentary rocks are generally associated with amphibolite derived from mafic igneous rocks. The region appears to represent a high-grade granite–greenstone terrane and may therefore be more prospective for mineralization than previously thought.

The Archaean rocks form two distinct units, called the Murchison

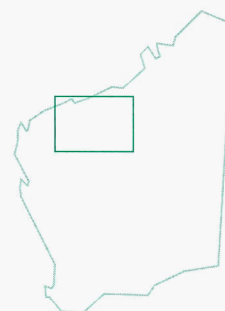
and Narryer Terranes, that had independent geological histories until they were united at about 2680 Ma. Rocks from the two terranes were tectonically interleaved by thrusts and then further deformed and metamorphosed together at high-grade, immediately prior to the widespread late Archaean episode of gold mineralization.

It is expected that mapping will be completed by the end of 1994 and that the second edition of BYRO will be published with explanatory notes during 1995.

J. S. Myers

## Subcomponent 3.1.1.2 Pilbara Craton

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



The Pilbara Craton is a major geological unit that contains substantial deposits of iron ore within the Hamersley Basin. These deposits are of national and international significance. Activities in 1993–94 were concentrated in two regions of the Hamersley Basin and led to the completion of field mapping for the second edition MOUNT BRUCE and ROY HILL 1:250 000 sheets in the west, and three 1:100 000 sheets (BRAESIDE, ISABELLA, and PEARANA) in the east (Fig. 4). A major Bulletin was also compiled on the late Archaean Fortescue Group and is currently being reviewed.

## MOUNT BRUCE and ROY HILL

MOUNT BRUCE and ROY HILL cover significant portions of the Hamersley Basin and contain the important iron-ore mining centres of Tom Price, Marandoo, Yandicoogina, and Mount Brockman. The previous map sheets were published in the 1960s, and the new mapping has led to significant

advances in understanding the stratigraphy and structure of the region. A highlight of the mapping was the recognition that much of the iron-ore mineralization in the southern Pilbara is related to wrench faulting. This was associated with reactivation of Archaean basement structures during late stages of the Early Proterozoic Capricorn Orogeny.

## BRAESIDE, ISABELLA, and PEARANA

BRAESIDE, ISABELLA, and PEARANA cover the Gregory Range, which forms the eastern margin of the Craton. It contains significant deposits of manganese as well as lead, silver, and copper. This margin was involved in deformation during

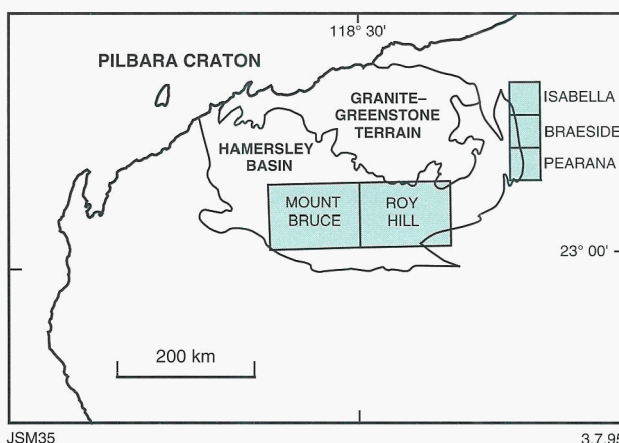


Figure 4. Map of the Pilbara Craton, showing the location of GSWA mapping projects under Subcomponent 3.1.1.2

the late Precambrian Paterson Orogeny, and the structure of this region is crucial in understanding the tectonic evolution of the richly mineralized Paterson Orogen.

The Gregory Range comprises a number of thrust slices that stacked up the stratigraphy of the Archaean and Early Proterozoic Fortescue and Hamersley Groups. The faults and associated folds indicate westward

transport of these basement rocks during the Late Proterozoic Paterson Orogeny.

### **Fortescue Bulletin**

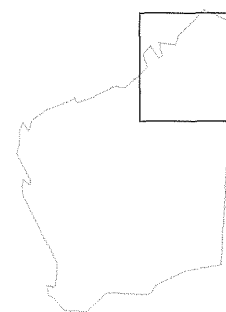
A Bulletin that describes the stratigraphy, physical volcanology, sedimentology, geochemistry, and economic geology of the Fortescue Group is in preparation. The

Fortescue Group represents one of the best-preserved and best-exposed examples of late Archaean volcanism and associated sedimentary deposition on Earth. Deformation and metamorphism are generally slight. This substantial work significantly improves our understanding of the Hamersley Basin and its associated mineralization. Publication is expected during 1995.

*J. S. Myers*

## **Subcomponent 3.1.1.3 King Leopold and Halls Creek Orogens**

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



The King Leopold and Halls Creek Orogens are major geological units that contain significant mineralization, including the world's largest diamond mine, and have the potential for further discoveries of base and precious metals, uranium, rare earths, and diamonds. Remapping of the King Leopold Orogen commenced in 1987, with remapping of the Halls Creek Orogen commencing in 1990 in conjunction with AGSO as part of the NGMA Kimberley–Arunta Project. A summary of the geology of the Halls Creek Orogen, together with a discussion of current ideas on its tectonic evolution and references to other recently published work appears in a technical paper elsewhere in this volume.

Explanatory notes for the YAMPI and LENNARD RIVER 1:250 000 map sheets

from the King Leopold Orogen were published in 1993–94 (Fig. 5). A Bulletin on the Precambrian geology of the King Leopold Orogen has been completed and is currently undergoing peer review. A 1:500 000 geological map to accompany the Bulletin is nearing completion.

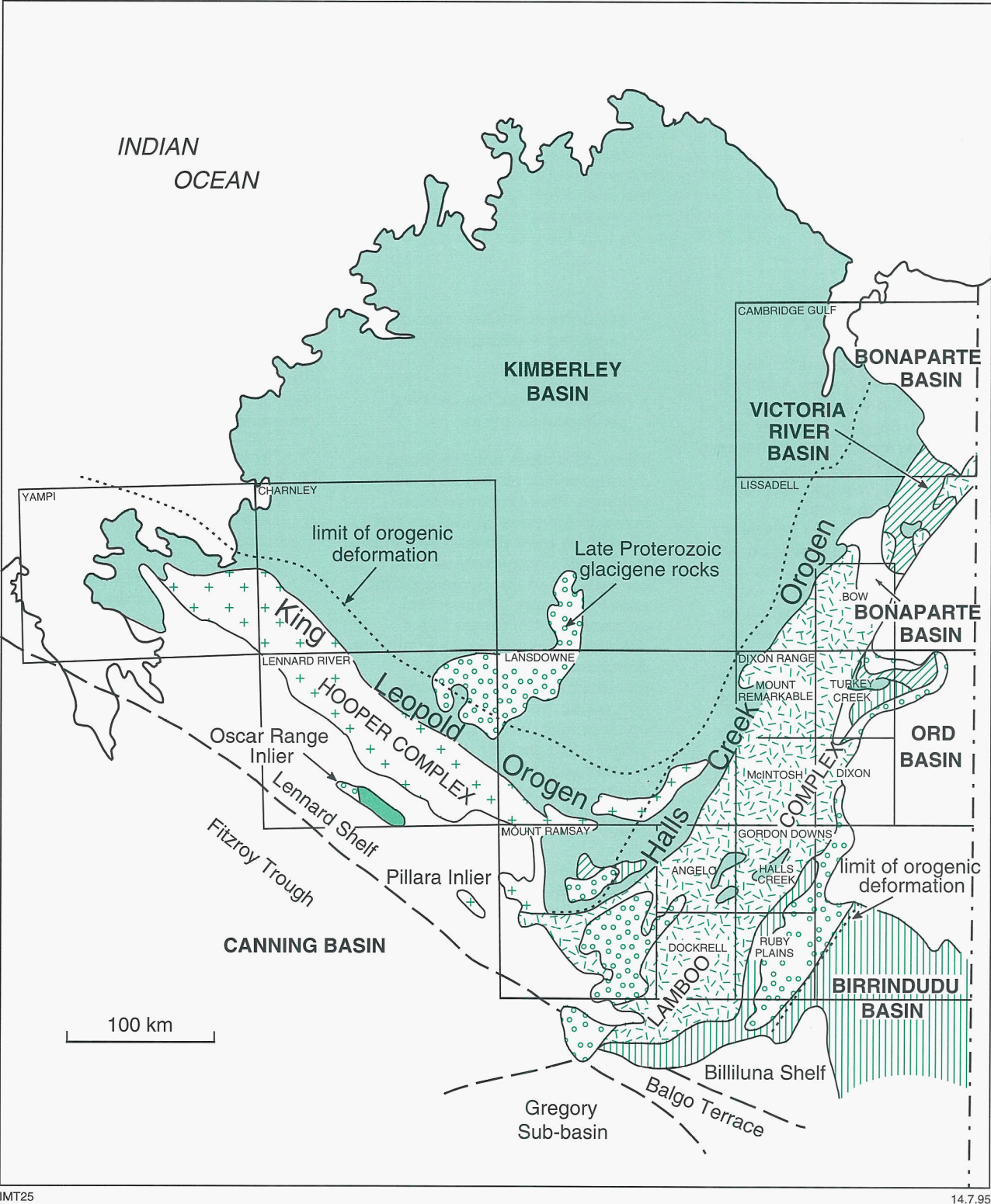
In the Halls Creek Orogen the first 1:100 000 map sheets, ANGELO and DOCKRELL, have been completed and published. Remapping of DIXON RANGE (1:250 000), together with compilation of the RUBY PLAINS and HALLS CREEK 1:100 000 sheets, continued in cooperation with AGSO. Fieldwork was completed on MCINTOSH, and work commenced on MOUNT REMARKABLE and TURKEY CREEK (all 1:100 000 sheets). This will include a study of granitic and gabbroic rocks, together with high-

grade metamorphic rocks in the vicinity of the Ord River, in conjunction with staff and students from Monash and Curtin Universities. A study on the sedimentology of the Middle Proterozoic rocks of the Osmond Range was also commenced.

During the 1994 season an extensive geochronology sampling program was undertaken in conjunction with Dr Rod Page from AGSO. Preliminary results are discussed in the technical paper elsewhere in this volume. The presence of two suites of felsic igneous rocks, which were intruded at c. 1860 Ma and c. 1820 Ma, is apparent in geochronological data obtained from the southern part of the Halls Creek Orogen.

*J. S. Myers*





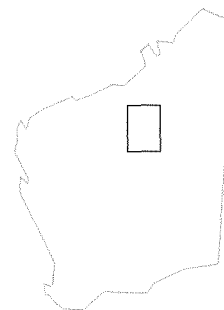
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Figure 5. Geological map of the Kimberley region showing the location of GSWA mapping projects under Subcomponent 3.1.1.3

### Subcomponent 3.1.1.4 Paterson Orogen

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



#### Progress summary

The Paterson Orogen occupies a remote area of Western Australia, and remained virtually unexplored until 1970. Because mapping and mineral exploration are still at early stages, published geological information is meagre, and relies on reconnaissance-scale investigations. The 1993–94 year saw the GSWA's mapping program move onto the CONNAUGHTON and THROSSELL 1:100 000 Sheets, with some additional investigation of northern GUNANYA. At the same time, compilation of the report to accompany the RUDALL map (based on 60 weeks of fieldwork during 1991 and 1992) resulted in (a) a completely new interpretation of the Rudall Complex, and (b) a much more detailed interpretation of the depositional environment of the Yeneena Group in this part of the Paterson Orogen.

#### Mapping methods

The Paterson Orogen contains three geological units, the Early–Middle Proterozoic Rudall Complex, and the Late Proterozoic Yeneena Group and Karara Formation.

The Rudall Complex presents unusual problems to the mapper. Accurate mapping of this unit is exceptionally time-consuming, and the difficulties experienced have required changes to normal mapping procedures. The main factors are:

- very restricted access for vehicles;
- limited value of aerial photographs, radiometric images, and aeromagnetic data in lithological interpretation;
- extreme structural complexity on all scales;

- extensive secondary alteration involving leaching and silicification;
- absence of previous detailed geological mapping.

These difficulties have required the examination of almost all available outcrops. Photo interpretation between traverses spaced several kilometres apart is very unreliable in the Rudall Complex. Most rock units are varieties of quartzofeldspathic gneiss, and only by close field examination can the geologist determine if particular outcrops are dominantly metamorphosed granitoid, sandstone, siltstone, greywacke, porphyry or felsic volcanic rock. Even units such as pelitic schist and BIF are commonly not recognizable on aerial photographs, and can be confused with shear zones or limonitic quartz veins.

Field observation placed emphasis on protolith identification, as well as recording metamorphic mineral assemblages. Protolith interpretation has proved to be most useful in map compilation, particularly in areas requiring the separation of sedimentary stratigraphic units.

#### Achievements during 1993–94

##### RUDALL

Detailed mapping of RUDALL provided a large amount of new data on stratigraphy, structure, metamorphism, and economic geology, particularly in the Rudall Complex. Synthesis of this information during 1993 and early 1994 led to a new interpretation of tectonic evolution and mineralization in the central part of the Paterson Orogen. The main features of this interpretation are

outlined in a technical paper elsewhere within this volume, but what may be termed the 'breakthroughs' in understanding the Orogen's geology can be summarized as follows:

- The metamorphosed sedimentary rocks of the Rudall Complex constitute a stratigraphic succession consisting of five formations.
- This succession pre-dates most of the orthogneiss of the Rudall Complex.
- The structural geology of the Rudall Complex is the product of several important phases of deformation. At least two pre-date deposition of the Yeneena Group and are related to episodal northeast–southwest plate collision. Three post-Yeneena events are associated with progressive deformation involving predominantly strike-slip movements.
- Deposition of the Yeneena Group was initially controlled by strike-slip basins within a northwesterly trending system of anastomosing dextral faults, but subsequently evolved into a less active, northeasterly deepening shelf.
- Mineralization is controlled by structure and lithology, individual deposit types apparently being concentrated in discrete, dominantly northwesterly striking zones.

##### CONNAUGHTON

Mapping of CONNAUGHTON commenced in mid-1993, and was nearing completion by the end of the 1993–94 year. The work has involved close liaison with the Parnngurr Community at Cotton



Creek to ensure that areas of particular significance have not been entered.

In southwestern CONNAUGHTON the Rudall Complex includes thick units of amphibolite (metamorphosed basalt, dolerite, or gabbro) BIF, metacarbonate, pelitic schist, and quartzite. These amphibolite–BIF successions are at least 2 km thick, and clearly constitute a different type of lithological association from clastic assemblages on RUDALL and BROADHURST. They may represent local volcanic-exhalative components of the otherwise predominantly clastic succession. Alternatively, the basalt–BIF units could be thrust slices of simatic crust (extensional basin), or be totally unrelated to the clastic succession of the Rudall Complex and juxtaposed by a major tectonic or stratigraphic break. The final stages of mapping will examine these alternative interpretations.

The basal part of the Yeneena Group on southern CONNAUGHTON contains a thin basal and lensoidal conglomerate overlain by a thin arkose followed with calcareous and carbonaceous shale, dolomite, and arenite. This sequence overlies a thin vesicular, and in places epidotized, basalt that unconformably overlies the Rudall Complex.

The Mount Eva thrust zone (Fig. 6) trends parallel to, and approximately coincides with, the southwestern edge of the Warri–Anketell Gravity Ridge. This zone consists of a number of anastomosing thrusts, includes high-grade mafic–ultramafic and anorthosite bodies, and may mark the contact (?suture zone) between two distinct geological terranes.

THROSSELL

About 75% of the sheet area was mapped between early July and mid-October 1993 and resulted in some important new observations and conclusions:

- The complexity and intensity of deformation in the Yeneena Group on eastern THROSSELL (tight, overturned folds; numerous faults and shear zones; penetrative foliation; multiple deformation events)

differs markedly from that along the western margin of THROSSELL (broad folds; some brittle fault zones; penetrative foliation absent; spaced cleavage in axial areas only; one main deformation event). This change appears to be abrupt, suggesting a faulted contact, and steep reverse or thrust faults are characteristic of the area concerned.

