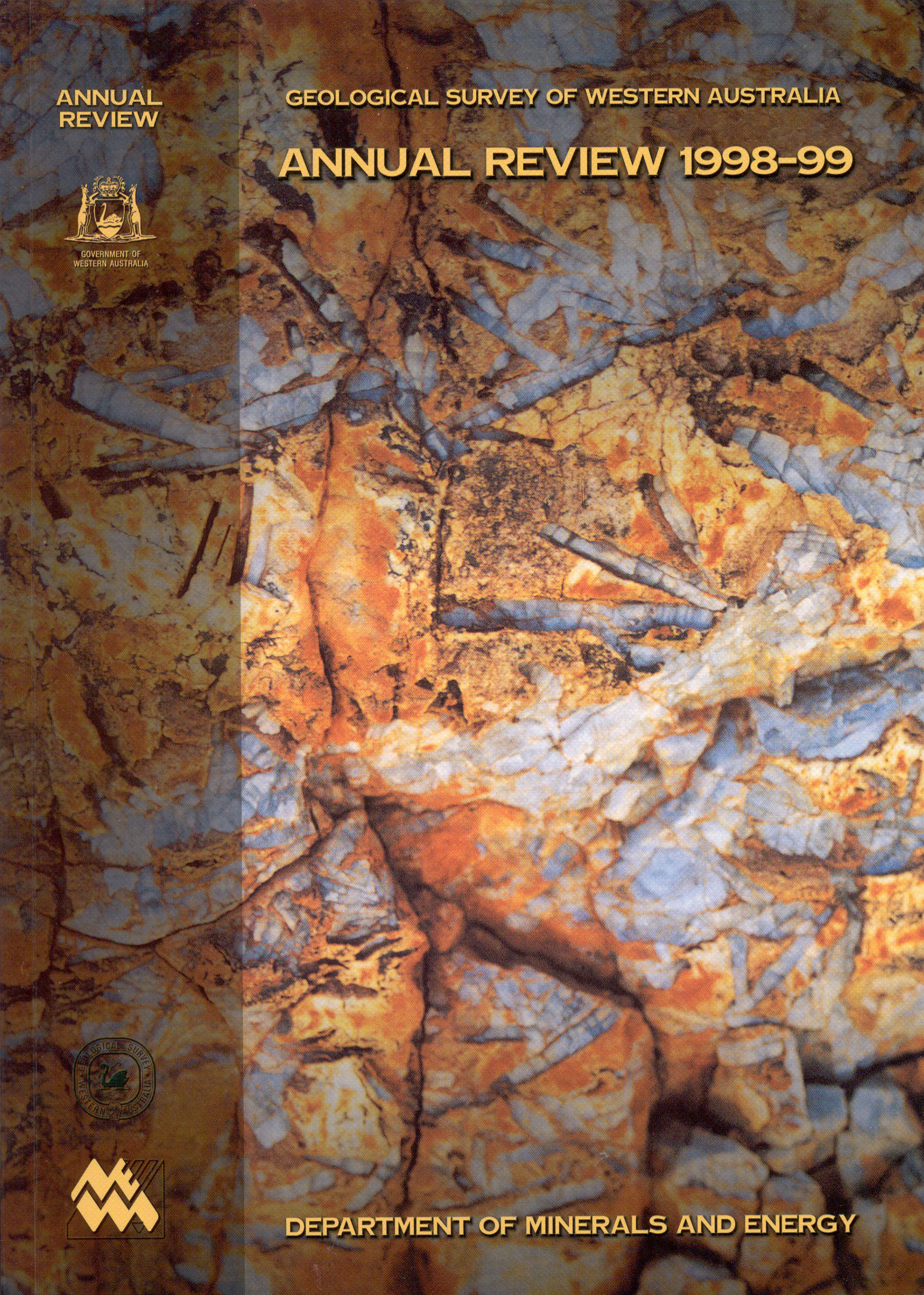
ANNUAL REVIEW

GOVERNMENT OF WESTERN AUSTRALIA

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 1998-99



DEPARTMENT OF MINERALS AND ENERGY

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA ANNUAL REVIEW 1998–99

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Cover:

Prismatic barite crystals in ferruginous chert, Dresser Formation, from the North Pole area on the NORTH SHAW 1:100 000 sheet, in the northern part of the Pilbara Craton. The barite crystals are approximately 2 cm in length.

Frontispiece:

Evidence of early life — 3.45 Ga fossil stromatolites from near Marble Bar in the eastern Pilbara region, Western Australia. The surface consists of three-dimensionally preserved conical stromatolites, and was recently presented to the Western Australian Museum for public display (photograph by Tyrone Knights Photography).

Contents

GSWA mission statement

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

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

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

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

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

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

The year in review

by David Blight

For industry-based geologists 1998–99 has been a particularly tough year. Confidence in the ability of explorationists to succeed has been eroded by sentiments fuelled by low commodity prices, particularly gold, perceived problems with the Asian economy, the difficulties of land access associated with the native title process, and the difficulties being experienced by smaller public companies in raising risk capital. Anecdotal evidence suggests that the resultant unemployment amongst geologists is now worse than that experienced at the end of the nickel boom in the early 1970s.

There are several risks to Australia associated with this downturn. Apart from the personal issues associated with employment, the country runs a real risk of losing valuable expertise both in the short-term, as geologists seek employment overseas, and in the long-term as geologists pursue alternative employment or business opportunities. Another long-term concern is that because exploration spending is low now, the real effect will impact in 10–15 years, as reserves currently being depleted are not replaced through discovery. While the mining industry is a large direct employer, it also has a significant effect on the general population and the Western Australian economy through a 3.5-times multiplier effect. Furthermore, its impact on the regional communities is far greater than on urban communities.

Such employment crises affecting geologists in the exploration industry are thankfully cyclic in nature, and there is no doubt in my mind that employment prospects will improve given time. In the meantime, the Geological Survey of Western Australia (GSWA) has varied its program and plan where possible to provide assistance in these difficult times. It is also pleasing to note the emergence of a self-help group called AGSEAN (Australian Geologist Skills and Employment Advancement Network). This apolitical group has highlighted, to the wider community, the poor state of the industry and the ramifications of unemployment among geoscientists.

The Australian Geological Survey Organisation (AGSO) has also suffered during this downturn. Federal funding to this organization has been reduced substantially, resulting in the need to shed approximately 90 positions. The most significant impact of this reduction on Western Australia was cuts to the Minerals Program and, in particular, the commitment to the National Geoscience Mapping Accord (NGMA). Nearly half the staff reductions were associated with the Minerals Program and NGMA activities for 1999–2000 have been put on hold to fund redundancies. The GSWA will endeavour to pick up much of the work not undertaken by AGSO, but will need to do this in the light of its own program and funding issues.

Highlights

Despite this gloom, I can report that 1998–99 was a productive year for GSWA. We published 28 maps (at various scales), 57 manuscripts, and five digital datasets, including topographical, geological, geophysical, geochemical, geochronological, and mineral occurrence data. This output, while slightly less than the previous year, nevertheless represented a 5% real productivity improvement. I am continually impressed with the attitude of GSWA staff as they strive for continuous improvement. Over the last five years, GSWA has delivered in excess of 5% real productivity improvement per annum.

One of the maps produced was the 1998 State Map — 'Geological map of Western Australia', 13th edition. New State geological maps, usually at a scale of 1:2 500 000, are published approximately every 10 years. This map was doubly significant because it represented the swansong for Dr John Myers, who retired from GSWA following the publication of this map. Dr Myers, who had been with GSWA since 1983, was the Chief Geoscientist and as such, with the assistance of Roger Hocking, was responsible for compiling this map, which summarizes advances made in understanding the geoscientific framework of Western Australia. The new map features several innovations, including the use of satellite-derived gravity data to interpret offshore structures, plotting of impact sites, and provision of depth-to-basement contours in sedimentary basins.