- The Coolbro Sandstone and the overlying Broadhurst Formation thin dramatically to

the southwest (4 km total thickness measured on BROADHURST is reduced to about 300 m south of the Three Sisters Hills; Fig. 6). The zone of intense faulting which runs through the Three Sisters Hills area may correspond to the western edge of the depocentre, a conclusion consistent with the interpretation on RUDALL (Hickman and Bagas, this volume).

- The ‘Tarcunyah Dome’ (Fig. 6) contains a mixed sandstone assemblage that is considerably

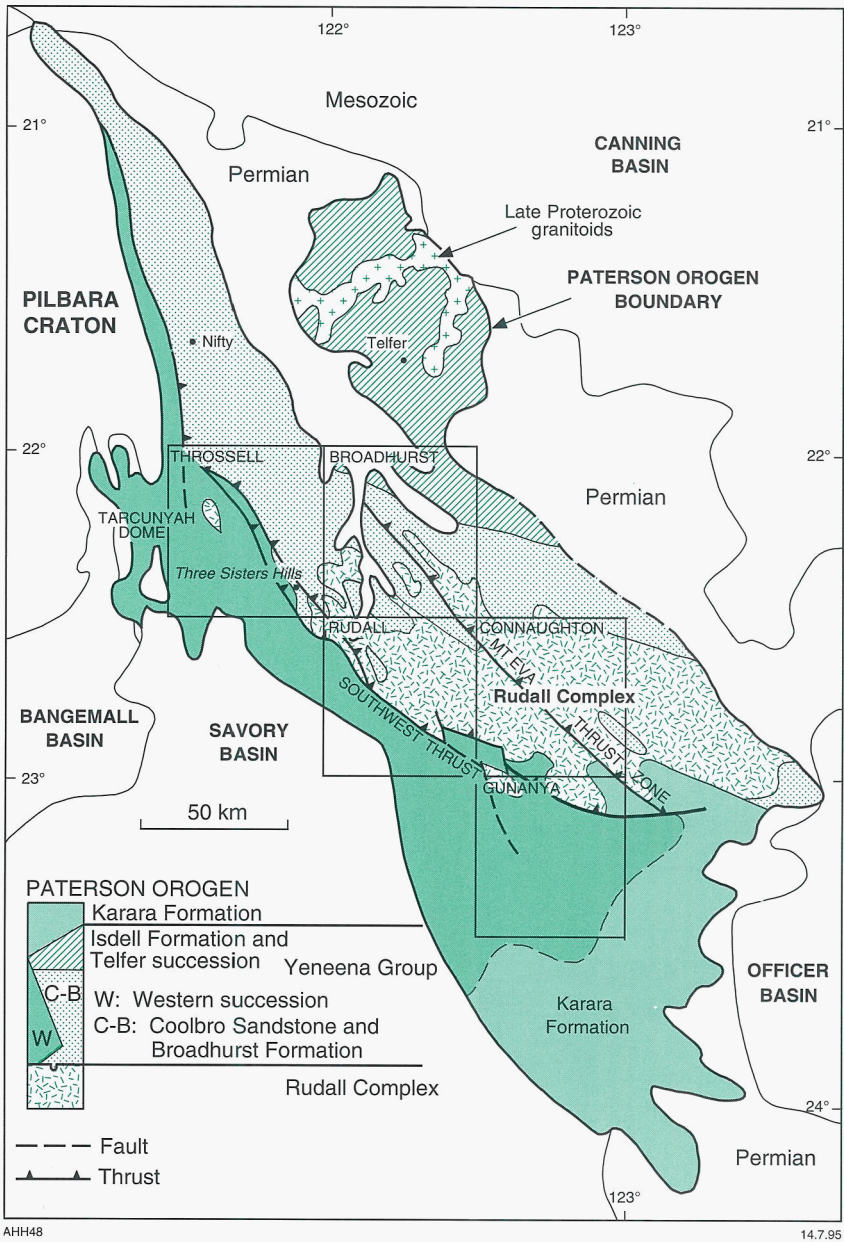


Figure 6. Geological map of the Paterson Range showing the location of mapped and partly mapped 1:100 000 sheets

less deformed than rocks of the adjacent Yeneena Group. This assemblage appears to be a fault-bounded unit of younger rocks.

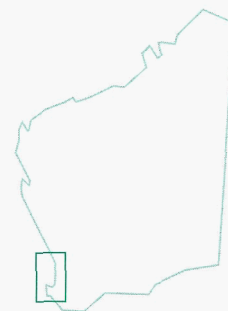
- Stromatolitic and non-stromatolitic carbonates are lithologically different, and are separated by the structural domain boundary between

eastern and western THROSELL. Further work is required to resolve the relationship between the eastern and western successions.

A. H. Hickman

### Subcomponent 3.1.1.5 Pinjarra Orogen

**Objective:** To increase geological knowledge of the Pinjarra Orogen by the collection, synthesis and dissemination of geological information, particularly through the production of geological maps and supporting publications that integrate field and laboratory studies including petrology, geochronology, geochemistry, and remote sensing.



The Pinjarra Orogen is a major geological unit that forms the base-ment to the Perth Basin. It reflects repeated Proterozoic tectonic activity along the western margin of the Yilgarn Craton. Major Proterozoic structures were reactivated during the Phanerozoic and had a significant influence on

the structural evolution of the Perth Basin.

The best-exposed part of the Pinjarra Orogen forms the Leeuwin Complex (Fig. 7), and this was mapped during 1991–93 as a contribution to the 1:50 000-scale maps of COWARAMUP and KARRIDALE–

AUGUSTA, the 1:100 000-scale maps of BUSSELTON and LEEUWIN, and a second edition of the very old 1:250 000 BUSSELTON–AUGUSTA sheet. It was intended that compilation of this mapping would be completed in 1993–94 and a Bulletin written on the basement rocks, but changing priorities led to indefinite postponement of this work.

The new mapping revealed that the high-grade gneisses that form the Leeuwin Complex were entirely derived from plutonic igneous rocks and not from sedimentary rocks as previously thought. Layered anorthosite-gabbro bodies rich in ilmenite were discovered, and are a major component of the complex. They may be the source of ilmenite that is a major component of the mineral sands mined along adjacent old shorelines. These rocks were veined and deformed together with granitic rocks before the intrusion of sheets of monzogranite and syeno-granite that make up most of the complex. All these rocks were then strongly deformed and recrystallized at granulite facies. They contain abundant melt patches and other evidence of both prograde and retrograde metamorphism, similar to the famous charnockites of southern India that are widely used as polished facing stones on city buildings, including those of Perth.

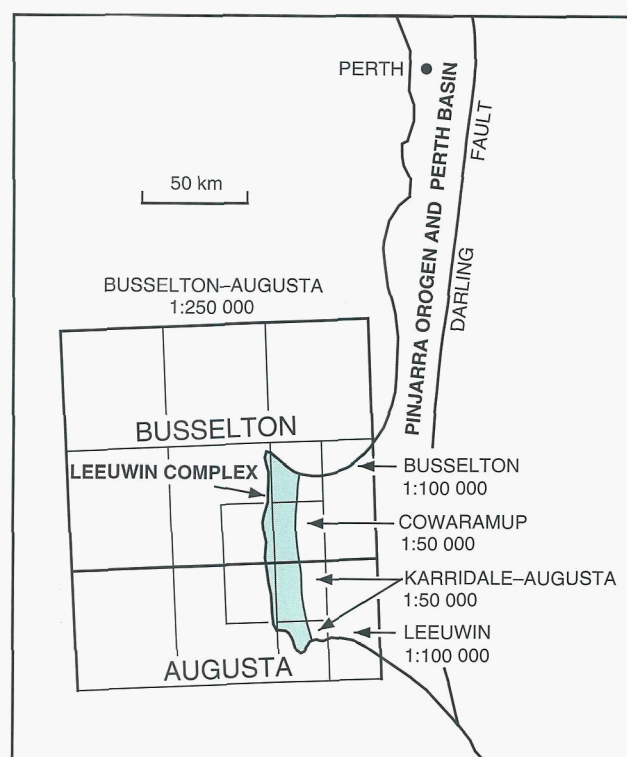


Figure 7.  
Map of the Pinjarra  
Orogen showing the  
location of GSWA  
mapping projects under  
Subcomponent 3.1.1.5

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J. S. Myers



Subcomponent 3.1.1.6  
Savory Basin

**Objective:** To increase geological knowledge of the Savory Basin by the collection, synthesis and dissemination of geological information, particularly through the production of geological maps and supporting publications that integrate field and laboratory studies including petrology, geochronology, geochemistry, and remote sensing.

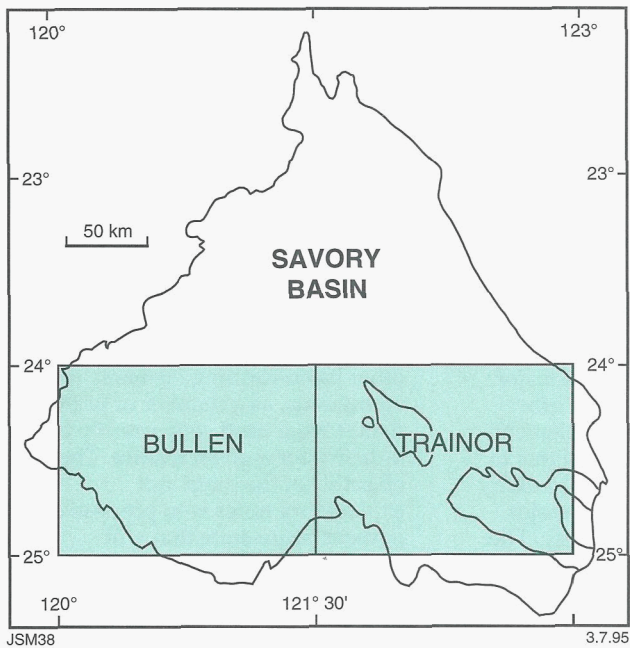
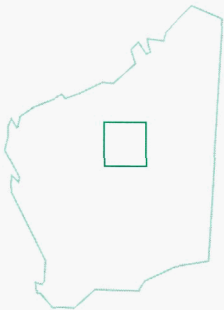


Figure 8.  
Map of the Savory  
Basin showing the  
location of the  
1:250 000 sheets  
compiled in 1993–94

The Savory Basin is an extensive Late Proterozoic sedimentary basin that was recently discovered by GSWA mapping between the Pilbara and Yilgarn Cratons. It is comparable with the Amadeus Basin of central Australia and is therefore a potential source of oil and gas.

A Bulletin describing the geology was published together with a 1:500 000 scale map in 1993. During 1993–94 the 1:250 000 map sheets of BULLEN and TRAINOR that cover a major part of the Savory Basin (Fig. 8) were compiled and prepared for printing together with explanatory notes.

J. S. Myers

Subcomponent 3.1.1.8  
Basin Studies

**Objectives:** To improve the understanding of the history, structure, and stratigraphy of the State's sedimentary basins. To assess the prospectivity of sedimentary basins for various resources, including petroleum, coal, coal-seam methane, and other minerals.



The primary objectives of the Basin and Fossil Fuels (BFF) geoscientific projects over the past year(s) has been to:

- Complete the regional 1:100 000-scale geological mapping of the north Perth Basin.
- Assess the coal resources of the Perth and Collie Basins.
- Complete an analysis of the Mesozoic stratigraphy of the North West Shelf.
- Continue the studies of the Devonian reef complexes of the Lennard Shelf in the Canning Basin.
- Undertake regional basin-studies projects by integrating surface and subsurface geological and geophysical data.
- Compile regional or statewide maps on given themes.
- Undertake cooperative research projects or subprojects with industry or tertiary education organizations.

## Work carried out 1993–94

### Surface mapping projects

The new generation of surface 1:100 000 maps in the Perth Basin have integrated a large body of petroleum exploration borehole and good quality seismic data that was not available in the 1970s during compilation of the previous generation of maps. These new sub-surface geological and geophysical data, when integrated and rationalized with the surface geology, have generated highly informative maps that reflect the current levels of stratigraphic and structural understanding in the basin.

During 1993–94, field work and data compilation for WEDGE ISLAND (1:100 000) was completed, concluding the mapping program of formal map sheet areas in the northern Perth Basin.

Together with the previously completed HILL RIVER–GREEN HEAD, ARROWSMITH–BEAGLE ISLANDS, and MINGENEW–DONGARA 1:100 000 sheets, WEDGE ISLAND will make available a fully integrated and consistent suite of maps and geoscientific data by one team of authors.

By integrating the surface and well bore geology with the seismic data, it has been possible to rationalize the surface geology with the subsurface stratigraphy and structure of the north Perth Basin. Consequently, a simplified stratigraphic table is proposed. The location of faults and other structural features in outcrop have been verified where possible by the seismic data. In addition to the petroleum industry, this interpretation is also of considerable interest to other state and local government planning and construction authorities, and for groundwater resource assessment purposes.

The Irwin River area was also remapped to assist with coal-resources assessment projects and incorporate the current levels of structural and stratigraphic understanding for the basin in that area. Surface mapping of Phanerozoic sediments on GERALDTON (1:250 000) was also commenced during the year. This mapping, to be completed in 1994–95, is a natural progression of the

program in the north of the basin and is essential in providing a link with forthcoming petroleum initiatives and projects during 1994–95 in the Southern Carnarvon Basin.

### Regional projects

#### North Perth Basin project

The objectives of the North Perth Basin project are to present a rationalized stratigraphic and structural review of the area. The extensive subsurface and surface geological and geophysical datasets have to be used to establish sequence-related depositional units, which in turn are consistent with mapped and recognized sequences in the onshore Carnarvon and Perth Basins. All currently available petroleum exploration seismic, aeromagnetic, and gravity data have been interpreted to produce regional structure and isopach maps at various stratigraphic levels. This study has helped to refine and corroborate the location of major faults, transfer zones, and other basin-forming structural elements, in turn providing new insights to the tectonic history of the basin by more clearly defining the major periods of structural activity. The study also presents models for the geothermal history of the basin in the light of the tectonic model. This information will be of great interest to both the exploration industries and other researchers.

#### North West Shelf Mesozoic project

The report on the 'Geology of the Triassic on the North West Shelf' was completed during late 1993–94 and concludes this project. As with the previous studies on the Cretaceous (MERIWA Report 55), and Jurassic (GSWA Record 1992/7) sequences, this publication on the Triassic focuses on the depositional environments, facies, thickness, and distribution of the Triassic units in the Southern Carnarvon and Roebuck (offshore Canning) Basins. All major wells that penetrate Triassic sediments are reviewed. Detailed descriptions of the sedimentology and depositional environment of all available Triassic cores are included in the report, together with the biostratigraphic control. Detailed regional stratigraphic sections between wells are used to illustrate the interpreted

correlations of the Triassic stratigraphic units and their depositional environments. The report also rationalizes the existing stratigraphic nomenclature, and seeks to establish future industry stratigraphic-nomenclature guidelines.

### State theme maps

Three 1:2 500 000 State theme maps were completed during 1993–94.

#### Basin subdivisions and tectonic elements map

The basin subdivisions and tectonic elements map ('Basin subdivisions of Western Australia') seeks to rationalize existing informal or formal nomenclature relating to basin and sub-basin boundaries, structural features and elements within basins. It was apparent that nomenclature relating to many onshore and offshore basins and sub-basin boundaries, tectonic and other basin-forming elements was ambiguous, as a number of terms or names were used concurrently by industry for a given feature. The objective of this map and explanatory notes is to propose a nomenclature suite that will eliminate ambiguities and allow for more effective communication between users. The map is available digitally and as hard copy.

#### Depth to base-Phanerozoic map

The 'Depth to base-Phanerozoic' map illustrates the location, structural setting and sediment thickness of all Phanerozoic onshore and offshore basins in Western Australia, compiled from existing industry and government datasets. This publication, when reviewed in conjunction with the 'Basin subdivisions' map, provides a regional insight to the distribution, thickness, and structural setting of the major sedimentary basins, and provides the basis for the terminology of that product. The map is available digitally and as hard copy.

#### Petroleum wells drilled

The 'Petroleum wells drilled' map updates, and makes available in digital and hard copy, the location and status of all petroleum wells drilled in the state. Enlarged maps for areas of high well density in the



North West Shelf, Perth Basin, and Canning Basin are included.

### **Regional seismic maps**

Seven 1:250 000-scale seismic-structure maps at the Valanginian (Lower Cretaceous) unconformity for the offshore Bonaparte Basin were completed for publishing. These maps were prepared by integrating industry seismic and well data.

With the completion of the Bonaparte series, seismic-structure contour map coverage now exists for all the surrounding offshore areas of Western Australia and the onshore Perth and Canning Basins. These maps provide an invaluable insight to the structural style and tectonic history of an area, and were designed to provide a 'quick look' structural assessment of a given area. These maps are available in hard copy and digital format.

### **Coal resources of the Perth Basin program**

A collaborative project between the GSWA and CRA integrated both

coal and petroleum industry borehole and geophysical data to generate a stratigraphic and structural review of the Permian coal measures of the Vasse Shelf region in the south Perth Basin. This review illustrates and tabulates the complex and discontinuous relationships of the major coal seams and proposes depositional environments that controlled those relationships and influenced the quality and potential size of that resource. The Vasse Shelf report is the last publication dealing with the Permian coal resources of the Perth and Collie Basins, and follows the earlier Collie Basin and Irwin River coal resource investigations.

### **Collaborative research projects**

#### **North Perth Basin gravity project**

Non-exclusive collaborative agreements with a number of petroleum exploration companies conducting seismic surveys in the north and central Perth Basin were initiated in order to increase the gravity-station density in the north Perth Basin area. By utilizing the accurate shot-point location data an additional 3299 stations were

recorded. These new gravity data were integrated into the existing database and processed through the newly acquired ER-Mapper facility at the GSWA. Sophisticated 'sun'-illuminated images of the data more clearly illustrate the position and relationship of faults and basement-related features. All participating companies received images of the total dataset and a GSWA interpretative report on conclusion of the gravity program. There is a strong belief within the GSWA and industry that the interpretation of seismic data and the structural understanding of an area can be greatly optimized through the use of gravity and magnetic data.

### **Industry liaison**

The Basin and Fossil Fuels Section continued to actively participate in industry-based professional organizations, including APEA, PESA, ASEG, and FESWA. A number of papers and field trips will be presented at the PESA and GSA conferences in Perth during August and September 1994.

A. K. Svalbe

## **Subcomponent 3.1.1.9 Statewide mineralization studies**

**Objective:** To document the distribution, geological controls and resources of selected minerals throughout Western Australia and publish the results as maps, bulletins, reports or digitally, as appropriate.

Information on the distribution and resources of minerals, when supplemented by descriptions of geological controls, assists mining companies to plan their exploration programs and guides prospectors to likely areas for further discoveries. The same data are needed for a wide range of Government planning activities, including landuse studies, availability of raw materials, and projections of infrastructure needs in various parts of the State. The GSWA has an ongoing program to meet these needs.

### **Activities in 1993-94**

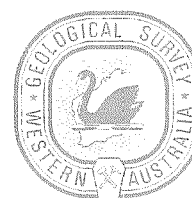
A Record, with accompanying map, on the mineral deposits of the Albany 1:1 000 000 sheet was published to assist mineral exploration and landuse planning in the State's most densely populated region.

A Record cataloguing known gypsum deposits in the State was passed in for final editing and drafting of figures. In addition to its more traditional uses in plaster and

cement, this mineral is in strong demand as a soil conditioner in the wheat belt. The potential for export markets is also being examined.

The first draft of a Mineral Resources Bulletin on talc and magnesite was completed. Information on these minerals was previously scattered through numerous publications and file reports.

A major revision of the existing Mineral Resources Bulletin on the



lead, zinc, and silver deposits of the State was undertaken. Contributions from companies holding some of the larger deposits were invited to ensure that the compilation is as up-to-date as possible.

Compilation of information on the fluorite and barite deposits of the State commenced during the year and is expected to be completed during 1994–95. Fluorite is a potential flux for metallurgical operations, whereas barite has applications in oil drilling, and as a coating for paper.

Work was also undertaken towards compiling a Record on the State's iron-ore resources, using information in the MINEDEX database. This will provide basic data for future planning, especially in the Pilbara region.

### *Future activities*

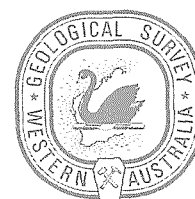
Studies of industrial minerals are expected to extend to salt, potash, and phosphates during 1994–95.

With the expansion of computer facilities within the Department, it is intended to begin work on placing mineral-deposit information onto a GIS database, to allow for faster publication and more frequent updates. A new edition of the State Mineral Deposits map is one planned outcome of this endeavour.

*J. G. Blockley*

## Subcomponent 3.1.1.10 Regional mineralization studies

**Objective:** *To document the resources and geological controls of mineralization in the State's principal mining districts.*



Mining is the mainstay of the Western Australian economy, contributing some \$12 billion in export earnings annually, and providing direct employment for at least 10 000 people. The long-term future of the industry depends upon discovering further deposits to replace those currently being mined out. The GSWA therefore carries out investigations of mining districts with the aim of producing detailed geological maps and determining the structural, stratigraphic, and lithological controls of mineralization.

Depending upon their scope, results of these regional investigations are made available as records, reports or bulletins, and the more significant conclusions may also become the subject of papers in international journals or be presented at conferences. These publications and presentations form a solid foundation for ongoing prospecting, mineral-exploration, and landuse studies.

### *Activities in 1993–94*

During 1993–94, the results of a major study of gold deposits in the belt of greenstones extending from Menzies to Kambalda, and including the famous Golden Mile, were published as a Report and three Records. An overview of the project's findings also appeared in the Australian Journal of Earth Sciences.

Work continued on a similar study of gold mineralization in the belt extending from Wiluna to Leonora, in the northern part of the Eastern Goldfields Province. A new map being compiled as part of the investigation should also assist exploration for nickel in this region.

Field work aimed at producing a map of the Karijini (Hamersley Range) National Park, with an assessment of its mineral resources, was completed during the year.

### *Future activities*

- Reports on the Wiluna to Leonora gold study, and the geology and mineral resources of the Karijini National Park, are to be compiled within the next 12 months.
- A major study of geology and mineralization in the granite-greenstone terranes of the Pilbara region is to begin in 1994–95.
- An investigation of the controls of gold mineralization in the Laverton gold belt will follow 1:100 000-scale regional mapping in the area.
- The current mapping in the Rudall Metamorphic Complex will be followed by a review of the mineral potential of the region.

*J. G. Blockley*

### Subcomponent 3.1.1.11

#### Mine mineralization studies

**Objective:** To undertake detailed geoscientific studies of selected mines or prospects to gain better understanding of their geological controls and to indicate scope for further exploration.



Many operating mines, particularly those mining gold, have short life-spans, and it is important to document their geology while they are still open. Detailed studies of individual mines or prospects may also provide keys to the understanding of regional mineralization patterns.

The GSWA is a participant in a project supported by MERIWA to systematically document the geology of opencut gold mines in the Yilgarn Craton. A postdoctoral fellow, Dr Fop Van der Hor, has been employed to coordinate the project, with supervision being provided by GSWA and the University of Western Australia (UWA). Upon completion of the project it is intended that a book will be produced documenting all deposits investigated, including documentation by post-graduate students at the Key Centre for

Teaching and Research in Strategic Mineral Deposits at UWA. Information will be presented in the form of data sheets for each mine, including such information as a description of the lode(s), the spatial relationships of mineralization to granitoids, and the inferred oxidation state of the mineralizing fluids, accompanied by diagrams showing geology and mineralization.

Miscellaneous inspections of individual mines and prospects are also made in response to requests by their owners, or to add to the information on the State's mineral resources.

#### *Activities in 1993–94*

Activities under the MERIWA project in 1993–94 focused on current mining activity in the

northeastern part of the Yilgarn Craton. Fieldwork for the Leonora, Laverton, Wiluna, and Sandstone regions was completed with visits to 24 mining operations comprising more than 100 opencut and underground mines. Detailed information, including mine maps and ore samples, was collected for 35 deposits.

#### *Future activities*

During 1994–95, it is intended to complete inspections of opencut gold mines in the Eastern Goldfields and commence examination of mines in the Murchison region.

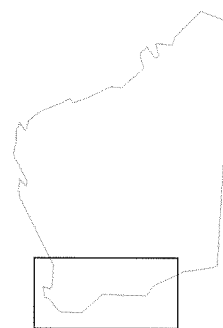
Inspections of new mineral discoveries will be made as these are announced.

*J. G. Blockley and F. Van der Hor*

### Subcomponent 3.1.1.12

#### Geology of 1:1 000 000 sheet areas

**Objective:** Compilation, interpretation, and publication of geological map sheets at 1:1 000 000 scale.

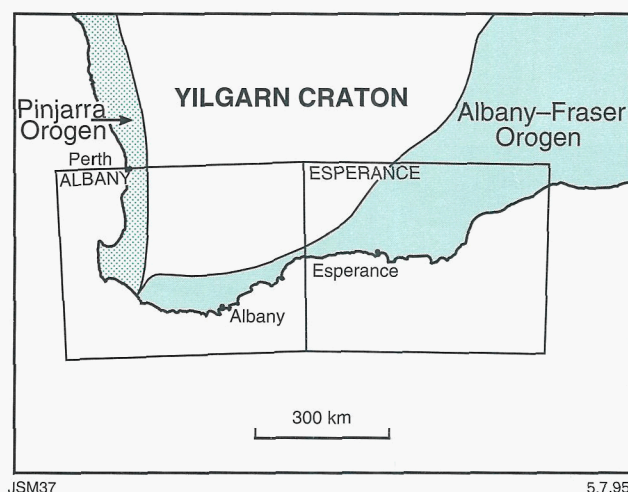


The 1:1 000 000-scale map series was initiated to provide regional overviews of the geology of Western Australia that are of value to both the exploration industry and the general public. They are based on

syntheses of existing 1:250 000 maps and new mapping in regions where the existing maps are clearly inadequate. Maps at 1:1 000 000 scale in the process of production are ALBANY and ESPERANCE (Fig. 9).

#### *ALBANY*

ALBANY and the explanatory notes were completed in March 1989. The map was published in June 1989 but publication of the explanatory



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Figure 9.  
Map of the  
southwestern corner of  
Western Australia  
showing the location of  
1:1 000 000 sheets

notes has been overtaken by higher priority projects. In 1993–94 they were revised to bring them up to date with recent published work and they are expected to be published in 1994–95.

### ESPERANCE

The second edition of *ESPERANCE* and the explanatory notes were completed in 1991. In 1993–94 the explanatory notes were revised to bring them up to date with recent work, and it is expected that they will be published together with the map sheet in 1994–95.

J. S. Myers

### Subcomponent 3.1.1.13 1:50 000 environmental geology mapping

**Objective:** To produce 1:50 000 maps and associated GIS systems of geological and hydrogeological features, and other constraints for urban and regional development.



#### Cowaramup environmental geology GIS

The activities for the 1993–94 year were dominated by the finalization of the Cowaramup Environmental Geology GIS database, which was developed by the GSWA as a landuse planning tool for COWARAMUP and MENTELLE (1:50 000). The region covered by the database is bounded by latitudes 33°45'00"S and 34°00'00"S and longitudes 114°58'30"E and 115°15'00"E.

A SPOT panchromatic satellite image, generated in October 1992, was obtained from the Australian Centre for Remote Sensing. The image, which has a resolution of 10 m, was imported into the Cowaramup Environmental Geology GIS. This image is used as a 'backdrop' for image presentation and interpretation.

The Cowaramup Environmental Geology GIS contains a range of

data on the area's features that must be considered when planning urban and regional development. These include:

- superficial geology (regolith);
- basement and structural geology;
- Mining Act tenements;
- extractive industry operations (past and present);
- landfill and waste-disposal sites (past and present);
- hydrogeology;
- groundwater-bore locations and logs;
- hydrography (drainage channels, swamps, and springs);
- karstic features;
- topographic contours;
- cadastral information (comprising property boundaries, roads, and town sites);

- CALM and Shire management units;
- Department of Agriculture soil units.

A range of maps have been produced using the database. These maps show the availability of limestone, gravel, sand, and clay resources on private land, possible landfill sites on Crown reserves, and a composite plan of appropriate data used for evaluating groundwater potential.

A report on the Cowaramup 1:50 000 Environmental Geology GIS is in draft form. The database is accessible to the public through the Surveys and Mapping Division of DME.

W. M. Carr



### Subcomponent 3.1.1.14 ROCKMIN

**Objective:** *ROCKMIN is designed for the storage, retrieval and manipulation of large volumes of data; it provides an index to the thin- and polished-section collection, and petrological and geochemical reports generated within the GSWA. ROCKMIN is the archival store for all GSWA petrological and geochemical data.*



ROCKMIN is a relational database, housed on the IBM mainframe, for all GSWA petrological information. ROCKMIN currently holds data on more than 59 000 thin sections, and about 1000 chemical analyses.

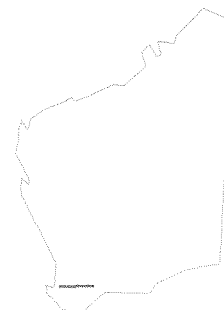
ROCKMIN, as currently configured, is unwieldy, difficult to access, and incompatible with other requirements of databases within the GSWA. In cooperation with the Surveys and Mapping Division, the GSWA is currently setting up a GIS

system for Regional Geochemical Mapping, to be accessed by local PCs. In the developed system it is proposed that petrological data will form an additional 'layer', and that ROCKMIN, as an independent database, will cease to exist.

J. D. Lewis

### Subcomponent 3.1.1.15 Reconnaissance gravity traverses

**Objective:** *To investigate and report on variations of Bouguer gravity across selected zones in the Western Gneiss Terrane.*



Following changes in the staffing of the Geophysics Section, the objectives of this subcomponent were re-evaluated early in the financial year. In keeping with the move towards project-based geoscience mapping, a decision was taken that this subcomponent would be suspended. Any regional gravity work would be carried out and reported under specific projects.

As a result, the only activity undertaken was to finalize the work remaining from the previous financial year: the Busselton to Lake Magenta gravity traverse.

The approximately 350 km-long gravity traverse is dominated by the effect of the Perth Basin, a spectacular gravity low, and the Darling Fault, with its high gravity gradient. A number of models were generated to explain the other features observed in the gravity profile. The models assumed a gradual deepening of the upper crust towards the east to explain the longest wavelength components of the traverse. Residual anomalies with wavelengths of the order of 100 km were explained by assuming variations in crustal thickness caused by warping or faulting

rather than changes in the near-surface rock densities. It was concluded that features with wavelengths shorter than these would require better definition with further data acquisition. However, one residual short wavelength gravity low about 13 km north-northeast of Kirup was reasonably modelled as an intracratonic basin filled with low-density sediments. The results are presented in Geophysical Report No. 1993/3 (unpublished).

S. H. D. Howard

### Subcomponent 3.1.1.16 Geophysical databases

**Objective:** To maintain indexes and databases for storing and retrieving information on gravity, well-logging data, and aeromagnetic surveys.



Three principal geophysical databases are maintained in the Geological Survey: gravity data, a well-log index, and an index of aeromagnetic surveys. All three are available to the public.

The databases have been maintained during the year with new data being added as they become available.

The gravity database contains 3300 records of data acquired by the GSWA, mainly over COLLIE (1:250 000). These data have been sent to AGSO for inclusion in the national database.