This map pushed our cartographic skills to the limit because it contains an enormous amount of information, but still allows viewers to stand back and obtain an immediate appreciation of the major geological elements of the State.

Following on from the successful GSWA '98 open day, we decided to run GSWA '99. This day-long event showcased recent work undertaken by GSWA, both in formal presentations and through poster displays, which were continuously staffed by geologists working on the various projects. Attendance at GSWA '99 was up on GSWA '98 and I believe it is an excellent method of transferring geoscientific information from GSWA to the minerals and petroleum industries. The highlight of GSWA '99 was the launch of the new State Map by Mr Ian Satchwell, CEO of the Chamber of Minerals and Energy of Western Australia.

At GSWA '99 we also previewed, for the first time, the 1:100 000-scale 'seamless' digital map of the Eastern Goldfields region. This map has been in development for about 2 years and is, I believe, a forerunner of the way GSWA will approach mapping in the future. As areas are mapped at 1:100 000 scale, these various 'tiles' will be integrated in digital form into a seamless map, which will be maintained and updated on a continuous basis. Hardcopy maps of any area within the seamless coverage can be plotted on demand.

Western Australia was host to the Chief Government Geologists Conference in April 1999. This two-day conference provides an important forum for examining issues affecting the role of Geological Surveys in the Australasian exploration industry. One of the most important outcomes of this year's conference was the adoption of national guidelines for the submission by exploration companies of geoscientific reports to government, in digital form. Uniform guidelines adopted by all States will mean that exploration data are more usable by companies undertaking exploration in the future and that companies working in more than one State do not have to meet a variety of reporting requirements. The guidelines adopted were essentially those developed by GSWA in consultation with industry. Because Western Australia hosted the Chief Government Geologists Conference it was in a position to recognize that although all States were developing their own guidelines, they all had very common themes and approaches. It was then able to coordinate these developments, leading to a set of national guidelines. In recognition of this changed approach to archiving data, GSWA no longer microfiches legacy exploration reports, but converts them to scanned images compatible with the guidelines. I believe this approach lays the foundations for easy integration into data-management systems of the future.

We have now completed all designs for the Kalgoorlie drillcore storage facility and operational base. Tenders will be invited in October 1999 and construction will follow shortly afterwards.

1998–99 work program

Regional mapping programs continued in the Pilbara, Gascoyne, Southern Cross, and Eastern Goldfields regions and in the Bangemall and Earaheedy Basins. New developments emerging from this mapping include:

- the recognition and verification of significant amounts of 2000 Ma granitic crust in the Gascoyne region;
- the current concept that structures resembling egg cartons in the Strelley Pool Chert in the North Pole area of the Pilbara region, initially discovered in 1989 by Dr Alec Trendall (a former Director), represent the oldest macroscopic evidence of life on earth.

The regolith geochemical mapping program continued apace in 1998–99 with the helicopter-assisted collection of more than 4000 samples spanning the AJANA, KINGSTON, and STANLEY 1:250 000 map sheet areas as well as an area equivalent to six 1:100 000 maps covering the Fraser Range region. Gravity data were also collected over these areas following the successful trialing in 1997–98 of integrated geochemical sampling and gravity measurement. Two regolith and geochemical map sheets were published during 1998–99: the COLLIER and WYLOO 1:250 000 map sheets.

The regional mineralization mapping team produced reports and maps of the Bangemall Basin and southwest Western Australia. Similar products for the west Pilbara and east Kimberley regions are being prepared. In addition, we also produced reports with detailed geological descriptions of many mineral occurrences in the east Kimberley and Mid West regions.

Fieldwork commenced in 1998–99 for our inaugural urban and development areas geological maps. The first 1:50 000-scale maps are due to be printed in 1999–2000 and will cover the Karridale–Leeuwin area in the South West region and the Geraldton area in the Mid West region. It is hoped that the maps in the former area will assist winemakers with the identification of potential further grape-growing areas. There is considerable competition for laterite gravel because it provides both an excellent road-forming material and a well-drained substrate suitable for viticulture. Clearly, however, development of laterite resources can cause conflict with other landuses such as tourism. I was pleased to note that there was no shortage of volunteers to undertake this arduous mapping project in the Margaret River area.

In the penultimate year of the petroleum initiatives program, GSWA achieved a notable success in its definition and verification, by gravity and magnetic surveys and drilling, of the Woodleigh impact structure. While, at this stage, our understanding of this 120 km-diameter buried crater may appear to be of relatively academic interest, I would point out that more than 50% of large impact structures are currently known to be associated with economic accumulations of minerals or petroleum.

At the end of 1998–99, GSWA spudded the Vines 1 stratigraphic borehole in the Waigen Sub-basin near the South Australia – Northern Territory – Western Australia border. This sub-basin has undergone no petroleum exploration at all and this hole will provide enormous advancements in our geological understanding of the Officer Basin. The detection of a gas show during the drilling of this hole is still subject to assessment, but is no doubt a most significant discovery.

Challenges for the future

While this article is essentially retrospective, I believe it is appropriate to examine some issues that will confront us as we move forward.

The Australian and New Zealand Minerals and Energy Council (ANZMEC — the national forum of Mines Ministers) has endorsed a marketing strategy promoted through the Chief Government Geologists Conference. This strategy involves the coordination by AGSO of displays from all participating States under the one Australian banner. It has been successfully implemented at the Prospectors and Developers Association of Canada (PDAC) annual conference held in Toronto and at the American Association of Petroleum Geologists (AAPG) conference held in the United States. We are currently liaising with other States and the Commonwealth to extend this coordinated approach to marketing and take in other significant international mineral and petroleum events. In addition, GSWA presented an oral paper at the 19th International Geochemical Exploration symposium in Vancouver.

I believe the biggest challenge facing GSWA in the short- and medium-term is how it elects to integrate its data-collection systems into the digital environment. Increasingly, our capabilities of archiving geoscientific data relevant to the State are being tested and we need to rapidly develop robust data-management systems that are not only easy to put information into, but also easy to get information from. We accept that *www.com* technology is essential to the way our clients and ourselves do business and are working towards this outlook. I believe 1999–2000 is the year the Geological Survey of Western Australia will be seen to be the benchmark for all other Geological Surveys to emulate.

Achievements

The GSWA has a long and proven tradition of producing quality maps and reports. With the pressure of continuous productivity improvements, we need to guard against taking shortcuts that compromise quality. The Geological Survey Liaison Committee monitors our quality, and I was particularly pleased that in 1998–99 we were the recipients of two awards that recognize quality. Our integrated regolith geochemistry and gravity program was a finalist in the 1998 Premier's Awards in the Process Improvement category, and our sensitive high-resolution ion microprobe (SHRIMP) geochronology team was the recipient of the StateWest Achievement Award for excellence in the workplace. These awards are public recognition that we are maintaining quality.

Conclusion

Finally, in closing this review of the past 12 months, I would like to pay tribute to Joe Lord who died in January 1999. Like many geologists of my vintage, Joe Lord was responsible for me working in Western Australia. He recruited me into GSWA in the mid-1970s and our paths crossed many times after both of us had left the Survey. He had a strong influence on my career, as I am sure he did many others, and I believe I am a substantially better person for having known him. Because Joe Lord laid the foundations of the modern Geological Survey of Western Australia, we have included elsewhere in this Annual Review a fuller outline of the career of this influential geologist.

Selected highlights of mineral and petroleum exploration and development in Western Australia in 1998–99

by D. J. Flint[1], Gao Mai, P. B. Abeysinghe, D. B. Townsend, and R. H. Bruce[2]

In 1998–99, the value of mineral production (including petroleum) fell by $1095 million (6.1%) but still totalled $16 075 million. Falls in the value of production of petroleum, nickel, and gold were only partially offset by the increased value of production of alumina and iron ore. In a world market context, Western Australia continues to be a very significant producer of gold, iron ore, bauxite–alumina, nickel, diamond, heavy-mineral sand products, salt, tantalite, spodumene (lithium), and liquefied natural gas (LNG).