The aeromagnetic survey index (MAGCAT) contains approximately 1900 records. An 'Open File' subset is made available for sale to the public with updates approximately

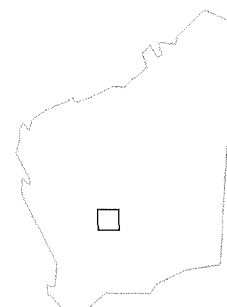
every quarter. A copy has been placed in the GSWA Library for public use.

The well-logs index (JEWEL) contains almost 3200 records. Maintenance of this database has been transferred from the Geophysics Section to the Hydrogeology Section as part of the general transfer of the geophysical logging of water wells.

S. H. D. Howard

### Subcomponent 3.1.1.17 Regolith

**Objectives:** To determine the nature and distribution of regolith over much of the Eastern Goldfields; map major components, establish their inter-relationships, and the evolution of the landscape. To investigate inverted-relief valley-fill laterite profiles in relation to their chemical and mineralogical composition, and their relationships with underlying bedrock.



Regolith activities have included the preparation of a Record on a number of deeply weathered (lateritic) profiles in the Leonora area (Record 1994/8). There is increasing evidence that some lateritic duricrusts are of allochthonous rather than autochthonous origin. A study of seven deeply weathered profiles capped by lateritic duricrust has clarified relationships between the lateritic duricrust and the underlying 'greenstone' bedrock.

Each profile has had a long and varied formational history, having been influenced by a number of complex geological, topographic, climatic and groundwater factors, and recent pedogenic processes. None of the studied profiles has a

unique mineralogy: variations reflect differences in the relative amounts of a small number of minerals.

The complex nature of the lateritic duricrusts and profile history complicates the determination of the residual or transported origin of a particular duricrust. Recognition of lateritic duricrusts developed in transported materials depends upon its geomorphic relationships, on profile characteristics, comparisons of mineral assemblages and chemical compositions, relict rock fabrics between the duricrusts and the underlying saprolite, and sources and movement of iron.

The results suggest that the lateritic duricrust at one of the seven

profiles may be of residual origin. Lateritic duricrusts overlying hardpanized colluvium probably formed in transported material. Major breaks in the proportions of immobile and less mobile elements between lateritic duricrust and the underlying deeply weathered profile at other sites suggest that development of the duricrusts there also took place in transported material.

Lateritic duricrusts that unconformably overlie deeply weathered profiles may be more widespread than was previously thought. This has some serious implications for the exploration industry.

R. Davy and J. R. Gozzard

### Component 3.1.3

## Airborne geophysical mapping

**Objective:** To provide uniform aeromagnetic and radiometric data coverage over specified geological provinces selected on the basis of prevailing subprogram priorities.



Special budget funding of \$500 000 was made available by the State Government in September 1993 for the acquisition of regional airborne geophysical data and appropriate data processing hardware and software to support a four year program of accelerated geological and geochemical mapping. During the following eight months, a processing system and data were acquired, and used as outlined below.

### Computer hardware and software

After undertaking a detailed evaluation of hardware and software options, the following configuration was installed:

- A Sun Sparc10/51 computer with 92 MB of memory, a 5 GB hard disk system, CD-ROM, and 8 mm, 5 GB tape drive.
- A HP Design Jet 650c A0 colour plotter.
- The Intrepid geophysical data processing package with modules for: data import, export and editing; gridding and contouring; map visualization and composition; numerical interpretation; line and grid filtering; and grid splicing.
- The ER-Mapper image-processing package.

### Data acquisition

Purchases were made of commercially available airborne geophysical data covering part of the Glengarry Basin (19 000 line km) and over WILUNA (1:250 000; 43 000 line-km). The latter purchase was shared with AGSO. The data were acquired on the basis that they be held confidential until 30 June 1996 (Wiluna) and 31 January 1997 (Glengarry).

Agreement was reached with AGSO for a jointly funded (60% AGSO; 40% GSWA) airborne survey of DUKETON (1:250 000). World Geoscience Corporation was awarded the tender for the survey. Final located data tapes were received at the end of June. Production of maps will commence in July 1994.

A request for public tender for a 100 000 line-km survey over the Peak Hill – Glengarry area was released in May 1994 and a contract for the survey was awarded to Tesla Airborne Geoscience.

AGSO data has been requested or received for the following project areas: Kimberley, Glengarry, Ravensthorpe, and Central Goldfields.

The total extent of GSWA regional airborne geophysical data holdings in digital format (confidential and open file) is now of the order of 420 000 line-km covering the areas shown in Figure 10.

### Data processing

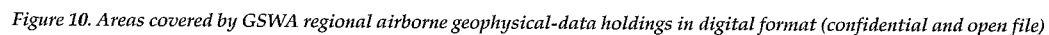
Geophysical images (screen and hard copy) have been produced for in-house use by geologists and geochemists on the following projects:

- Eastern Goldfields
- Glengarry Basin
- Geochemical mapping
- Pilbara
- Halls Creek and King Leopold Orogens
- Mineralization studies
- Basin studies.

### Interpretation

Magnetic-data enhancements to show contacts and depths to magnetic sources, and to produce an apparent susceptibility map of SIR SAMUEL (1:250 000), have been carried out by an external consulting group under contract. A qualitative 'litho-structural' interpretation is also being carried out by an external consultant. It is planned to release the results from these interpretations as a pilot set of 1:250 000-scale 'magnetic features' maps in 1994–95 to gauge industry interest. If sufficient interest is shown, consideration will be given to producing such maps on a regular basis as a complement to the standard geological fact maps.

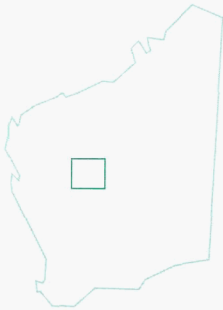
S. H. D. Howard





Component 3.1.4  
Glengarry Basin regional geological mapping

**Objective:** To increase geoscientific knowledge of the Glengarry Basin through 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, and remote sensing.



The geological terranes of the Glengarry Basin are situated along the northern margin of the Yilgarn Craton, between the Earraheedy Basin in the east and the Narryer Complex in the west. The Glengarry terranes are of Early Proterozoic age (2.0–1.8 Ga), are part of the Capricorn Orogen, and host a number of gold and base-metal deposits.

Late in 1993 a comprehensive program was initiated to include systematic geological mapping, basin analysis, geotectonic, geophysical, geochemical, petrological, and ore-deposits studies. A team, comprising a manager and three field geologists, was appointed for this purpose.

Following an initial phase of literature research and field reconnaissance (November 1993 to February 1994), geological mapping was commenced in March 1994. This work is underway and progress is briefly reported below.

Methods

The immediate objective of the GSWA’s program in the Glengarry Basin is to produce geological maps at scales of 1:25 000, 1:50 000, and 1:100 000. Field geological mapping of the Glengarry Basin is being conducted using colour (1:25 000 scale) and black and white (1:50 000) aerial photography. Photogeological interpretation is subsequently undertaken between field traverses.

Field work is aided by, and integrated with, the available mineral-exploration surface and subsurface data, obtained from M-series reports (DME files). Thesis projects (completed and underway)

from the University of Western Australia provide additional information.

Work done and results during 1993–94

Initial field-reconnaissance work was conducted in November–December 1993 and March 1994. During this time most of the key localities — in terms of rock exposure and geological significance

— were visited, and samples were collected for laboratory investigations.

Systematic geological mapping was commenced in April 1994 on BRYAH, DOOLGUNNA, and MOUNT BARTLE (1:100 000 sheets). Areas covered to the end of June 1994 are shown in Figure 11.

During the period from November 1993 to June 1994, 811 rock and core samples were collected, and 599 thin sections, polished sections, and

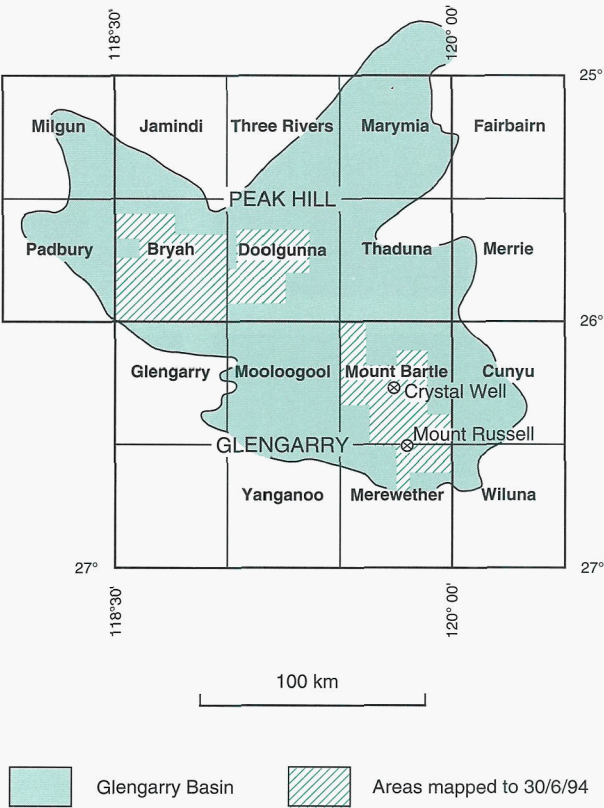


Figure 11. Outline of the Glengarry Basin (including inliers) showing 1:100 000 map sheets and areas mapped to the end of June 1994

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polished thin sections were prepared. Approximately 120 major- and/or trace-element analyses were performed at the Chemistry Centre of Western Australia.

### BRYAH

BRYAH is in the southwest corner of PEAK HILL (1:250 000; Fig. 11). It covers an important area that hosts economic gold mineralization, and is currently the focus of intense exploration activity. BRYAH is also particularly significant in terms of its geotectonic architecture, and constitutes an important element in the understanding of the geodynamic evolution of the Glengarry Basin as a whole.

The BRYAH lithologies are structurally complex and variably metamorphosed. The known geological elements are mafic and

ultramafic rocks of the Narracoota Volcanics, BIF units of the Horseshoe Formation, the Peak Hill mylonitic schists (previously known as Peak Hill metamorphic suite or complex), and sedimentary rocks of the Padbury Group. Several gold deposits (including one copper–gold deposit) in the area are associated with the Narracoota Volcanics and the rocks of the Peak Hill mylonitic schists. Examples of BRYAH lithologies are shown in Figure 12a–d.

Detailed geological mapping of BRYAH has revealed some important, previously unrecognized, features. Firstly, field observations suggest that there may be more than one sequence of mafic volcanic rocks. In the Peak Hill area the mafic volcanic rocks contain pillow structures and are generally deformed and metamorphosed (Pirajno et al., this volume). Shear zones that cut through these rocks

are associated with gold mineralization. To the south, a belt of mafic volcanic rocks is characterized by hyaloclastites and breccias. These rocks are metamorphosed to an assemblage containing epidote and actinolite–tremolite. Here too, shear zones are present, and are associated with gold and copper–gold mineralization. The area of metamorphic rocks (greenschist to lower amphibolite facies) is extensive and is associated with pervasive deformation, mylonitic rocks, and shear-zone domains (e.g. Peak Hill mylonitic schist).

### DOOLGUNNA

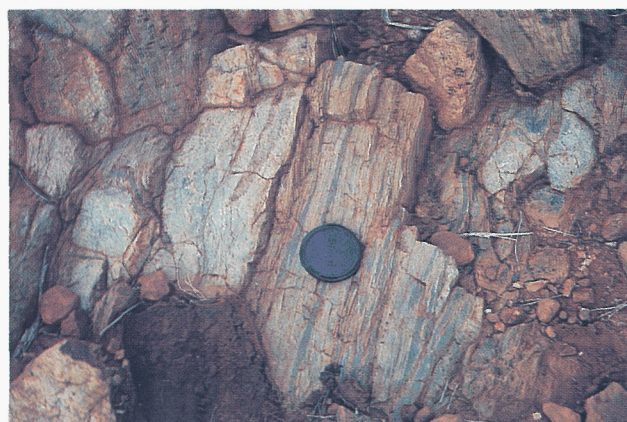
DOOLGUNNA is adjacent to and east of BRYAH (Fig. 11). A belt of predominantly clastic and carbonate rocks occurs along the northwestern side of the Goodin Dome, which occupies the southeastern portion



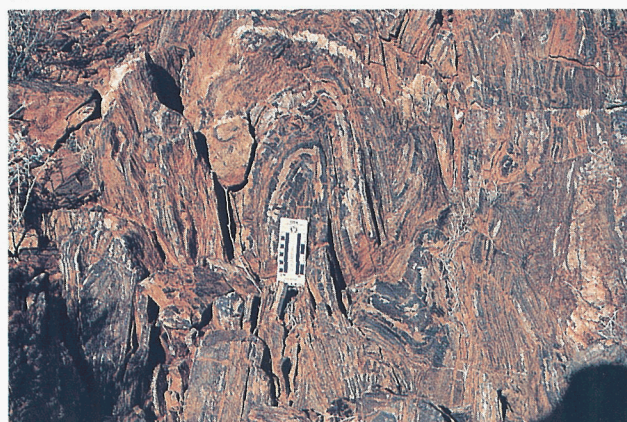
(a)



(b)



(c)



(d)

Figure 12. Deformed and metamorphosed rocks in the western portion of the Glengarry Basin: (a) volcanic breccia at the Cashman copper–gold deposit; (b) intersecting cleavages in shales of the Millidie Formation; (c) quartz mylonites south of the Peak Hill mine; (d) folded BIF of the Padbury Group





(a)



(b)



(c)

Figure 13.  
(a) Wave ripple cross-lamination in quartz arenite — Finlayson Member;  
(b) polygonal remains of a desiccated mud-flake layer Finlayson Member.  
Both (a) and (b) are from a tidal-flat palaeoenvironment.  
(c) Micritic dolostone with remains of algal laminae forming a stromatolitic bioherm — Earraheedy Group

of DOOLGUNNA. This belt contains quartz arenites and dolomitic lithologies of the Juderina Formation and the Johnson Cairn Shale, which are overlain by the turbiditic immature wackes of the Doolgunna Formation. Blocks of silica-cemented grey quartz arenite, microbial cherts, and chert breccia occur within this formation. Their tectonic contacts with the enclosing rocks, the size of the blocks (up to several tens of metres), and their exotic nature suggest that they may be olistostromes related to a

deepening trough and accompanying rapid erosion. The source of these blocks and the granitic source from which the bulk of the Doolgunna Formation was derived is yet to be determined. Intense deformation and mylonitization, which affected the Juderina and Doolgunna Formations in the northwestern corner of the Doolgunna area along the contact zone between the Narracoota Volcanics and the Marymia granitic rocks, may be associated with the closure of the trough, and related

compression against the rigid Marymia Dome.

### MOUNT BARTLE

MOUNT BARTLE lies in the southeastern part of the Glengarry Basin (Fig. 11), and contains a thick sequence of mafic volcanic and sedimentary rocks. In the southwest the exposed strata are predominantly carbonaceous pyritic siltstones and green-grey dolomitic marl attributed to the Maraloou Formation. Laminated and graded bedding indicate alternating periods of suspension and turbidite deposition. These rocks are relatively flat-lying and weakly folded, and have northerly trending flute-marked surfaces. This is indicative of syndepositional gradient changes, possibly in the form of movement along listric-fault scarps.

The central portion of the area is dominated by a broad southerly trending synclinal structure containing numerous stromatolitic cherty carbonate units separated by thin cross-stratified calcareous sandstone. They are underlain by a sequence of mature stratified quartz-pebble conglomerate and cross-stratified sandstone. These units are assigned to the Yelma Formation of the Earraheedy Group. The Earraheedy Group is underlain by a carbonate unit of several hundred metres thickness. A number of ring-shaped structures up to 500 m in diameter are characterized by concentrically dipping strata, and locally silicified and brecciated carbonate units. These are interpreted as karst-collapse features.

In the north, the structural disturbance of the strata is more pronounced. These rocks are characterized by turbidites that are dominated by thick ferruginous (volcaniclastic) litharenite, which was deposited in numerous upward-thinning cycles. These are intercalated with mafic volcanic and intrusive rocks. Sulfides occur locally in the amygdaloids of the volcanic rocks, and also as millimetre-scale blebs in the mafic intrusive bodies.