Exploration in Australia and throughout the world declined sharply during 1998–99, leading to large reductions in exploration activity and postponements of many planned developments, particularly in the hard-hit gold sector. The decline in Australia was caused by a combination of reasons, including the Asian economic crisis and slowdown in world growth, lower commodity prices, partial demonetization of gold, and the continued impact of Native Title issues.

General trends in mineral and petroleum exploration expenditure

Western Australia's prospectivity is highlighted by the continuing high proportion of Australian exploration expenditure that the State attracts, but Western Australia, like the other States, experienced a reduction in exploration activity during the year. In 1998–99, mineral exploration expenditure (excluding petroleum) in Western Australia was $523.1 million, a decrease of $137.3 million or 20.8% on the previous year. This is the second successive annual decline in total exploration expenditure after seven successive years of growth (Fig. 1). The decline is much larger than for the previous year, when it was only $31.3 million or 4.5%.

Falls in mineral exploration expenditure have occurred much more widely than in Australia alone. The Canadian-based Metals Economic Group reported that world-wide exploration budgets (for 182 companies with exploration budgets greater than $2.9 million) declined by 31% in 1998 when compared with 1997.

The fall in exploration activity, both in Western Australia and the other States, has led to Australia-wide exploration (excluding petroleum) falling back below the record levels of over $1000 million that were achieved in each of the previous two years. Australia-wide exploration expenditure dropped by $229 million (21.5%) to $837.8 million during 1998–99. In dollar terms, most of the fall was in Western Australia — falling $137.3 million out of the national drop of $229 million. However, in percentage terms, the decline in exploration activity during the year was almost identical when

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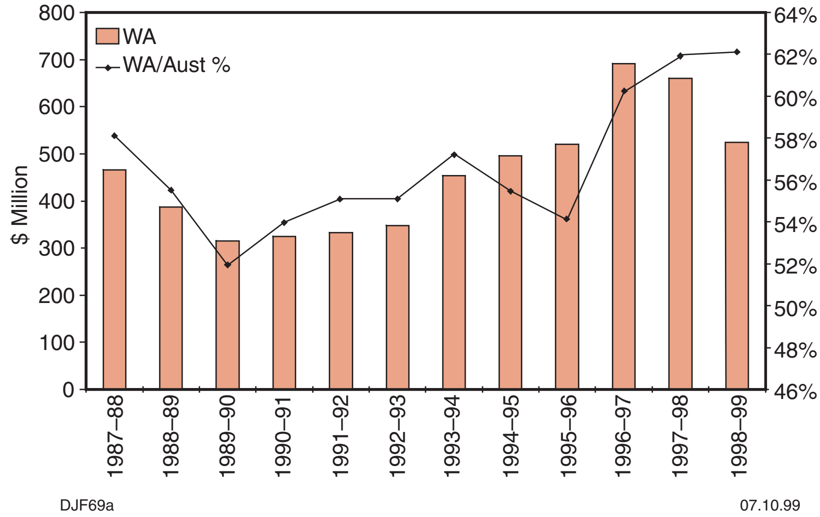


Figure 1. Mineral exploration expenditure (excluding petroleum) in Western Australia (dollars of the day)

figures for Australia and Western Australia are compared. As a result, Western Australia continues to attract the greatest portion, 62.4% (61.9% previously), of all Australian exploration expenditure (Fig. 1). This is the highest the proportion has been since at least 1986–87, and it reflects the slightly larger falls (in percentage terms) in the other States. During the last decade, Western Australia's proportion of Australia-wide exploration has been increasing, rising from 51.9% in 1989–90 to 62.4% in 1998–99.

In 1998–99, petroleum exploration expenditure in the State set a new record for the third year in a row, totalling $530.8 million ($463.9 million previously). This is an increase of $66.9 million or 14.4% on the previous year, and it extends a significant period of increasing petroleum exploration in Western Australia, which now attracts around 61% of all Australian petroleum exploration expenditure (Fig. 2).

Exploration expenditure by commodity

Gold bore the brunt of the decline in mineral exploration in Western Australia — falling by $128.6 million (28%) to $330.7 million, out of the State total fall of $137.3 million for 1998–99 (Fig. 3). This is a startling reduction from the expenditure level of $459.3 million in 1997–98. The seriousness of

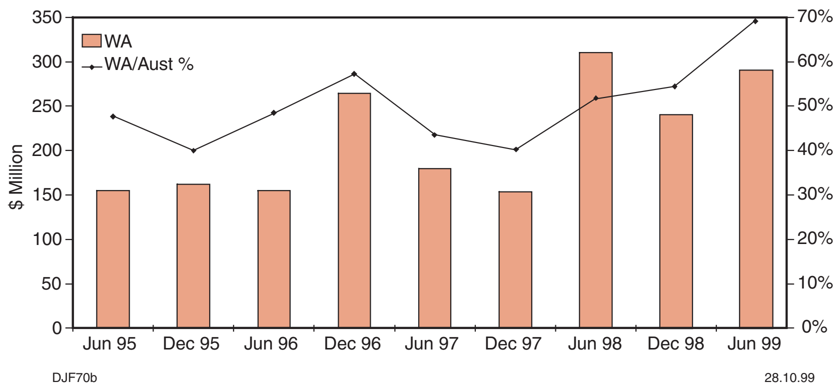


Figure 2. Petroleum exploration expenditure in Western Australia, by half year (dollars of the day)

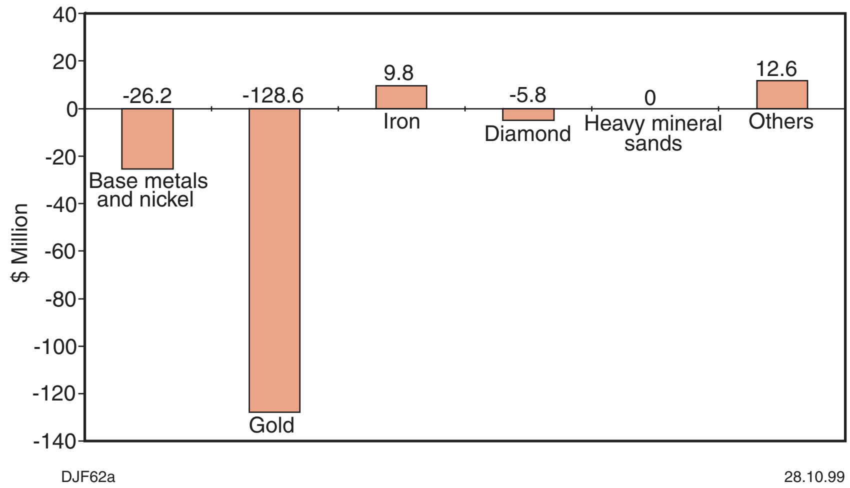


Figure 3. Change in mineral exploration expenditure in Western Australia from 1997–98 to 1998–99, by commodity

the decline is also evident when the fall for the last two years is compared with the two-year fall immediately following the world-wide stock market crash of October 1987 (Fig. 4). In 1998–99 dollars, the fall in gold exploration in Western Australia over the last two years is $207.6 million (38.5%), which is almost as severe as the fall in 1988–89 and 1989–90 ($248.8 million; 48.8%). On a yearly basis, gold exploration activity is now at levels last experienced in 1993–94 (Fig. 4). On a quarterly basis, gold exploration expenditure in Western Australia has dropped about 50% over the last two years, falling from a level of about $150 million per quarter in mid-1997 to only about $70 million per quarter in mid-1999 (Fig. 5).

The drop in gold exploration is primarily attributed to the low gold price, both in $US and $A terms. During 1998–99, the monthly average price for gold fell $US31 (10%) and $A86 (18%), and reached a 20-year low point.

Exploration for base metals (including nickel and cobalt) also dropped sharply during 1998–99, falling by $26.2 million (22.3%) to $90.9 million

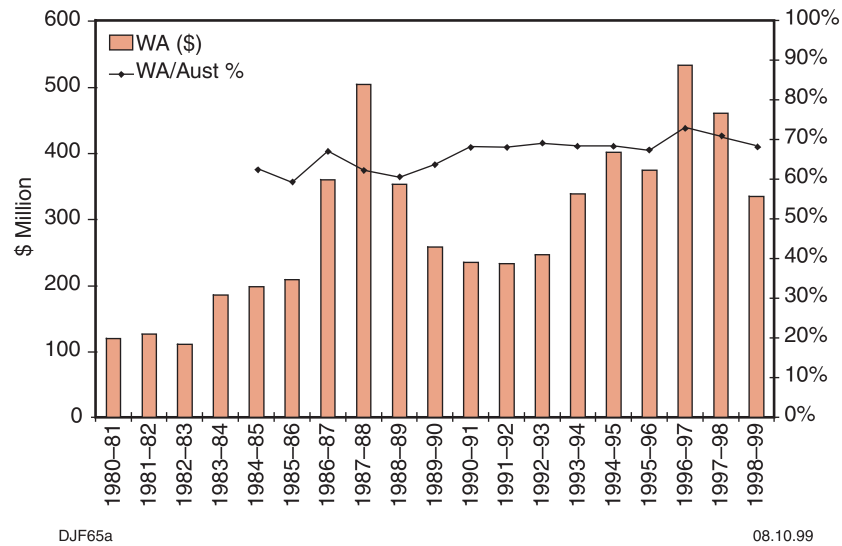


Figure 4. Gold exploration expenditure in Western Australia (1998–99 dollars)

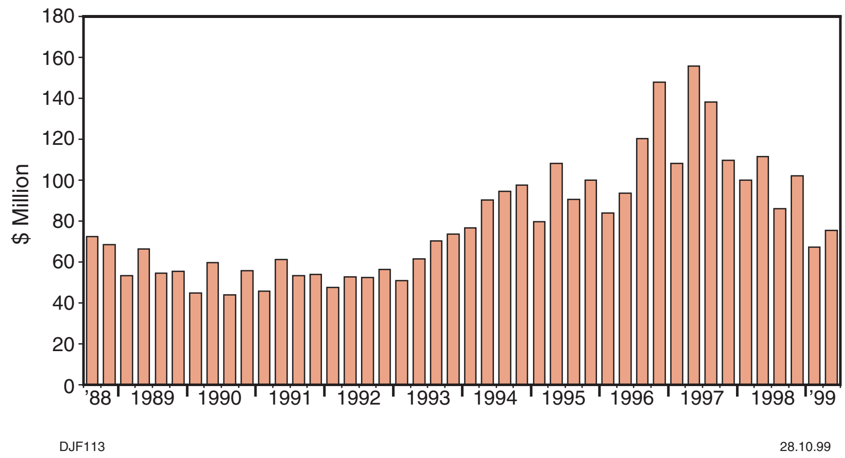


Figure 5. Gold exploration expenditure in Western Australia, by quarter (dollars of the day)

(Fig. 3). There are two reasons for this — lower commodity prices and the move from the phase of very active exploration to the phases of commissioning and production at the major lateritic nickel projects, particularly at Murrin Murrin and Cawse.

Diamond exploration fell by $5.8 million (18%) to $25.6 million during 1998–99, while exploration for heavy mineral sands remained unchanged (Fig. 3). Going against the trend were iron ore and 'other minerals', which both attracted additional exploration during 1998–99. Exploration expenditure for iron ore increased by $9.8 million (32%) to $39.6 million, despite lower contract prices. This is the fourth year in a row in which exploration expenditure for iron ore has increased. 'Other minerals' are mostly industrial minerals, but also include vanadium and manganese, where exploration has been revived recently to reassess known resources for future planned development. Exploration expenditure for 'other minerals' increased by $12.6 million (108%) to $24.2 million.

Although gold remains the main focus of exploration effort in Western Australia, its paramount lead is continually being eroded. Gold now accounts for only around 63% of all exploration expenditure in Western Australia (other than petroleum; Fig. 6), and this is a sharp fall from 76% of the total in mid-1997 and 69% of the total last year. Other notable changes in the balance of exploration between commodities during 1998–99 are that exploration for iron ore and 'other minerals' have increased to 8% (5% previously) and 5% (1–2% previously) respectively. The proportion spent on exploration for base metals and nickel–cobalt has remained relatively static at 17–18%.

Despite the large fall in exploration activity in Western Australia during 1998–99, Western Australia continues to attract the major part of the Australian exploration dollar for iron ore (95.4%), gold (68.0%), diamond (62.6%), and heavy mineral sands (46.3%). However, exploration expenditure for heavy mineral sands is sharply down from the 62.9% of the Australian total in 1997–98. This reflects the swing in exploration focus towards the Murray Basin (Victoria, South Australia, and New South Wales), which has attracted additional exploration support. Exploration expenditure for heavy minerals in Australia jumped by almost $5 million (36%) to $19.0 million in 1998–99, representing the highest level in the last decade. In exploration for base metals (Cu–Pb–Zn–Ni–Co), for the second consecutive year and possibly only the second time ever, Western Australia attracted over 50% (51.4%) of the Australian exploration dollar. The percentage for Ni–Co exploration is presumed to be higher, but data released by the Australian Bureau of Statistics (ABS) do not show Ni–Co separately.

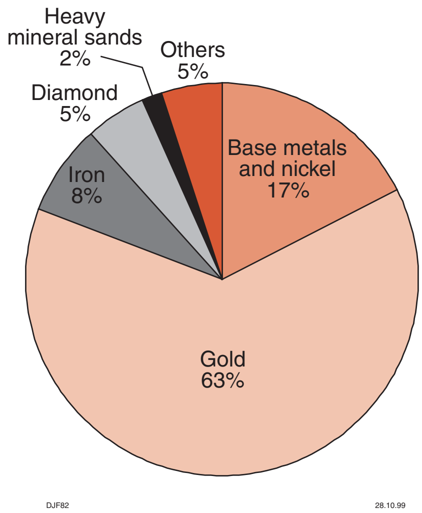


Figure 6. ***Mineral exploration expenditure (excluding petroleum) in Western Australia, by commodity, 1998–99***

Mineral resources and reserves

Despite the severe cutbacks in gold exploration and the strong pessimism prevailing in many parts of the gold sector, the State's inventory of measured and indicated gold resources (including any converted to reserves) still managed to increase during 1998–99. Undoubtedly, proven and probable reserves would have decreased because of the lower gold price and resulting mine closures. Gold resources (measured and indicated only) increased by 120 t (3.6%) to 3496 t (Table 1). This increase in gold resources was at a slower rate than previously, and, given the exploration cutbacks that occurred during 1997–98 and 1998–99, it is unlikely that resources will continue to grow over the next year or two.

Significant increases in resources of nickel and heavy mineral sands were recorded during 1998–99. Nickel resources (measured and indicated) increased by 3.36 Mt (25.1%) to 16.77 Mt of contained metal. This is the third year in succession with large increases in nickel resources, and they have now more than doubled over the last three years (Table 1). All of the increase has come from lateritic nickel deposits, where resources increased by 3.7 Mt (64%) to 9.5 Mt of contained nickel. For sulfide nickel deposits, total measured and indicated resources decreased by 0.3 Mt (4%) to 7.3 Mt of contained nickel. For the first time, contained nickel (in measured and indicated resources) within lateritic nickel deposits has eclipsed contained nickel within sulfide deposits — 57% versus 43% respectively.

Resources of heavy minerals, including garnet, also increased substantially during 1998–99 — rising by 45 Mt (27.7%) to 208.7 Mt of contained heavy minerals. This continues the long trend of increasing known resources despite ongoing production. Measured and indicated resources of heavy minerals have increased from 60 Mt in 1989 to 208.7 Mt of contained heavy minerals in 1998, an increase of around 250%. Total production for the same period is of the order of 20 Mt of heavy minerals.