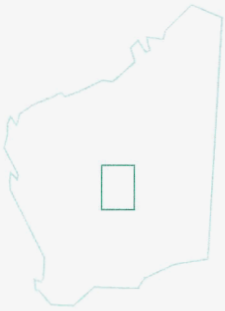
Examples of Mount Bartle lithologies are shown in Figure 13a–c.

F. Pirajno



Component 3.1.5  
Eastern Goldfields regional geological mapping

**Objective:** To increase geoscientific knowledge of the Eastern Goldfields Province 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.

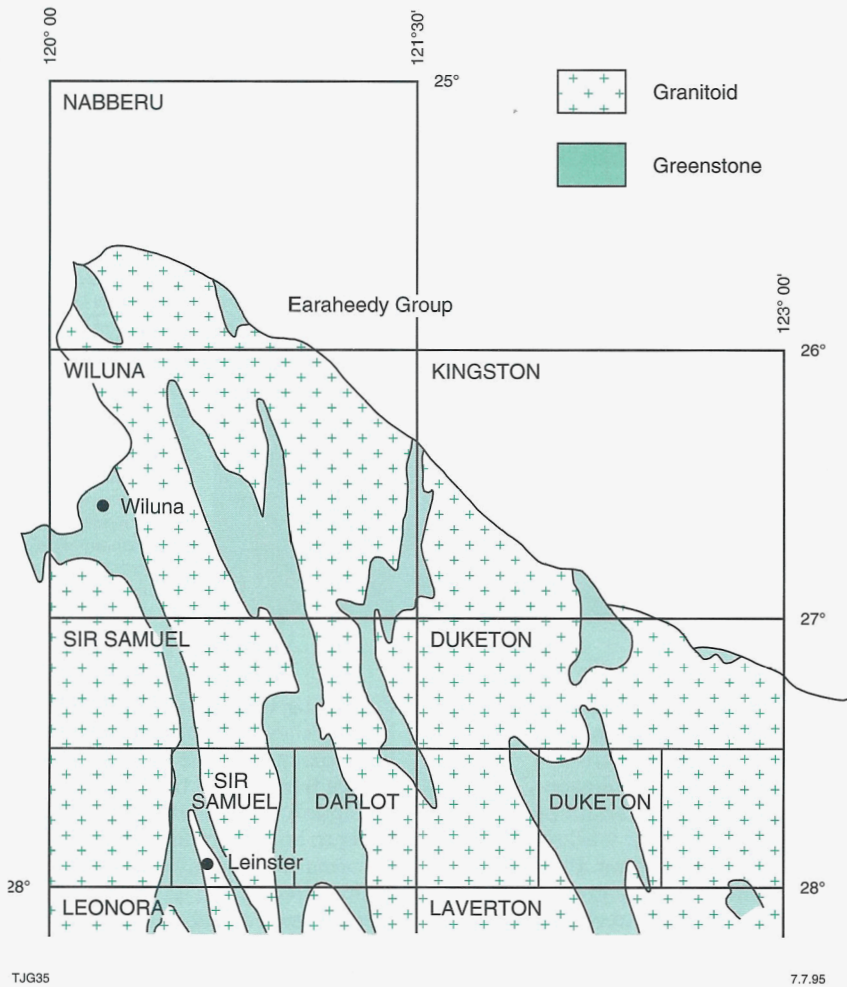


Summary

Regional mapping in the Eastern Goldfields was given a boost from the 1993–94 State budget with the injection of additional resources under the new initiatives program of the GSWA. Our efforts were concentrated in two areas of special interest to the minerals industry. Firstly, emphasis was placed on accelerating the publication of maps and explanatory notes of critical areas of granite–greenstone geology in the southern part of the Eastern Goldfields. The field mapping for these maps was completed in 1992–93. Many of these map sheets have now been released to the public and exploration industry, and preparations are well advanced for release of the remaining maps during the second half of 1994. Secondly, a program of accelerated mapping began in the northern Eastern Goldfields, between Wiluna and Laverton, to provide 1:100 000-scale maps of the highly prospective Mount Keith, Yandal, and Duketon greenstone belts. During 1993–94, field mapping has concentrated on the SIR SAMUEL and DUKETON 1:250 000 sheets (Fig. 14). AGSO has extended their NGMA project in the Eastern Goldfields to map alongside GSWA. Each organization will map transects across the trends of the granite–greenstones: GSWA to the south, where work will concentrate on the SIR SAMUEL, DARLOT and DUKETON 1:100 000 sheets; and AGSO mapping the northern transect.

metamorphosed volcanic and sedimentary rocks, which in the northern Eastern Goldfields form narrow, elongate belts trending north-northwest. They are separated by large tracts of granitic rocks which intruded the greenstone sequences. The granitic rocks, which include banded gneisses, are also

variably metamorphosed and deformed. Remapping of the Eastern Goldfields began in 1980 with the first phase of standard 1:100 000 geological maps. The fieldwork in the southern and central parts of the Eastern Goldfields Province has been completed, and emphasis has been



Introduction

The Eastern Goldfields Province is an area of granite–greenstones in the eastern Yilgarn Craton. The greenstones consist of

Figure 14. Simplified geology of the northern part of the Eastern Goldfields showing the location of the three 1:100 000 map sheets where field mapping was undertaken in 1993–94



placed on the publication of these maps and reports at 1:100 000 and 1:250 000 scale by both GSWA and AGSO.

The greenstones of the northern part of the Eastern Goldfields, like the other parts of the Eastern Goldfields, are of significant interest because they host major deposits of nickel (e.g. Perseverance, Rocky's Reward, Yakabindie, Mount Keith, and Honeymoon Well) and gold (e.g. Emu, Bellevue, Wiluna, Mount McClure, Darlot, Bronzewing, and Bannego).

The current mapping is aimed at providing an up-to-date and more comprehensive regional database to encourage further exploration in the northern part of the Eastern Goldfields, with the initial objective to generate new outcrop maps at 1:100 000 and 1:250 000 based on field mapping, satellite imagery and regional geophysics. The field mapping is essential for the interpretation of geophysical and satellite data. In addition, thematic and interpretive maps and datasets will be produced.

### *Approach to mapping*

The rocks in the northern Eastern Goldfields are poorly exposed due to deep weathering, extensive sand cover (particularly over the granites), and residual lateritic surfaces. Outcrop mapping is supported by mapping of rock chips from the extensive shallow drilling carried out by exploration companies. In addition, reports on mineral exploration contained in the WAMEX library, along with detailed interpretation of aerial photographs, satellite imagery, and geophysical interpretation, are used to compile the maps and generate geological models.

New colour aerial photography at 1:25 000 scale has been flown to cover the major greenstone belts, and as a result provides systematic coverage of the MOUNT KEITH, WANGGANNOO, SIR SAMUEL, DARLOT, and DUKETON 1:100 000 sheets. This photography is available to industry and the public through DOLA.

Airborne geophysical surveys were commissioned or purchased with the assistance of AGSO to provide a better basis for the mapping and

interpretation of the geology. Aeromagnetic and radiometric data at 400 m line spacing has been obtained. The data for SIR SAMUEL and DUKETON is available from GSWA or AGSO, and the data for WILUNA will become available from these organizations in the second half of 1996.

Map production is carried out in a digital environment, thus enabling the new geological maps to be combined with other digital data as part of a GIS package.

### *Progress to date*

An additional three staff were recruited for the project in 1994 to support the three geologists based at the Kalgoorlie Office of the GSWA. AGSO have four geologists working on the project. Field mapping by GSWA commenced in February 1994 and is approximately 80% complete for the SIR SAMUEL, DARLOT, and DUKETON 1:100 000 sheets (Fig. 14). Briefly, some important observations from this mapping are as follows:

1. Conglomeratic rocks in the Jones Creek – Kathleen Valley area on SIR SAMUEL and MOUNT KEITH have a wide range of textures and compositions. Some are almost matrix free, others contain a few coarse clasts, and the clasts and matrix vary in composition from granitic to mafic. Foliated granite-boulder conglomeratic rocks with both granitic clasts and a granitic matrix at Yellow Aster contain gold mineralization. Recent mapping indicates that some of these conglomeratic rocks may be subvolcanic or volcanic in origin. The fragmentation and rounding of at least some of the granitic clasts may be related to later high-level magmatic activity.
2. Conglomerates, derived from a range of rock types, represent a significant component of the greenstones on the western limb of the Lawlers Anticline on SIR SAMUEL. These range from granitic clasts in a granitic matrix, through granitic clasts in a mafic matrix, to mafic clasts in a mafic matrix. They are similar to the conglomerates in the north of the sheet at Jones Creek. These conglomeratic metasedimentary

rocks contrast with the felsic volcanoclastic metasedimentary rocks that outcrop on the eastern limb of the Lawlers Anticline. They form a significant component of the greenstone sequence and indicate that some of the granitoids intruded prior to the cessation of deposition of the greenstone succession.

3. Basaltic rocks, characterized by flattened pillow-lava structures and unusually large plagioclase megacrysts up to 20 cm across (Fig. 15a), outcrop on an island in Lake Miranda on SIR SAMUEL. The largest crystals occur only in the more massive flows, whereas only the smaller megacrysts occur in the central parts of flattened pillows (Fig. 15b). These rocks are possibly related to leucogabbro, with coarse plagioclase, in the Kathleen Valley Gabbro, a layered mafic intrusive body beneath the metabasalt.
4. Retrogressed coarse andalusite and cordierite schists have been identified within the greenstone succession northeast of Yakabindie on SIR SAMUEL. Relict elongate andalusite grains, up to 3 cm long, and equant cordierite, 2.5 cm across, occur in layers, presumably reflecting original compositional differences in the metasedimentary rocks. They confirm the presence of pelitic metasedimentary rocks within the predominantly mafic greenstone succession.
5. Mesoscopic isoclinal folds with near-horizontal plunges have been refolded into macroscopic isoclinal folds with moderate to steep north-northwesterly plunges in silica-rich horizons east of Mount Sir Samuel on SIR SAMUEL. These rocks are part of the Mount Keith – Perseverance greenstone belt which hosts a number of major nickel deposits. The presence of several ultramafic units could be accounted for by the tight multiple deformation in these rocks, which may have produced structural repetition.
6. The basaltic rocks that contain the very coarse plagioclase megacrysts on SIR SAMUEL record three ductile deformation events. The earliest deformation is

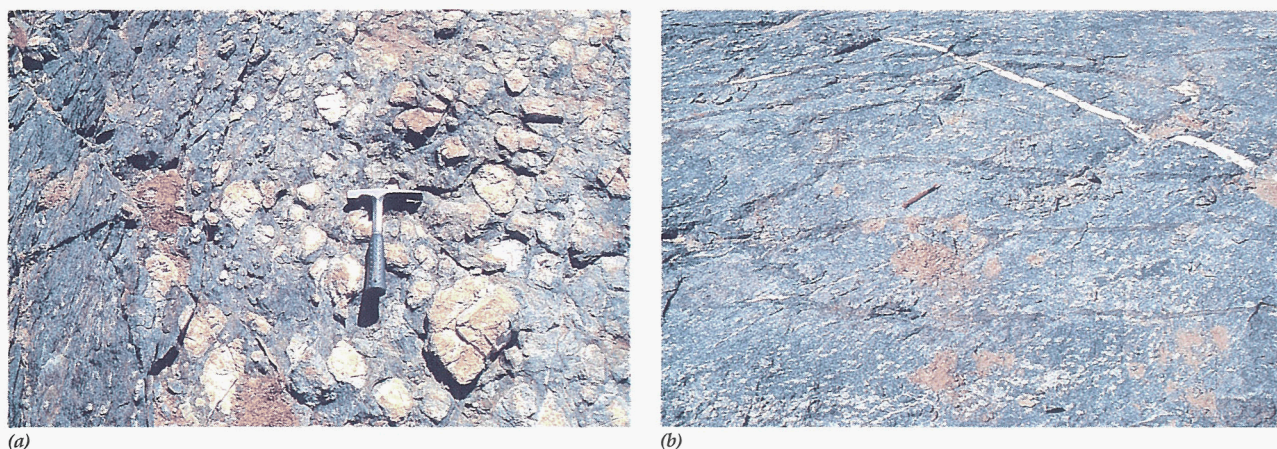


Figure 15. Metamorphosed, plagioclase-megacrystic basalt, which is exposed on an island in Lake Miranda, south of Bellevue Gold Mine. (a) Megacrysts of plagioclase in foliated metabasalt. The largest crystal is 20 cm across. (b) Flattened pillow structures, outlined by dark, fine-grained margins, with plagioclase megacrysts up to 3 cm long aligned parallel to the flattening direction. The pencil shows the trend of the major foliation, which is oblique to the flattening and formed by the second deformation event recognized in these rocks

represented by flattened pillows and preferentially oriented plagioclase phenocrysts. The planar fabric was overprinted by a second deformation which produced an upright schistosity oblique to the earlier flattening (Fig. 15b). This schistosity was refolded during the third deformation event, which also folded a quartz feldspar porphyry dyke, resulting in a second upright foliation.

7. Spherulitic textures in weathered, massive, fine-grained porphyry at Mason Hill on DUKETON confirm the presence of felsic volcanics associated with volcanoclastic rocks in the poorly exposed, extensive felsic unit in the central part of the Duketon greenstone belt.
8. Large pavements of granitic rocks in the Lizzars Well area on DUKETON confirm the presence of banded gneiss along the western

margin of the Duketon greenstone belt. The gneissic fabric is defined by moderate, yet distinct, compositional and grainsize variations, and the foliation is parallel to the layering and quite variable in its intensity. The gneissic banding, which includes narrow strips of deformed greenstones, is apparently the result of both multiple intrusion of granitic material and intense deformation that may have included tectonic interleaving.

9. The Ockerburry Fault is recognized as a major tectonic feature of the Yandal greenstone belt, and may be a regional structural-stratigraphic discontinuity (domain boundary). It extends from the southern boundary of DARLOT in the vicinity of Weebo Homestead north onto WANGGANNOO, passing to the west of Yandal Homestead. The part that

outcrops to the west is characterized by cherts and associated sedimentary rocks, abundant mafic and subordinate ultramafic rocks, and minor felsic to intermediate volcanic and volcanoclastic rocks. Limited outcrop and recent exploration drilling suggests that the felsic rocks may comprise much of the non-outcropping sequence west of the fault. Calc-alkaline volcanics of the Spring Well complex lie east of the fault. However, the relationship between this complex and the mafic intrusive and extrusive rocks further east has not yet been established.

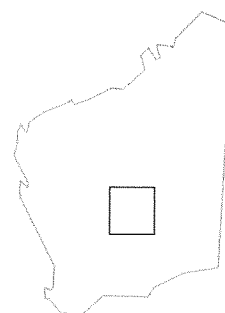
Gold mineralization at Mount McClure and Darlot, either side of the Ockerburry Fault, occurs in structures that are mainly parallel to the regional trends in the greenstones. It does not appear to be confined to a particular rock type or association.

T. J. Griffin

## Component 3.1.6

### Regional geochemical and regolith mapping

**Objectives:** To determine regolith divisions over selected 1:250 000 map sheets, map major components where these divisions have not been determined, sample, and have analysed, drainage sediments from these map sheets, and interpret the findings in terms of regolith units and underlying bedrock, and the evolution of the landscape.



#### Progress summary

A program of regional regolith and geochemical mapping commenced in 1993–94. Sampling on MENZIES began in February 1994, and was followed by sampling on LEONORA in June 1994.

#### Nature of program

Funds were provided in the September 1993 budget for a program of regolith and geochemical mapping on a regional scale. The objectives of this program are:

- Identification of metallogenic provinces and of specific areas in the state with potential for undiscovered mineralization.
- Assistance in recognition of properties of different geological units.
- Provision of base geochemical information for use in agricultural and pastoral activities.
- Recognition of areas with potential for, or with actual, pollution problems.