Resources of high-grade iron ore and bauxite have changed little from the previous year. Estimated resources of diamond continued to decline; figures for 1998–99 show a 6.3% decrease due to production from Argyle (Table 1).

Mining tenement activity

The general state of the mineral exploration sector is also highlighted by the large reduction in the number of mining tenements in force as at 30 June 1999 and the area held under tenure (by comparison with the same point in time 12 months previously). For all tenement types under the Mining Acts of 1904 and 1978, the area held showed a disappointing decrease of 31.6%

Table 1. Mineral resources inventory, Western Australia

Commodity	*Units*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*
Iron ore (high grade)	Mt	18 400	19 750	22 230	22 840	22 320	22 700	22 540	21 960	22 539	22 407
Gold	t	1 216	1 980	1 999	1 867	2 141	2 347	2 696	3 009	3 376	3 496
Bauxite ore	Mt	960	1 368	1 318	1 383	2 886	2 840	2 817	3 359	3 386	3 387
Mineral sands	Mt	60	77	81	87	111.5	106.4	150.9	128.9	163.4	208.7
Nickel	Mt	6.30	5.45	5.71	5.67	7.22	8.42	7.70	10.73	13.41	16.77
Diamond	Mct	458	756	766	700	630	585	583	583	546	534

NOTE: Data sourced from MINEDEX database
Only measured and indicated resources are shown
For iron ore and bauxite, the quantity of ore is shown
For all other commodities, the contained element/mineral in the ore is shown
High-grade iron ore is based on iron content only, but cut-off grade (55% or 60% Fe) depends on mineralization type
Diamonds include undivided industrial and gem-quality grades

Table 2. Mining tenements current as at 30 June 1999, Western Australia

	1995–96		*1996–97*		*1997–98*		*1998–99*	
	No.	*Area (ha)*	*No.*	*Area (ha)*	*No.*	*Area (ha)*	*No.*	*Area (ha)*
Tenements current as at 30 June 1999 (1978 Mining Act)								
Prospecting Licences	8 111	1 098 339	8 212	1 099 671	7525	992 392	6 242	808 792
Exploration Licences	4 417	37 845 997	4 718	38 279 436	4505	35 992 499	3 463	23 732 102
Mining Leases and others	7 373	2 134 622	6 717	2 135 806	6717	2 238 301	7 555	2 263 145
Tenements current as at 30 June 1999 (1904 Mining Act)								
Mineral claims and others	320	34 090	310	34 133	309	34 132	307	34 130
Total (all tenements)	**20 221**	**41 113 048**	**19 957**	**41 594 046**	**19 056**	**39 257 324**	**17 567**	**26 838 169**
Tenement applications yet to be granted as at 30 June 1999								
Prospecting Licences	–	–	985	–	1 142	–	1 735	–
Exploration Licences	–	–	2 060	–	2 012	–	2 904	–
Mining Leases	1871	–	3 167	–	4 562	–	4 944	–
Others	–	–	357	–	1 493	–	1 512	–
Total	**–**	**–**	**6 569**	**–**	**9 209**	**–**	**11 095**	**–**

Figure 7. Mineral exploration drilling in Western Australia, by drilling type. Note that 1998–99 figures are estimates

(12.4 million hectares) to 26.8 million hectares. Much of this decrease (98.7%) is attributable to fewer exploration licences (Table 2), which dropped by 23%, whereas the area under tenure dropped by 34%. These data indicate that large, greenfields-type exploration licences were being dropped during 1998–99. The fall in area held under prospecting licences was about 18%, close to the fall in exploration expenditure overall (20.8%). As in the case of the decrease in exploration expenditure, the rate of fall for both the number of tenements held and the area under tenure was greater in 1998–99 than in the previous year. The area held under mining and 'other' leases remained almost unchanged during 1998–99.

These trends are perhaps the most reliable available indicators of the swing from 'greenfields' to 'brownfields' exploration.

Native Title issues continue to cause delays to the planning of many exploration and development programs, and these issues add further to the slowdown in exploration attributable to the effects of the Asian economic crisis and lower commodity prices generally. Another issue affecting exploration and development is competing landuse, especially in the State's southwest and in or near national parks.

Statistics that highlight these problems are shown by the large number of pending tenement applications (yet to be granted) as at 30 June 1999 (Table 2). Over the last three years, the number of outstanding applications has increased each year. During 1998–99, the number of pending applications increased for all tenement types — prospecting licences by 52%, exploration licences by 44%, mining leases by 8%, and 'others' by 1%. These delays are predominantly caused by Native Title issues and the figures clearly show the magnitude of the problem. Access to land for mineral exploration is essential for the continuing development of the State's resources and for the future economic well-being of the State.

Drilling activity

Drilling statistics also provide a measure of exploration activity in Western Australia. The following comments relate to drilling statistics in the Department's WAMEX database, as compiled from mineral exploration reports received by the Department during the period.

The trend in drilling activity since the peak shown in the June 1997 quarter is readily evident (Fig. 7). 1997–98 was characterized (in drilling activity terms) by a sharp decline (30%) in RAB drilling, reflecting a move from greenfields to brownfields exploration. During 1998–99, there was a decline in all drilling activity, but with the sharpest declines in diamond drilling (down 68%) and RC drilling (down 16%), which suggests a drop in resource-definition drilling. The earlier sharp fall in RAB drilling is consistent with the concept of a trend away from greenfields exploration in 1997–98, but the decline in exploration drilling during 1998–99 was more general, and is similar in both greenfields and brownfields areas. The level of drilling activity is now comparable to that of 1994–95.

Precious metals

Gold

The gold price, both in $US and $A terms, fell for most of the year and reached several successive 20-year low points. It finally reached $US253 in early July 1999 when the Bank of England sold-off the first 25 t of its planned sales program of 415 t of gold. The price was not helped by plans announced by the International Monetary Fund to fund debt relief of heavily indebted developing countries by selling up to 10 million ounces of gold. In addition, the international demonetization of gold continued formally when Switzerland approved a revised constitution that ended the backing of the Swiss franc by gold. The Swiss Government has 2600 t of gold, the fifth largest central bank holding in the world. During the year some producers wound back their hedged positions, taking advantage of low prices to allow large profits to be realized. Producers also switched to an emphasis on options rather than straightforward gold sales as a means of protecting income. Fortunately, hedging through forward sales kept some companies profitable at a time when their production would not have been profitable if sold at spot prices.

During 1998–99, the broad industry trends evident in 1997–98 continued, but were exacerbated by a slightly stronger $A and uncertainty in the economic outlook for world growth. These resulted in, amongst other things,:

- further closures of unprofitable high-cost gold mines that lacked hedge protection;
- continued efforts to reduce operating costs and improve cash margins; downgrading of estimates of reserves (often re-estimated at $A400–450 per ounce);
- further revision of mine plans;
- a squeeze on junior exploration companies with limited working capital;
- greatly reduced cash flows and profits for service companies (particularly drilling and analytical companies);
- the trend away from using contract miners in large long-life operations, for example, at the Superpit at Kalgoorlie;
- larger cutbacks in exploration budgets and associated lay-offs of staff;
- bargain hunting by local and overseas companies with strong balance sheets;
- further abnormal write-offs and write-downs in the assessed market value of mines, plant and equipment, stockpiles, and capitalized exploration expenditure.

Announcements during the year of dramatic cutbacks to exploration (in 1999–2000) continued as companies were forced to adjust to a gold price that might persist for the longer term, with several companies closing their Western Australian offices. It is clear that exploration strategies were being further reviewed in a scenario of possibly sustained low gold prices.

The changing face of the gold industry in Western Australia was again evident by further numerous significant corporate changes in 1998–99; these included takeovers and insolvencies.

The Australian Stock Exchange decided to introduce a new $10 billion Australian Gold Index in an attempt to attract interest from international investors, particularly those who invest on an index-weighted basis. The new index will have about double the market capitalization of the old gold index, and will feature 48 companies rather than the previous 14. The Australian Gold Council is investigating the possibility of a comprehensive explorers index to cater for the more than 260 listed exploration companies. The majority of junior listed companies had less than $0.5 million in cash reserves in mid-1999, and were in desperate need of capital. Many companies changed business direction completely and converted to information technology companies, often with an immediate boost to their market capitalization.

Gold resources (measured and indicated only) within the State increased in 1998 by 120 t (3.6%) to 3496 t (Table 1). This translates, after allowing for production, to an average discovery cost of around $A30/oz for 1998 — the highest figure for the last six years, despite the dramatic cutbacks in exploration expenditure (Table 3). It should be noted that this applies to

Table 3. Gold discovery costs per ounce of measured and indicated resources, Western Australia

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

measured and indicated resources only (including any reclassified as reserves); no allowance is made for inferred resources. The increase in discovery cost is apparently due to a combination of fewer discoveries and a greater focus on converting resources to reserves.

Discoveries during the year, apart from those on the margins of existing mines, were limited and included those at Magnum, East Kundana, Enigma, Mikado, Kirgella Gift, Red Legs, and Great Western (see below). Two of these (East Kundana and Red Legs) had a resource estimate completed within 12 months of discovery. Of particular significance was the outstanding success of Wallaby (discovered in early 1998), with several million ounces of resources established within 12 months of discovery. The deposit is now one of the most significant discoveries of the decade.

With a weakening gold price and additional mine closures, gold production in Western Australia decreased by 7.8% from 239.4 t in 1997–98 to 220.8 t. Mine closures were not as frequent as in 1997–98, but included Nevoria and Laverton–Barnicoat (Sons of Gwalia Ltd), Bannockburn (Consolidated Gold Mines Ltd), Mount Gibson (PacMin Mining Corporation Ltd), Ora Banda (Centaur Mining and Exploration Ltd), Coolgardie and Sandstone (Herald Resources Ltd), and Gidgee and Mount McClure (Australian Resources Ltd). Mine openings were infrequent, with only Golden Feather (Delta Gold NL) and Paraburdoo – Mount Olympus (Lynas Gold NL and Sipa Resources International Ltd) opening during 1998–99.

Another way to illustrate major trends within the gold sector is to examine gold exploration expenditure per ounce of gold production, as this is widely used as a component of total costs of production. Table 4 illustrates that average exploration expenditure per ounce of production has been generally rising in Western Australia since 1992–93, with a peak of $A72 during the gold boom of 1996–97, but has declined sharply over the last two years. The current level of $47 per ounce of production is the lowest since about 1993. At a time of low commodity prices, with a squeeze on cash margins and profits, it is obvious that many companies have viewed such high rates of capitalized exploration expenditure as imprudent. The current rate of gold exploration per ounce of production, around $50 per ounce, is considered more sustainable in the longer term. A major trend is also evident in the percentage of the gross value of gold production that is returned as exploration funds. During the recent boom years of gold exploration and production, about 13–15.5% of the gross value of gold production was returned as exploration funds — a level that is markedly higher than for other commodities in Western Australia, except recently for petroleum. Corresponding figures for other commodities during 1998–99 are iron ore 1.0%, heavy mineral sands 1.3%, diamond 4.2%, and nickel–cobalt plus base metals 8.2%, with only petroleum showing a higher percentage (13.0%). A level for gold of around 8–11% is considered more sustainable in the longer term.

Although the market has been decidedly negative throughout the year, there are numerous highlights for 1998–99, including:

- Resources at the Wallaby deposit, 11 km southwest of Granny Smith, now total about 2.3 million ounces of contained gold (at June 1999) — an outstanding success since its discovery in early 1998. A feasibility study

Table 4. Gold exploration expenditure versus production, Western Australia

Year	*1992–93*	*1993–94*	*1994–95*	*1995–96*	*1996–97*	*1997–98*	*1998–99*
Exploration dollars per ounce of production ($/ounce)	38	50	63	56	72	59	47
Exploration expenditure/value of production (%)	7.8	9.1	12.1	10.8	15.5	13.2	10.2

on Wallaby is expected to be completed in late 1999, and is likely to lead to a significant extension of the Granny Smith project.

- Resources at the Cleo mine, part of the Sunrise Dam project, also continue to increase. Measured and indicated resources for the Cleo openpit total 2.4 million ounces, with an additional 1 million ounces of gold contained within inferred resources. For the high-grade (7.2 g/t Au) Cleo underground deposit, inferred resources increased during the year to 511 000 ounces of contained gold.
- The discovery in mid-1998 of Au–Cu(–Ag) mineralization by Gindalbie Gold NL, Croesus Mining NL, and BHP World Minerals Ltd at the Magnum prospect in the northern part of the Paterson Orogen, 150 km north of Telfer. Limited diamond drilling of a large electromagnetic anomaly has revealed massive pyrrhotite and chalcopyrite mineralization in quartz reefs hosted by a gabbro sill.
- Within one year after discovery, resources at the East Kundana project (Gilt-Edged Mining NL and Tribune Resources NL) increased to 310 000 ounces of contained gold in the Hornet, Rubicon, and Pegasus deposits.
- New Hampton Goldfields Ltd intersected high-grade mineralization (32 m at 23.2 g/t Au from a depth of 175 m) at East Location 51, 40 km south-southeast of Kalgoorlie.
- Exodus Minerals Ltd discovered potentially economic mineralization at the Mikado prospect, 20 km from the Granny Smith mine.
- Burdekin Resources NL discovered potentially economic mineralization at the Kirgella Gift prospect, at the southern end of the Pinjin greenstone belt and 13 km south of the historic Anglo Saxon workings.
- Savage Resources Ltd and Barranco Resources NL discovered potentially economic mineralization at the Red Legs prospect, located near the northern end of the Johnston Range greenstone belt; inferred resources are estimated at 420 000 t averaging 2.6 g/t Au, for about 270 000 ounces of contained gold.
- Kanowna Lights NL released information on high-grade intersections from its Great Western Gold project, north of Leonora.
- Mining by Delta Gold NL at the Golden Feather project (Mulgarrie and BLC pits) commenced during the year, with 62 000 ounces of gold produced until the end of June 1999. The plan is to recover at least 200 000 ounces of gold from 1.5 Mt of ore (averaging 4.43 g/t Au) over a two-year period. In addition, Delta Gold NL is undertaking feasibility studies on mining supergene and laterite mineralization in the Lizard and Iguana deposits.
- The Paraburdoo gold project (Lynas Gold NL and Sipa Resources International NL) poured its first gold on 31 December 1998. Forecast production is at the rate of 60 000 ounces per year.
- Sons of Gwalia plan to start development of the Red October deposit in late 1999, with ore to be trucked to Leonora. Planned production for 1999–2000 is 175 000 ounces, rising to 200 000 ounces in 2000–01.
- Feasibility studies on mining the large but low-grade porphyry copper-style Wandoo deposit, part of the Boddington project, indicated that expanded production, of around 18 Mt of ore to yield 500 000 ounces of gold per year, would be required in order to bring operating costs down below $300 per ounce. Resources within the project were lifted by around 30% during the year, and now total about 11.74 million ounces of contained gold and 393 000 t of copper, but at low grades. This is still the largest undeveloped gold resource in Australia.
- Two scoping and pre-feasibility projects at Telfer commenced in 1998 and have the potential to add significantly to both production and mine

life. The $7.8 million Isdell Series Project (ISP) involves the assessment of the deep (900–1000 m below surface), high-grade I30 reef and associated mineralization for underground mining — targeting grades of 10–15 g/t Au. The $13 million Sulfide Extension Project (SEP) is to outline a bulk sulfide resource that could be mined by deepening the existing Main Dome and West Dome pits. The SEP project requires delineation of at least 130 Mt of bulk mineable ore and would need a new 12 Mtpa treatment plant.