For this project the GSWA is assisted by an Advisory Committee drawn from industry and the CSIRO. The current program is directed to the Eastern Goldfields (to provide some rationalization for areas known to be mineralized), and the Glengarry Basin and surrounds (an area believed to have potential for the discovery of further mineralization).

Regional geochemical mapping requires the mapping of surficial materials (regolith) and the sampling and analysis of drainage and other sediments at regular

intervals over large set areas, in this project over 1:250 000 map sheets. Sampling is coupled with regolith mapping to facilitate interpretation of the chemical data obtained.

#### Status of project

In 1993–94, MENZIES has been sampled, and sampling has commenced on LEONORA. Samples from both areas are being analysed.

Results for these sheets, which will include a digital dataset as well as hard copy maps, together with Explanatory Notes, are expected to be published early in 1995.

The project is continuing in 1994–95 with sampling of PEAK HILL and GLENGARRY in 1994 and SIR SAMUEL in 1995. It is expected that finance will be available to continue the project in 1995–96.

#### Mapping methods

MENZIES has been sampled at approximately one sample per 16 km², with collection of a total of 1077 samples. Samples have been taken of drainage sediments where possible, but in areas with little visible drainage, samples of sheetwash or soil, representative of the local regolith unit, have been collected. Samples were sieved on-site to less than 2 mm and greater than 450 mm, with a separate minus 2 mm fraction collected for archiving; amounts collected were 1.5 kg and 3 kg respectively. A few samples of lateritic material have also been collected for inclusion in the CSIRO/AGE database.

Sampling on MENZIES was effected using three two-person ground-based teams; on LEONORA four teams are being used. Each team comprises

a geologist and assistant. The GSWA has provided one team and has overall responsibility for the project. Geochemex Australia has assisted in sampling, providing the remaining teams and logistical support. A helicopter was used to acquire samples in those areas on MENZIES, such as the saline drainages, that are difficult to access. Samples have been submitted for commercial chemical analysis for 46 components.

Sampling began on MENZIES in February 1994; sampling on LEONORA commenced in June.

A detailed regolith map of PEAK HILL has been prepared and a similar map for GLENGARRY has been started. Use has been made of regolith maps at the 1:250 000 scale provided by AGSO to assist in control of sampling on MENZIES and LEONORA. The permission of AGSO to use these unpublished maps is gratefully acknowledged.

#### Data storage and output

Data collected in the field and from chemical analysis is being stored in a GIS using ARC-INFO, with ORACLE as the main database. Use of a GIS will allow information to be displayed in layers.

The work will be reported in the form of Explanatory Notes for each map sheet, accompanied by data presented in digital form, and in hard copy as maps or plans covering both geochemistry and regolith. Output to be prepared will include location maps, material maps, landform maps (particularly for PEAK HILL and GLENGARRY), element-distribution maps, and some basic statistics. Some plans may be produced 'on demand'.

R. Davy



## Component 3.2.1

### Groundwater exploration assessment and mapping

**Objectives:** To explore and assess the State's groundwater resources in a long-term program to promote and assist State development, landuse planning, and groundwater management by maintaining a database on the State's groundwater resources, and by carrying out regional hydrogeological mapping of the State to produce maps at an appropriate scale and in a readily understandable format.



Considerable progress has been made this year towards the long-term objectives of this component. In particular drilling and sampling programs have been completed in the Perth Basin, a major study of the groundwater resources of the Perth Metropolitan area has been written, external funding has enabled the computerization of the groundwater database to rapidly proceed, and several hydrogeological maps have been published, whereas others are in progress.

#### Activities and outcomes

Groundwater resources assessment programs were finalized early in the year in two parts of the Perth Basin. The Scott Coastal Plain program completed a regional investigation in the southern Perth Basin, and the data obtained from this program has enabled a clearer assessment of the quantity and quality of the shallow unconfined aquifer in the area, and its relationship with the underlying major sandstone aquifer, the Yarragadee Formation. In particular it has enabled a more detailed determination of the probable recharge area for the latter formation.

The second program was completed in the northern part of the Perth Basin (Leeman Shallow Stage 2) and was designed to complement the earlier Stage 1 of 1992–93. The program investigated the groundwater resources of the superficial formations and indicated fresh water in the southern half of the project area, which becomes brackish to the north. It also indicated that fresh groundwater was available within the underlying Lesueur Sandstone and the Yarragadee Formation.

Concurrent with the above programs is a program of carbon dating of water samples from the Perth Basin. An initial program of groundwater sampling in the Southern Perth Basin has indicated a regional rate of groundwater flow for the Yarragadee Formation of about 3 m/year and a hydraulic conductivity of about 6 to 7 m/day. A second program covering the Northern Perth Basin is in progress; 85 samples have been collected and are being processed.

The information obtained from these studies in the Perth Basin will be incorporated into a Bulletin on the Hydrogeology of the Perth Basin, which will be commenced in 1994–95.

The proposed Bulletin on the Geology and Hydrogeology of the Perth Metropolitan area has been completed, and is expected to be published by mid 1994–95. The Bulletin is the culmination of some 30 years of drilling, testing, and monitoring within the Metropolitan region in conjunction with the former Metropolitan Water Board and subsequently the Water Authority of Western Australia. Considerable redefinition of the geology of the area has been carried out together with assessments of available sustainable groundwater resources in each of the aquifer systems beneath Perth. Fresh insight has been provided in the assessment of recharge, groundwater flow, and discharge, and will greatly aid future management.

With the support of funding obtained during 1993–94, initially from the National Soil Conservation Program, and subsequently from the National Landcare Program, the development of a fully computerized database (AQWABase) has

proceeded according to the designed timetable. During the year the required hardware was purchased, the software for the database completed, and the linkage from the database to LIS capability developed. To date, information from more than 30 000 bore data cards have been entered into AQWABase, while five 1:250 000 and about 130, 1:50 000 bore location sheets have been digitized. The value of this database has already been demonstrated; data for a regional groundwater assessment, that would normally have taken several days to manually locate and plot, has been plotted and sorted in a few hours.

Two regional assessments are in progress at present. A review of the regional groundwater resources of the north Eastern Goldfields is currently being prepared for the Department of Agriculture of Western Australia (DAWA) as part of their Rangeland Survey program in the current Decade of Landcare. This follows a similar review of the Upper Murchison area, and will be followed by further reports for incorporation into the Yalgoo–Sandstone and Pilbara Rangeland Surveys.

A second regional assessment of groundwater resources, for the Busselton–Walpole region, is currently being undertaken for the Water Authority, as part of the Authority's continuing program of regional assessments of divertible water resources. The area covers two major geological units — the southern Perth Basin and the Yilgarn Craton — and the program is designed to locate prospective areas of substantial groundwater resources capable of development for future regional supplies or for major country water supplies, either



for domestic or for stock purposes. The study follows a similar study carried out in 1992–93, for the Albany – Mount Barker area, and will be followed by a comparable program in 1994–95 for the Pilbara Region.

Hydrogeological mapping has proceeded on schedule this year. Four 1:250 000 maps (KALGOORLIE, WIDGIEMOOLTHA, BOORABBIN, and KURNALPI) in the Goldfields have been completed; all except KURNALPI were in print at the end of June 1994. Hydrogeological mapping along the south coast, undertaken at the request of, and with technical support from, the Albany and Esperance offices of DAWA, has also achieved the stated goals. All fieldwork has been completed for

both ALBANY – MOUNT BARKER and ESPERANCE (1:250 000 sheets); the first draft of the former map is in editing, and the first draft of the latter nears completion. The maps have been prepared using the same techniques developed during the preparation of the Dumbleyung 'special' hydrogeological map. Because the maps are fully computer-drafted, the step from editing to publishing will be considerably reduced.

The Dumbleyung hydrogeological map was prepared at the request of, and funded by, the Dumbleyung Land Conservation District (LCD) from a grant obtained through the State Landcare Program in 1992–93. During 1993–94, the Dumbleyung LCD, with the assistance and advice of the GSWA, has interrogated the

hydrogeological information at catchment scales of 1:25 000 to 1:50 000, and designed catchment management plans to combat land and water salinization.

Two major funding proposals were formulated and submitted to the National Landcare Program for funding. If successful, they will result in a major hydrogeological mapping program to cover the Southwest Dryland Farming area of Western Australia, as part of the State's Farmwater Plan, and a major hydrogeological mapping program of the Blackwood River Catchment, aimed at providing the hydrogeological base for management of the resources of the catchment.

A. T. Laws

## Component 3.2.2

### Advisory services and investigations

**Objectives:** *To provide reliable, up-to-date advice on the distribution and quality of the State's groundwater resources to Government and the general public. To carry out investigations of the extent of groundwater contamination and pollution, and land and stream salinization as a basis for the provision of expert advice to Government Agencies with statutory responsibilities for environmental assessment, agricultural and water resources management, and health matters.*



Considerable work has been carried out in 1993–94 in the provision of technical advice and assistance to other Government departments, agencies and authorities, and the general public, but at the same time several in-house projects have been completed within the Section.

The main advisory services have been provided to the Water Authority for water resources investigations and management; to other Government departments (such as the Department of Environmental Protection (DEP) and the Department of Health) and to Local Government authorities on aspects of groundwater pollution and contamination; and to DAWA,

CSIRO, LCDs and others, on aspects of land and water salinization. Concurrent in-house investigations have looked at the wider aspects of groundwater contamination, with the provision of maps, technical reports, and guidelines, as appropriate, and at aspects of the effects of agricultural practices on groundwater resources.

Advisory services have been provided to the general public, mostly on the availability of groundwater resources for domestic, garden or farmwater supplies. Submissions to Parliamentary Committees have also been of particular importance.

#### *Activities and outcomes*

The provision of advice to the Water Authority is provided by a small seconded unit, and falls within three categories in the field of evaluation and assessment of groundwater resources for: the Perth Metropolitan Area; country towns and other areas; and aboriginal communities. In the Metropolitan area, major Authority drilling programs in the north coastal areas of Whitfords and Barragoon have been supervised as part of an investigation into the availability of groundwater resources to supply expansion of the Metropolitan area into the northwest corridor. The results of these investigations, and the

interpretation of the results, indicate the availability of significant sustainable groundwater resources.

In the provision of technical advice on groundwater resources for towns and other areas, there has been continued major involvement in the evaluation of existing monitoring data and irrigation bores and wells in the Carnarvon irrigation area, together with the successful completion of a major drought-proofing drilling program in the Gascoyne River flood plain. In the latter program, 26 investigation bores were drilled and a total sustainable supply of 12 500 m³/day was obtained from six production bores.

Successful investigation bores were also drilled for the Halls Creek and Esperance town water supplies, following intensive field investigations and site selection. An additional supply of 1000 m³/day was obtained for Halls Creek, whereas production bores are yet to be drilled for Esperance. Technical advice was also provided for several other country towns, and numerous town water supply-scheme reviews were appraised by the seconded unit. General advice to the Water Authority on day-to-day groundwater matters relating to the management of urban water supplies is an ongoing function of the unit.

Technical assistance in the location of water supplies for aboriginal communities continues to be provided, funded by the Aboriginal and Torres Straight Islanders Commission (ATSIC). In 1993-94, ten communities in the Pilbara, Central Reserves, and Mid-West regions were visited and a total of 60 sites were selected. In some areas, because of the difficulty of locating adequate supplies, on-site supervision of drilling was undertaken. Water supplies for all

communities were successfully located.

A considerable amount of advice and technical assistance on groundwater contamination and pollution has been provided to DEP and the Health Department concerning the location, delineation, treatment, and management of contaminated groundwater. Several minor and three major contamination incidents resulting from spills or leaks of chlorinated solvents, pesticides, and petroleum hydrocarbons were investigated. Numerous proposed and existing landfill sites and septage treatment facilities were assessed for the Health Department and Local Government authorities, and several environmental reviews were carried out for the DEP.

A detailed study has been undertaken into groundwater discharge of nutrients into Oyster Harbour, Albany, funded by the Waterways Commission. The study indicated that some 4 t per year of nitrogen and 0.4 t per year of phosphorus are discharged into the harbour, mostly through the unconfined aquifer. Proposed urban development in the region has the potential to increase the nitrogen flux considerably.

A detailed submission was prepared for, and a briefing given to, the Senate Select Committee on Metropolitan Development and Ground Water Supplies. Detailed input was also provided to the Senior Officers Group involved in the preparation of a policy for contaminated land and water in Western Australia. Successful adoption of the policy will lead to the development of a contaminated land and water registry for the State, with prime responsibility for the development and maintenance of the groundwater

aspects of the registry being vested in the GSWA.

During 1993-94, the Groundwater Vulnerability Maps and Explanatory Notes for the Perth Basin were published, highlighting the areas where shallow watertables and sandy soils combine to form areas of high vulnerability. In addition, three pamphlets, in a series of publications dealing with groundwater contamination issues, have been produced.

A detailed study of non-point source pollution in the Perth Basin has been commenced to complement a similar point-source study. About 3000 water samples have been collected from about 600 shallow bores and wells for field and laboratory analysis. Preliminary results indicate that the shallow groundwater of the Perth Basin is largely unaffected by serious contamination from pesticides or fertilizers.

With regards to advice related to groundwater and agriculture, detailed input has been made to the group formulating the Farmwater Plan (formerly the Farm Water Strategy). As part of this, under Component 3.2.1, funding has been sought for hydrogeological mapping. Detailed advice has also been provided to the working group reviewing the proposed Federal policies on riparian studies.

Detailed appraisal of data from mining-company reports over parts of the Ord River Irrigation Area (ORIA) has identified significant occurrences of gravel deposits likely to contain groundwater of sufficient quantity and quality to sustain or supplement irrigation. Under Component 3.2.4 an initial drilling program will be undertaken in June 1994, to be followed by a second, more detailed program in late 1994.

*A. T. Laws*

## Component 3.2.4

### Groundwater exploration

**Objectives:** To explore and assess the State's groundwater resources in a long-term program to promote and assist State development, landuse planning, and groundwater management by carrying out exploratory drilling.



The Groundwater Exploration Initiative (GEI) commenced in late 1993, following the formal approval of funding for the first of three years' activity. The program involved selection and initial assessment of twelve projects in nine areas, following a review of the proposed program by the GSWA Hydrogeology Subcommittee. The GEI mainly comprised a program of exploration drilling and construction of monitoring bores in each project area. Initial work, in late 1993, was carried out by permanent staff until additional contract staff could be recruited in

early 1994. Four new staff members are now working full-time on the GEI.

Funding for several of the projects was supplemented by external organizations:

- Water Authority of Western Australia
- Kimberley Development Commission
- Great Southern Development Commission
- Towerrinning Catchment Group.

The drilling was completed in all but two of these project areas within the 1993–94 financial year, despite the late start to the program. The budget allowance was not exceeded.

#### *Project activities and outcomes*

Table 1 summarizes the purposes and outcomes of each of the programs.

The programs undertaken south of Perth confirmed several localized

Table 1. Summary of the Groundwater Exploration Initiative 1993–94

Project	Program	Results
Albany	Investigation of potential for low-salinity groundwater and support for hydrogeological mapping	Low-salinity groundwater in three areas within Plantagenet Group sediments
Boscabel	Investigation of low-salinity groundwater in the Kojonup area	Fresh groundwater along approximately 7 km of palaeochannel
Boyup and Wilga Basins	Initial assessment of two small basins in Donnybrook – Boyup Brook area	Low-salinity groundwater at shallow depth in the Wilga Basin; remainder brackish
Esperance	Hydrogeological mapping support	Groundwater brackish to saline
Greenough Shallow	Completion of long-term study of Swan Coastal Plain	Brackish groundwater
Manjimup Sedimentary	Ongoing exploration for low-salinity groundwater	Potentially useful aquifer; salinity variable
Manjimup Fractured Rock	Initial investigation of potential quartzite aquifers	Low-salinity groundwater at all sites
Nabawa	Initial investigation of the Nabawa sandplain	Mainly brackish water
Onslow (Ashburton River)	Investigation of sediments of the Ashburton River floodplain	Mainly brackish water, even in palaeochannel sediments
Onslow (Cane River)	Investigation of the Birdrong Sandstone near the Cane River	Fresh groundwater near Cane River; brackish at greater distance
Ord River Irrigation Area	Investigation of hydrogeology and the potential of using groundwater for irrigation near Kununurra	Gravel/sand aquifer in two areas; drilling still in progress
Towerrinning	Investigation of low-salinity groundwater in the Lake Towerrinning – Duranillin area	Low-salinity groundwater identified along approximately 7 km of palaeochannel

occurrences of low-salinity groundwater in different hydrogeological environments, all within the Yilgarn Craton. The aquifers include Tertiary sands, both in shallow basins (Manjimup) and palaeochannel deposits (Boscabel and Towerinning), and also fractured Proterozoic quartzites (Manjimup). This is an outcome of considerable local significance, since the results point to the potential availability of low-salinity groundwater resources that may be sufficient to support new developments in some areas. These areas, and others with similar groundwater potential, warrant further investigation.