- Resources at the Carosue Dam project (previously Khartoum project) doubled during the year to more than 1.1 million ounces, and PacMin Mining Corporation announced plans to proceed with a bankable feasibility study on a 120 000 – 150 000 ounces a year operation.
- Deep drilling continued at several mines, including at Mount Magnet (1400–1720 m below surface; Hill 50 Gold NL) and Sons of Gwalia (1200–1300 m below surface; Sons of Gwalia Ltd).
- There was a rapid upgrade by Taipan Resources NL of the resources at the old Paulsen workings (Ashburton project; Wyloo Dome) with about 510 000 ounces of contained gold in measured and indicated resources and 240 000 ounces of contained gold in inferred resources.

In addition to the mine closures (listed above), the depressed gold market and gloomy outlook led to many deferments of planned developments. These included, but were not limited to:

- Deferment of the development of a $100 million shaft at the Kanowna Belle mine, which was replaced by the option to haul ore from 1 km underground by trucks. The option produces large savings in capital costs, but at the expense of higher operating costs as the mine matures.
- Deferment of the development by AMX Resources Ltd of the Golden Cities project (with about 800 000 ounces of contained gold in the granitoid-hosted Havana–Suva deposits).
- Deferment of the development of White Foil, with its 770 000 oz of gold contained in measured and indicated resources.
- Centaur Mining and Exploration Ltd scaled back its operations at the Mount Pleasant project, concentrating on the Quarters pit.
- Production from Mount Charlotte was further reduced, and all development work cancelled.

Silver

Mine evaluation work by East Coast Minerals NL and Legend Mining NL continued during the year at the Elizabeth Hill silver deposit, 40 km south of Karratha in the west Pilbara. Site preparation has been completed and a 24 000 tpa processing plant assembled and commissioned; by year-end the processing plant was treating about 80–100 tpd of ore. Trial mining commenced in April 1999 and several parcels of concentrate have already been shipped to refiners, with some direct smelting of small selected parcels. Underground mine development continues between 52 and 102 m below surface. An underground diamond-drilling program was undertaken in early 1999 to assist in defining silver mineralization limits for mine planning. Visible silver was recorded in 12 of the 14 holes completed. Results of fire assays and screened fire assays were erratic due to the extremely high-grade veins and local erratic concentrations of native silver. Best results included 3.1 m at 2167 g/t, 1.72 m at 3664 g/t, 2 m at 3655 g/t, 3.9 m at 3312 g/t, and 2.3 m at 5047 g/t.

Steel-industry metals

Iron ore

Highlights during the year included initial production from Hamersley's Yandicoogina deposit and BHP's hot-briquetted iron (HBI) plant at Port Hedland, approval to Hamersley for extension of mining operations at the Brockman mine, commitment by Hamersley to proceed with development of its Nammuldi deposit (a 'Marra Mamba' iron ore deposit), and formal government approval to BHP to develop the Mining Area C project.

One of Western Australia's most significant resource developments, BHP's massive HBI plant at Port Hedland, produced its first HBI in February 1999. Unfortunately, the project incurred cost overruns of about $1 billion and was commissioned more than 12 months behind schedule. BHP has stated that it expects its $2300 million HBI project to be cash-flow positive by May 2001, based on the project achieving its designed production capacity of 2.5 Mtpa and using 5.5 Mt of iron ore fines.

In mid-1999, the long-running negotiations over the proposed merger of BHP's and Rio Tinto's global iron ore businesses were terminated without agreement being reached. The $14 billion merger proposal collapsed after both parties failed to reach an agreement on the value of their respective iron ore operations in the Pilbara region and following lukewarm government response.

North Ltd's hopes of reducing the capital cost of developing its West Angelas iron ore project by sharing Rio Tinto's rail system in the Pilbara were dashed by a Federal Court ruling in early 1999. Rio Tinto established, to the satisfaction of the court, that its process of using the rail link to blend iron ore from different sources brought it within an 'integrated production process', that is, it is within the ambit of Part 3a of the Trade Practices Act. The court decision was consistent with an earlier decision of the National Competition Council. The capital cost of the West Angelas project could double to more than $1000 million if North Ltd has to build its own rail system.

Hamersley Iron began construction of its Yandicoogina project in the eastern Hamersley Ranges in January 1998. Development was completed in December 1998 at a cost of $US360 million; $US155 million under budget and five months ahead of schedule. The first Yandicoogina ore was shipped in January 1999. The initial production rate is planned at 9 Mtpa, rising in line with market demand to 15 Mtpa. The orebody is a pisolitic or channel iron deposit, typically 500 m wide and 45 m thick, extending over a length of 80 km. Proved reserves at Yandicoogina are estimated at 310 Mt averaging 58.5% Fe, with indicated resources estimated at 830 Mt averaging 58% Fe.

In mid-1998, the Western Australian Government gave approval for Hamersley Iron to extend mining operations at the Brockman mine. A new pit (Pit 6) is being established and is expected to give a further 2.5 years of mine life. In December 1998, Hamersley Iron announced its commitment to proceed with the development of its Nammuldi deposit. Nammuldi is one of Hamersley's three 'Marra Mamba' iron ore deposits, which form part of the large Homestead Valley project, adjacent to its existing Brockman mine. The first stage of the project is to provide bulk samples to customers for evaluation as a separate product to Hamersley's existing Brockman blend. The project can advance with minimal capital outlay and additional infrastructure.

BHP is proposing to mine deposits within the northern portion of Mining Area C, 100 km northwest of Newman. To date, 14 deposits with combined resources of over 1200 Mt of iron ore have been identified. Formal environmental approval for the project was given in December 1998. The mine plan requires construction of only 35 km of new railway, which would connect with BHP's existing line from Newman to Port Hedland. Timing for development will be determined by market place requirements.

The $96 million development of BHP's Orebody 18 mine, 32 km east of Newman, remains suspended as a result of changing market conditions. The mine was planned to be in full production from mid-1998 and producing 5–10 Mtpa. Sufficient design work has been completed to enable rapid construction and commissioning in response to improved market conditions.

Nickel–cobalt

Low nickel prices during the year, which saw a low point of only $US1.76/pound in October 1998 (LME monthly average price), led to the closure of some mines around the world, including in Western Australia. During the period, WMC Ltd closed three mines at Kambalda (Long, Otter–

Juan, and Mariners), thus reducing its overall output by 15 000 t of contained nickel. The closure of higher cost mines throughout the world has partly reduced the imbalance between nickel supply and demand, and therefore resulted in an upward trend in nickel prices.

During 1998–99, construction of the pressure acid leach, solvent extraction, and electrowinning circuits (SX–EW) for the Murrin Murrin, Bulong, and Cawse lateritic nickel projects were completed and 'ramping up' to full production capacity is scheduled to continue at least to early 2000. All have produced saleable nickel and cobalt products to the predicted standards. However, the three production circuits have experienced some technical problems that caused commissioning delays and associated cost increases. The success of these projects is still the key to Western Australia significantly expanding its nickel output and increasing its share of the low-cost world nickel market.

Amongst other nickel laterite developments, Comet Resources NL's Ravensthorpe project is the most advanced. Feasibility studies indicate that a $750 million, 4.0 Mt/year operation could produce nickel with production costs of less than $US1.00/pound. Comet has a contract with Multiplex Constructions Pty Ltd to build the infrastructure and SX–EW plant, but finance for the project is not yet complete. Planned production rates are 25 000 tpa of nickel and 1900 tpa of cobalt sulfide.

Anaconda Nickel NL holds a dominant position in the Western Australian nickel industry with respect to resources under its control. It now controls about 30% of the State's nickel contained within measured and indicated resources of all deposit types, and about 53% of the State's nickel in measured and indicated resources for lateritic deposits.