Studies which elucidate the regional hydrogeology of low-lying areas

within the wheatbelt, such as the Boscabel–Towerinning Project, are also important in the context of land management. Much current 'landcare' work relies of necessity only on shallow drilling, and the conclusions drawn may be handicapped by lack of knowledge of broader-scale hydrogeological systems and processes.

To the north of Perth, the Greenough Shallow Project completed several decades of investigations into the superficial deposits of the Swan Coastal Plain. Although the groundwater that was identified there is brackish, it is nevertheless a resource which may be developed at some stage. The program also provided valuable geological information

about the Mesozoic formations in a little-known part of the Perth Basin. Initial appraisal of the Nabawa and Ashburton floodplain programs suggests that neither area has much potential for groundwater beyond small stock and domestic supplies. Some groundwater in the Cane River area is low in salinity and further evaluation of the magnitude of the resource may be worthwhile.

Drilling in the Ord River Irrigation Area was delayed by difficulties in obtaining clearances for drillsites, and the work (Stage 1 of a two-stage study) is expected to be completed in August 1994.

*J. D. Waterhouse*

### Subcomponent 3.3.1.1 Dams and damsites

**Objective:** *To undertake geotechnical investigations necessary to provide appropriate advice to the Water Authority in connection with proposed damsites, dams under construction, or existing dams and ancillary works.*



This year saw the culmination for the GSWA of approximately 57 years of site investigations at the North Dandalup Dam site, south of Perth. The Water Authority completed the construction of the 60 m-high North Dandalup Main Dam and the 12 m- and 20 m-high Saddle Dams in 1994.

This year, the Engineering Geology Section (EGS) was involved with site mapping of the left abutment of the Main Dam foundation, the spillway chute, the rock quarry, and construction documentation.

The foundation rock and the quarry conditions defined during the investigations were generally confirmed during the excavation of what were probably three of the largest continuous hard-rock exposures ever seen in the Darling Ranges. Advice provided to the Water Authority assisted with the positioning of the excavated surface of the foundation for the earth core, in addition to the spillway-crest block foundation.

Although the North Dandalup Dam will possibly be the last

dam constructed by the Water Authority for some years, the EGS also provided site investigation assistance for the Lower South Dandalup scheme, located near Pinjarra, where there is a pipehead dam located in a steep, rocky valley, which one day may be developed as a major storage dam. During the year, EGS mapping provided input to preliminary design concepts and costings, so that appropriate dam design selection could be completed.

*I. H. Lewis*



### Subcomponent 3.3.1.2

#### Foundation and construction materials

**Objective:** To undertake field investigations and provide advice on foundation conditions and the suitability of geological materials for use in Government construction projects.



The scenic town of Bremer Bay in the southeast of the state is the location of investigations for a proposed small boat harbour. Big swells rolling in from the Southern Ocean frequently cause problems for the local fishing fleet, and the Department of Transport are designing a safe harbour for them. The EGS have been involved in the assessment of sources and quality of possible natural rock materials from which to build the breakwater. Field-reconnaissance and drilling programs have been completed this year. The documentation to be prepared by the EGS will provide input to the quarrying tender documentation so that an accurate picture of

subsurface conditions will be available to possible contractors.

A horrific fatal accident involving a run-away semi-trailer occurred on the Greenmount Hill section of the Great Eastern Highway. Main Roads Western Australia requested EGS to participate in an investigation of foundation conditions for the installation of arrestor beds. Arrestor beds, which consist of contained deposits of gravel materials, are to be installed alongside the road alignment to provide safe stopping points for vehicles with brake problems. The EGS supervised a program of drilling and testing in situ, and has prepared a report which will be

made available by Main Roads for foundation design and contract tender purposes.

Many engineering organizations are becoming 'Quality Assured', and require that other service groups also have quality standards. To this end, EGS have arranged for the most experienced Engineering Geologist in the State to prepare a complete and comprehensive site-investigation manual, which is designed to be the standard procedures manual for all investigations performed in the future by the EGS. This document promises to be a 'best seller' with potential applications in most engineering organizations.

I. H. Lewis

### Subcomponent 3.3.1.3

#### Geotechnical data

**Objective:** Develop appropriate geotechnical data storage, retrieval, and manipulation facilities for use in civil and mining geotechnical applications.



#### Perth geotechnical database

The flurry of building activity in the Perth Central Business District (CBD) during the 1980s and earlier building booms has indirectly resulted in the accumulation of a vast amount of scientific data. This data, which is now available to the EGS, will be used to solve some of the geological mysteries of the past, while at the same time providing valuable preliminary information during the site-

investigation and foundation-design stage of future building projects.

As a result of collaboration between the EGS, the Perth City Council, and leading geotechnical consultants, geotechnical reports of site investigations performed within the CBD area have been made available. Personnel from the EGS have established a pilot geotechnical database for a small study area within the CBD. The

pilot study was successful in producing geological, geotechnical, and hydrogeological plans, sections, and graphs by utilizing an ArcInfo GIS. The scope of the studies will be enlarged to cover the whole of the Perth CBD area, with the aim of producing subcrop and other geological and geotechnical maps. It is also planned to use ArcView software to allow user groups to inspect and manipulate data, for their own uses.

### Tailings storage database

Tailings are the fine-grained waste products left after mine and industrial processing is complete. Tailings are commonly transported to their storage sites hydraulically, and large volumes of process fluids with contained chemicals are frequently retained with the tailings in the storages. Historically, tailings have been sources of pollution and land degradation due to uncontrolled releases, dusting, and seepage, as well as remaining as aesthetically ugly landforms with no other possible landuses.

The EGS has progressively developed a database of information

on 142 mine sites and 272 separate storages, with information derived from reports provided to MOD as part of the mining-approval process. This data will be utilized to understand the present standards operating in the industry, and will be updated progressively to monitor design standards and conditions.

### Openpit database

During the late 1980s and early 1990s there was considerable interest in the use of cable-bolt reinforced pit walls in the Western Australian mining industry. There was, and still is, no rational and

comprehensive design methodology for the selection of reinforcement for openpit walls. As the result of a number of wall failures, there has been a trend away from using cable bolts in openpit walls.

A database using dBase IV has been established to record some of the geotechnical information associated with openpit mines. The information recorded focuses on the geotechnical conditions associated with reinforced openpit walls. The aim of the database is to determine the likely influence of the reinforcement in pit walls by enabling steeper wall designs to be used.

I. H. Lewis

## Subcomponent 3.3.1.4 Geophysical investigations and advice

**Objective:** To undertake geophysical investigations for other government agencies and provide geophysical advice when requested.

A series of electrical resistivity soundings and traverses were made as part of a MERIWA-sponsored project coordinated by the EGS to investigate subsidence detection in the Collie area.

In recent years there has been a dramatic reduction in the number of requests received from other sections of the GSWA and from other agencies for shallow geophysical engineering site-investigation services. A review of the structure and objectives of the

Geophysics Section concluded that the shallow geophysical site investigation services that had been provided by the Section in the past could be carried out more economically by external (private sector) suppliers, particularly considering the cost of replacement of the Geophysics Section's aging equipment asset base and the need to maintain specialist field staff. In view of the increased importance of regional geophysics as a support for and a complement to geological and geochemical mapping, the focus of

the Geophysics Section was altered from providing engineering site-investigation services to providing project coordination services for regional geophysical mapping (see report under Component 3.1.3).

By the end of March 1994, the Section was no longer providing any investigatory services. However, advice regarding the applicability of such services will still be given as appropriate to other Sections of the GSWA and to other agencies.

S. H. D. Howard



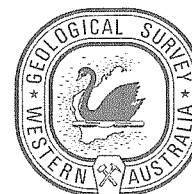
## Program 6.0

### CORPORATE SERVICES

#### Component 6.3.3

#### Library and information services

**Objective:** To respond appropriately and efficiently to the geoscientific information needs of the Department, minerals and petroleum industry, educational institutions, and the general public.



#### Library

During the year the number of public users of the library increased by 11% compared with the previous year, and the number of users of microfilm facilities for access to open-file exploration reports increased by 16%. These figures reflect the high level of mining and exploration activity over the past year and the consequent increase in demand for library services. The Library continued to focus on the provision of reference information services and viewing facilities to successfully meet the increased demand. The positive public response to on-line access to WAMEX continued.

#### Implementation of an automated Library system

Acquisition in 1993 of the Oracle Libraries software package will significantly increase the efficiency of Library operations and provide a more responsive and effective service. Industry and public users will have access to the on-line catalogue through a PC in the Library.

Customization of the Oracle system to meet the Department's needs, and extensive testing, took place in 1993–94. Internal policies and procedures were determined and documented to ensure that a quality database is established and maintained. An implementation strategy has been formulated to provide for systematic uptake of

data and the new system will be operational in the first half of 1994–95.

#### Production of Library services information brochures

The Library commenced the production of a series of information brochures designed to increase client awareness of Library services available. A brochure describing databases that can be accessed through the Library was printed during the year. Brochures covering access to open-file mineral and petroleum exploration company data (WAMEX and WAPEX) are planned for 1994–95.

#### Museum

Some progress was made during 1993–94 in the further development of the Museum as an educational resource centre. The newly completed interactive model — 'Mining and our Way of Life' — and its accompanying Fact Sheet and quiz were enthusiastically received by visiting school groups (Fig. 16).

Contact has been established with the Secondary Schools Geology Syllabus Coordinator and a one-hour lesson on mineral identification has been developed and presented in the Museum to a number of schools. Several other lessons are planned and will be trialed on classes from Trinity College.

During the year the Museum mineral collection was reviewed and evaluated with a view to replacing inappropriate or damaged specimens, and renewing labelling and catalogues.

#### Promotional material

The style and presentation of GSWA geoscientific publications was reviewed during 1993–94. A more up-to-date and attractive cover format was designed and put into production for Bulletins, Reports, Explanatory Notes, and Records. A new series of Explanatory Notes was initiated for 1:1 000 000-scale geological mapping, and it was decided to commence publication of a new Annual Review in 1994.

A 1993 edition of the 'Overview of Minerals and Energy in Western Australia' was published and distributed. In addition to providing the basic platform to satisfy general enquiries, this publication continues to be used by the Chamber of Mines and Energy in their teacher education program.

In September 1993, a new edition of the GSWA Catalogue of Publications was published and a new, colourful catalogue of geoscientific maps was released.

Basic geoscientific text and illustrations were provided to the Communications Branch and subsequently published by them

in the Fact Sheet series on the following subjects:

- Geology of the North West Cape
- Geology of Kennedy Range
- The Bungle Bungles
- Nickel
- Tin, tantalum, and lithium.

Educational resource kits containing rock and mineral specimens, fact sheets, information booklets, and maps were supplied to 38 schools during 1993–94.

Displays were mounted and sales booths staffed at the following conferences during 1993–94:

- Kalgoorlie '93
- Australian Society of Exploration Geophysicists Conference
- Gold '94.

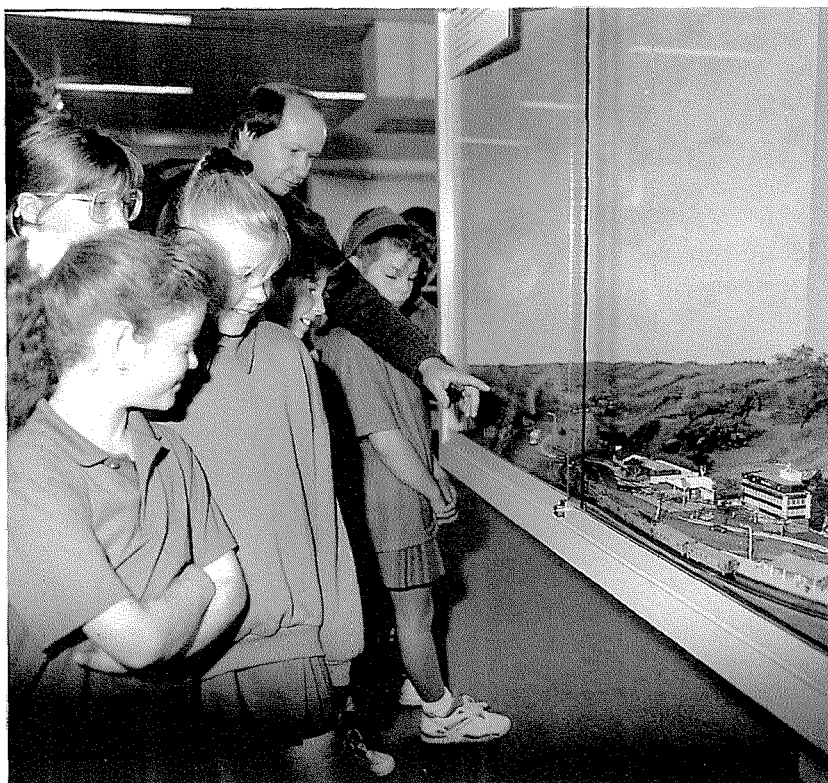


Figure 16. Students on an educational tour of the Geological Survey Museum in the Department of Minerals and Energy

### *Public enquiries*

General enquiries on geology and mining in Western Australia were received and responded to at a rate of approximately 100 per month. Areas covered included information

and assistance for prospectors, tourists and amateur fossickers, urban geology for landowners,

mining and its environmental implications, and educational geology for teachers and students.

A. S. Forbes





# Appendices

<b>Publications released 1993–94 .....</b>	<b>147</b>
<b>Organization chart .....</b>	<b>150</b>
<b>Staff list .....</b>	<b>151</b>
<b>List of acronyms and abbreviations .....</b>	<b>154</b>





## Publications released 1993–94

### Reports

31. A structural study of the southern Perth Basin, Western Australia
34. Professional Papers
  - (1) Salinity control by groundwater pumping at Lake Toolibin, Western Australia;
  - (2) The geology and hydrogeology of the superficial formations between Cervantes and Lancelin, Western Australia;
  - (3) The location and significance of point sources of groundwater contamination in the Perth Basin;
  - (4) Proposed stratigraphic subdivisions of the Marra Mamba Iron Formation and the lower Wittenoom Dolomite, Hamersley Group, Western Australia;
  - (5) Lithology and proposed revisions in stratigraphic nomenclature of the Wittenoom Formation (Dolomite) and overlying formations, Hamersley Group, Western Australia;
  - (6) Further isotopic evidence for the existence of two distinct terranes in the southern Pinjarra Orogen, Western Australia;
  - (7) Cainozoic stratigraphy in the Roe Palaeodrainage of the Kalgoorlie region, Western Australia;
  - (8) Municipal waste disposal in Perth and its impact on groundwater quality;
  - (9) Palynology and correlation of Permian sediments in the Perth, Collie, and Officer Basins, Western Australia;
  - (10) Hydrogeology of the Collie Basin, Western Australia.
35. Geology of the granite–greenstone terrane of the Kalgoorlie and Yilmia 1:100 000 sheets, Western Australia
36. Archaean mafic and ultramafic volcanic rocks, Menzies to Norseman, Western Australia
37. Professional Papers
  - (1) Geology and hydrogeology of the Karridale Borehole Line, Perth Basin;
  - (2) The impact of stormwater infiltration basins on groundwater quality, Perth Metropolitan Region;
  - (3) Mafic dykes in the Williams–Wandering area, Western Australia;
  - (4) Chlorine-36 and carbon-14 measurements on hypersaline groundwater in Tertiary palaeochannels near Kalgoorlie, Western Australia;
  - (5) Sm–Nd model ages of granitoid rocks in the Yilgarn Craton;
  - (6) Hydrogeology of the Robe River alluvium, Ashburton Plain, Carnarvon Basin;
  - (7) Hydrogeology of the Fortescue River alluvium, Ashburton Plain, Carnarvon Basin.
38. Geology and Permian coal resources of the Collie Basin, Western Australia
39. Gold mineralization in the Menzies–Kambalda region, Eastern Goldfields, Western Australia
41. Proterozoic rocks on the Glengarry 1:250 000 sheet — stratigraphy, structure and stromatolite biostratigraphy

**Geological maps****1:100 000 series**

ANGELO  
ARROWSMITH – BEAGLE ISLANDS  
DOCKRELL  
EDJUDINA–YABBOO  
HILL RIVER – GREEN HEAD  
KURNALPI  
MULGABBIE  
NORSEMAN  
PARABURDOO  
PINJIN

**1:250 000 series**

KALGOORLIE (2nd edition)  
LENNARD RIVER  
  
EDMUND (reprint)  
MENZIES (reprint)  
KALGOORLIE (hydrogeology)

**Project maps**

Report 39, Plates 1A and 1B: Gold deposits of the Menzies–Kambalda Belt, Eastern Goldfields Province (1:100 000)

Report 39, Plate 2: Geology of selected portions of the Menzies–Boorara Shear Zone (1:25 000)

Geology of the Archaean Kalgoorlie Terrane (reprint)  
northern sheet (1:250 000)  
southern sheet (1:250 000)

Groundwater vulnerability to contamination  
southern part of Perth Basin (1:500 000)  
northern part of Perth Basin (1:500 000)

Wells drilled for petroleum in Western Australia  
Sheet 1: Western Australia (1:2 500 000)  
Sheet 2: Carnarvon Basin North (1:500 000)  
Sheet 3: Canning Basin North (1:500 000)  
Perth Basin North (1:500 000)

**Explanatory Notes****1:100 000 Geological Series**

DAVYHURST  
DUNNSVILLE  
KURNALPI  
MELITA  
MENZIES (and adjacent Ghost Rocks area)  
NEWMAN  
PARABURDOO

**1:250 000 Geological Series**

LENNARD RIVER (3rd edition)  
YAMPI

**Records**

- 1992/5** Explanatory notes on the LENNARD RIVER 1:250 000 geological sheet, Western Australia (third edition)
- 1992/11** Geology of the PARABURDOO 1:100 000 sheet, Western Australia
- 1992/13** Gold deposits of the Menzies and Broad Arrow areas, Western Australia
- 1992/14** Gold deposits of the Mt Pleasant–Ora Banda areas, Western Australia
- 1992/15** Gold deposits of the Kalgoorlie–Kambalda–St Ives areas, Western Australia
- 1993/1** Geological Survey of Western Australia — Work program for 1993–94
- 1993/6** Explanatory notes for the Perth Basin groundwater contamination vulnerability map
- 1994/2** The geology and mineral resources of the proposed Dampier Archipelago National Park



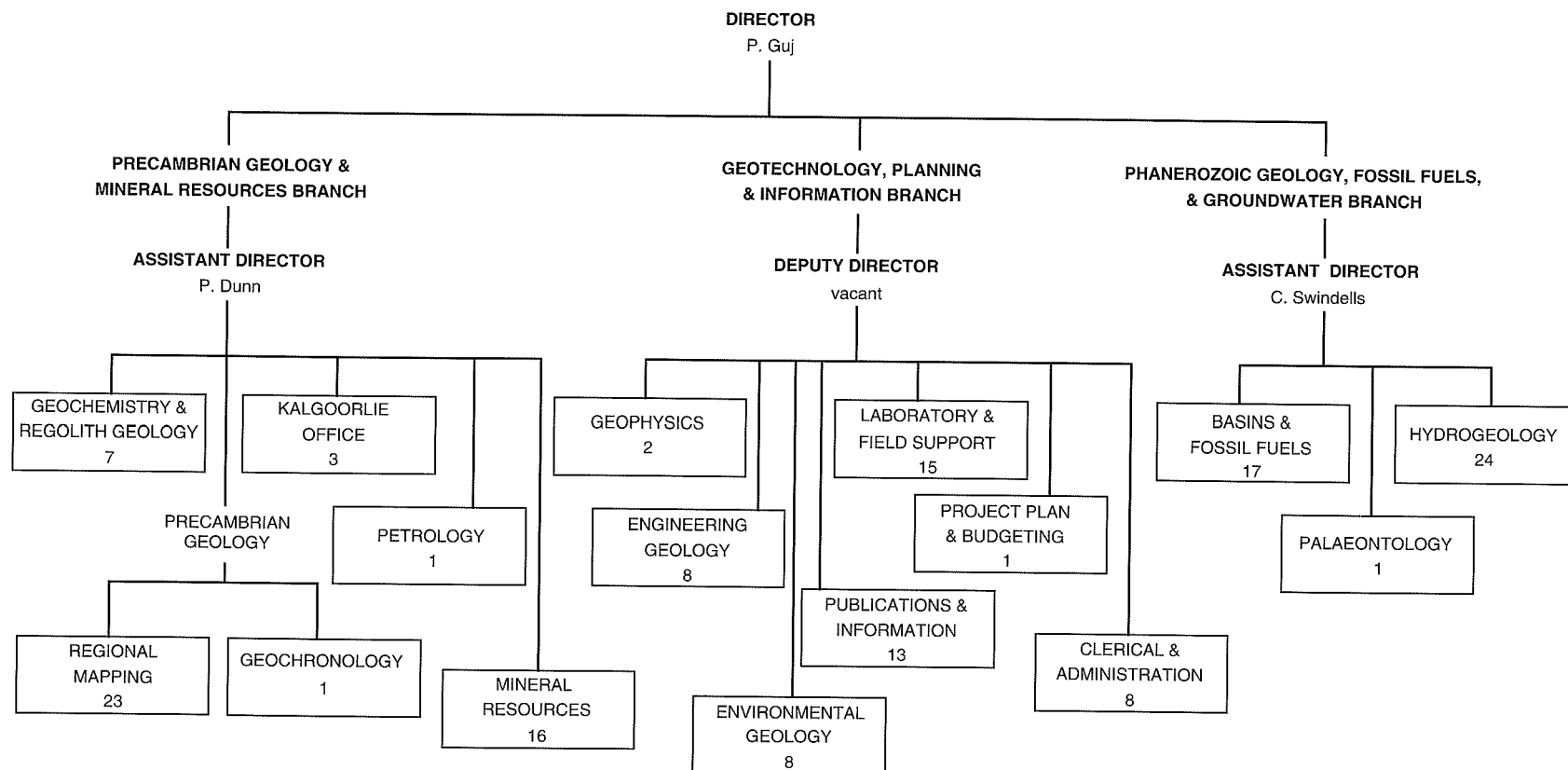
- 1994/7** Explanatory notes for the hydrogeological map and groundwater database of the Dumbleyung Land Conservation District, Western Australia

***Miscellaneous publications***

An Overview of Minerals and Energy in Western Australia  
Guidelines for groundwater monitoring at municipal landfill sites  
Geological and hydrogeological guidelines for landfill site selection  
A review of deep-well injection and its applicability in Western Australia  
Catalogue of geological maps

**Fact sheets**

- 19.** The Bungle Bungles  
**22.** Tin, tantalum and lithium  
**23.** Geology of the North West Cape  
**24.** Geology of the Kennedy Range



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA  
ORGANIZATION CHART AS OF  
30 JUNE 1994  
Numbers indicate personnel assigned to each section (n = 152)



## Staff list

(30 June 1994)

GUJ, Pietro (Director)

### *Geotechnology, Planning, and Information Branch*

Vacant (Deputy Director)

#### **Engineering Geology**

BRICE, Stephen  
JACKSON, Michael  
LANG, Adrian  
LEWIS, Ian  
MANNING, Philip  
MISICH, Ian  
RANASOORIYA, Jayantha  
STEWART, Douglas

#### **Environmental Geology**

CARR, William (Bill)  
FREEMAN, Michael  
HASSAN, Lee  
LEONHARD, Edward (Laz)  
NOVAK, Vera  
SIMMS, Virginia  
SMURTHWAITE, Anthony  
TUCKER, Quinton

#### **Publications and Information**

CROSS, Robert  
DAW-SMITH, David  
FERDINANDO, Darren  
FORBES, Alex  
GRIEW, Jane  
JOHNSTON, Jean  
KNYN, Brian  
MIKUCKI, Jennifer  
NOWAK, Ian  
RAMSEY, Byron  
STRONG, Caroline  
THOM, Julia  
THOMAS, Hugh

#### **Laboratory and Field Support**

AGOSTINELLI, Joanne  
BONER, Peter  
BRADLEY, John  
BRZUSEK, Marianna  
DOMBROWSKY, Peter  
FAIR, John  
HOLMES, Mario  
LOCKYER, Stuart  
MOORE, Brian  
PAPICCIO, Marlene  
REID, David  
RICKETT, Melanie  
WALLACE, Steven  
WILLIAMS, Gary  
WILLIAMS, John

#### **Clerical and Administration**

BRADSHAW, Brian  
BRITNELL, Christine  
DURR, Kathryn  
IPSARO-PASSIONE, Louise  
LAPTHORNE, John  
NOONAN, Kathleen  
PETROVIC, Lidija  
STOYANOFF, Nell

#### **Geophysics**

HOWARD, David  
WATT, John

#### **Program Planning and Budgeting**

FETHERSTON, Michael

***Precambrian Geology and Mineral Resources Branch***

DUNN, Peter (Assistant Director)

**Geochemistry and Regolith Geology**

BRADLEY, Daniel  
 DAVY, Richard  
 FAULKNER, Joan  
 GOZZARD, Bob  
 KOJAN, Chris  
 STOREY, Jeremy  
 SUBRAMANYA, Anil

**Mineral Resources**

ABEYSINGHE, Pathmasekara (Abey)  
 ALLEN, Karen  
 BLOCKLEY, John  
 FERGUSON, Kenneth  
 JONES, Katherine  
 LESIAK, Irena  
 MASON, Jan Sandra  
 McCORQUODALE, Fiona  
 McGORRIN, Yvonne  
 PAGEL, Jutta  
 PRESTON, William (Bill)  
 RUDDOCK, Ian  
 SEARLES, Pamela  
 STAPLETON, Gladys  
 TOWNSEND, David  
 WITT, Walter

**Petrology**

LEWIS, John

**Precambrian Geology**

ADAMIDES, Nicos  
 BAGAS, Leon  
 CAREW, Eugene  
 CLARK, Dean  
 DAWES, Peter  
 GRIFFIN, Tim  
 HICKMAN, Arthur  
 LANGFORD, Richard  
 LE BLANC SMITH, Guy  
 LIU, Songfa  
 MARCOS, George  
 MAYER, Ian  
 MYERS, John  
 NELSON, David  
 OCCHIPINTI, Sandra  
 PERHAM, Sandra  
 PIRAJNO, Franco  
 SHEPPARD, Steve  
 SMITHIES, Hugh  
 THORNE, Alan  
 TYLER, Ian  
 WILLIAMS, Ian

**Kalgoorlie Office**

FARRELL, Terry  
 WESTAWAY, Jane  
 WYCHE, Stephen

***Phanerozoic Geology, Fossil Fuels, and Groundwater Branch***

SWINDELLS, Chris (Assistant Director)

**Hydrogeology**

ALLEN, Anthony  
 APPLEYARD, Stephen  
 BACHE, Dixie  
 BADDOCK, Leonard  
 COMMANDER, Phillip  
 COOPER, Sandra  
 DAVIDSON, Angus  
 FARRELL, Pauline  
 GESTE, Peter  
 HEPBURN, Jane  
 HIRSCHBERG, Klaus  
 KERN, Alex  
 KOOMBERI, Hazli  
 LAWS, Anthony  
 MARTIN, Michael  
 NIDAGAL, Viswanath  
 NIXON, Richard  
 PRANGLEY, Chad  
 SADGROVE, Geoffrey  
 SKIDMORE, David  
 SMITH, Robin  
 THORPE, Peter  
 WARDEKI, Hannah  
 WATERHOUSE, John

**Basins and Fossil Fuels**

ADAMS, Christopher  
 ALEXANDER, Leanne  
 ARATHOON, Claudette  
 CHEVTCHENKO, Serguei  
 COPP, Iain  
 CROSTELLA, Angelo  
 DE LEUW, Lorraine  
 FRIDAY, Corina  
 HAWORTH, Jeffrey  
 HOCKING, Roger  
 HOGAN, Susan  
 HOLLAND, Trevor  
 IASKY, Robert  
 LIVINGSTONE, Elissa  
 LOPEZ, Annabelle  
 MORY, Arthur  
 PLAYFORD, Philip  
 SVALBE, Andrew  
 WONG, Henrietta

**Palaeontology**

BACKHOUSE, John



**Staff changes 1993–94****Commencements***Basic program*

ADAMS, Christopher  
 CHEVTCHENKO, Serguei  
 CROSTELLA, Angelo  
 IPSARO-PASSIONE, Louise

MISICH, Ian  
 THOM, Julia  
 MANNING, Philip

*New Initiatives*

ADAMIDES, Nicos  
 AGOSTINELLI, Joanne  
 BRADLEY, Daniel  
 DAWES, Peter¹  
 FAULKNER, Joan  
 FERDINANDO, Darren  
 HASSAN, Lee  
 HOGAN, Susan  
 HYMUS, Patricia  
 LIU, Songfa  
 MIKUCKI, Jennifer

NIXON, Richard  
 OCCHIPINTI, Sandra  
 PIRAJNO, Franco  
 PRANGLEY, Chad  
 RAMSEY, Byron  
 RICKETT, Melanie  
 SKIDMORE, David  
 STOREY, Jeremy  
 SUBRAMANYA, Anil  
 WATERHOUSE, John  
 WESTAWAY, Jane

**Resignations**

BEVERIDGE, Peter  
 FAHMY, Hassan  
 JOHNSON, Nigel  
 KENT, Stephan  
 LUCK, Graham  
 MATHER, Philip  
 VINES, Greg

**Secondment / study leave**

CLARKE, John²  
 COLDICUTT, Sue-Ellen²  
 MORRIS, Paul³  
 SWAGER, Cees¹

**Retirement**

KEVI, Lazlo

¹ Scientific exchange with Greenland

² Seconded to the Office of Traditional Land Use

³ Study leave in Japan



## List of acronyms and abbreviations

---

ABS	Australian Bureau of Statistics
AGSO	Australian Geological Survey Organisation
AMF	Australian Mineral Foundation
APEA	Australian Petroleum Exploration Association Limited
ASEG	Australian Society of Exploration Geophysicists
AusIMM	Australasian Institute of Mining and Metallurgy
BIF	Banded-iron formation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAWA	Department of Agriculture of Western Australia
DME	Department of Minerals and Energy
EGS	Engineering Geology Section
FESWA	Formation Evaluation Society of Western Australia
GIS	Geographical Information System
GSWA	Geological Survey of Western Australia
LCD	Land Conservation District
MERIWA	Minerals and Energy Research Institute of Western Australia
MINEDEX	Mines and mineral deposits information database
MOD	Mining Operations Division
NGMA	National Geoscience Mapping Accord
PESA	Petroleum Exploration Society of Australia
USGS	United States Geological Survey
WAMEX*	Western Australian Mineral Exploration Index
WAPEX*	Western Australian Petroleum Exploration Index

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