Exploration for nickel sulfide deposits most likely decreased in 1998–99, with the low nickel prices forcing miners to suspend feasibility studies and reassess mine planning.

The Forrestania sulfide-nickel mine was closed in August 1999, after seven years of operation, due to exhaustion of ore reserves. Total production was 3.8 Mt of ore at 1.5% Ni for 55 000 t of contained nickel in concentrates. Its owner, Outokumpu Australia Pty Ltd, intends to replace this production loss by moving the Forrestania plant to Black Swan, northeast of Kalgoorlie, thus increasing throughput capacity from 12 000 to 18 000 tpa. Ore from the high-grade (9% Ni) Silver Swan deposit will be blended with Cygnet ore (2.3% Ni) to deliver around 450 000 t of ore at 4.5% Ni to the upgraded plant.

At Radio Hill in the west Pilbara, Titan Resources NL completed one full year of mining massive sulfide mineralization, processing 199 497 t of ore to produce 41 613 t of flotation concentrate containing 4432 t of Ni, 2600 t of Cu, and 253 t of Co. The cash cost of production, after byproduct credits, averaged $US1.19 per pound of nickel. Titan Resources is evaluating the innovative biological oxidation and heap leaching of disseminated Cu–Ni–Co sulfide mineralization, and has finalized legal arrangements with UK-based Bio-Hydro Metallurgy Ltd to use its technology. This treatment is particularly suited to the disseminated Cu–Ni–Co sulfide mineralization at Mount Sholl and Radio Hill. This method has the potential to treat mineralization that is not otherwise currently economic, and at the same time produce copper, nickel, and cobalt at very low capital and cash costs.

Feasibility studies based on the June 1999 nickel price of $US2.40/pound indicated that mining of Cosmos and RAV8 sulfide deposits would be profitable. Planning for development of both deposits is at an advanced level and, with favorable conditions, construction at the Cosmos opencut Ni–Cu–Co deposit could be complete by mid-2000. At Cosmos, opencut reserves are estimated at 420 000 t averaging 7.52% Ni. At RAV8, measured and indicated resources are estimated at 144 000 t averaging 5.12% Ni.

Vanadium

Construction of Australia's only vanadium mine commenced in November 1998 at the Windimurra site, 75 km southeast of Mount Magnet, and is progressing towards commissioning in late 1999. Windimurra is a magmatic Fe–Ti–V deposit with vanadium present in magnetite and ilmenite. The proven oxidized reserves are estimated at 55.4 Mt at 0.497% V_2O_5. When at full production, vanadium output from Windimurra is anticipated to be 15.8 million pounds (7200 t) a year, which will have a major impact on the world market as it represents about 10% of world production. Windimurra's output for the first decade of production is contracted under take-or-pay terms to the world's largest consumer of the metal, ferrochrome producer Glencore Corp.

The high vanadium prices in early 1998, when vanadium reached $US6.60 per pound, and the partial development of Windimurra, have sparked very strong interest in other vanadium deposits in Western Australia, particularly at Balla Balla and Don Well (west Pilbara), Gabanintha–Yarrabubba, and Youanmi (both in the Murchison district). Unfortunately, vanadium prices subsequently dropped to around $US2.10 per pound in mid-1999, which will slow the current boom in vanadium exploration. Attention will then be focused on those deposits potentially capable of yielding a low-cost product, as world-wide production capacity is likely to increase.

Tanganyika Gold NL has started a full feasibility study on developing the Balla Balla vanadium deposit, located in the west Pilbara near the coast, 10 km north-northwest of Whim Creek. It is close to existing infrastructure, including a power supply and low-cost supply of natural gas. Pre-feasibility studies reveal indicated and inferred resources of 84.8 Mt at an average grade of 0.79% V_2O_5 with a 0.6% V_2O_5 cut-off grade. Production of around 6000–9000 tonnes of V_2O_5 per annum is envisaged over a 30-year mine life. Tanganyika Gold NL's current objective is to complete a full feasibility study by the end of 1999.

Nearby at Don Well, 16 km northwest of Whim Creek, Dominion Mining Ltd has upgraded the significance of the deposit. Drilling is revealing relatively good lateral continuity of high-grade mineralization (0.6 – 0.8% V_2O_5), and inferred resources are estimated at 40.8 Mt averaging 0.57% V_2O_5 with a 0.3% V_2O_5 cut-off grade.

Base metals

Base metal exploration in Western Australia remains at low levels, with emphasis on the major projects on the Lennard Shelf of the Canning Basin, the Nifty–Maroochydore area of the Paterson Orogen, the Golden Grove area of the Murchison Province, and the Albany–Fraser Orogen along the southern margin of the Yilgarn Craton.

Western Metals Ltd continues to successfully develop the Lennard Shelf as one of the world's major zinc-producing provinces. Combined production from the Goongewa, Kapok, and Pillara mines for 1998–99 was 2.2 Mt averaging 7.04% Zn and 3.37% Pb, showing an increase of 152% on the previous year. Exploration success continues, with a drilling program at Kutarta defining an extensive area of zinc mineralization enclosing two discrete zones of thick high-grade mineralization (K1 and K2). Mineralization is present in the hanging wall of the Cadjebut Fault and is principally hosted by dolomitized rock-matrix breccias.

The Golden Grove – Gossan Hill copper–zinc–gold project, located 55 km south of Yalgoo, comprises the Scuddles zinc–copper mine and concentrator, and the Gossan Hill copper–zinc–gold–silver resource. At Gossan Hill in 1998, a feasibility study focused on underground development of zinc and copper orebodies with openpit extraction of the oxide copper deposit. Drilling at Gossan Hill intersected high-grade zinc mineralization at a vertical depth of 800 m, 250 m below the deepest previous intersection. Delineation drilling of the Gossan Hill Deeps mineralization during 1998–99 enabled part of the existing resources to be reclassified to proved and probable reserves. At the Scuddles mine, Normandy Mining Ltd continues to explore deep mineralization. Total resources for Scuddles and Gossan Hill are estimated at 18.08 Mt at 5.04% Zn, 2.36% Cu, 0.42% Pb, 48.9 g/t Ag, and 0.74 g/t Au.

Energy minerals

Petroleum

Offshore Western Australia, and the North West Shelf in particular, continues to be recognized internationally as a premier place for new petroleum ventures based on favourable prospectivity, success rates, legislative and taxation regime, and political stability. Previous significant discoveries made on the North West Shelf continue to encourage further exploration, and offshore exploration drilling remained at record levels despite a period of low oil prices. Petroleum exploration expenditure in the State set a new record in 1998–99, totalling $529 million (65% of the total for Australia).

In 1998–99, the value of petroleum production amounted to $4065 million. Western Australia, after increasing its share of production in recent years, continues to lead the country in both gas and liquid petroleum production, and it ranks fourth in the world for LNG production.

The 1998–99 financial year has been a dramatic time for the petroleum exploration industry in Western Australia and internationally, with the oil price dropping to less than $US10 per barrel before recovering spectacularly. The year was also marked by some very significant mergers and takeovers, such as BP–Amoco and Exxon–Mobil.

In the 1998–99 financial year, a total of 59 petroleum wells were spudded in Western Australia, compared with 108 in the 1997–98 financial year. Of the wells spudded, 41 were new-field wildcat wells, three were extension wells, and 15 were development wells. Appraisal and, particularly, development drilling were significantly less than in the previous financial year, with a combined total of 18 wells compared to 64 in 1997–98. A new record high number of offshore new-field wildcat wells were drilled, and the level of 3D seismic acquisition has continued to increase.

Offshore

Offshore exploration drilling continued at record levels, with the primary focus of exploration being the offshore Carnarvon Basin. A total of 38 new-field wildcat wells were spudded during the 1998–99 financial year. The corresponding total for the 1997–98 financial year was 31 wells.

The Northern Carnarvon Basin continues to be the most explored basin in Western Australia. During the 1998–99 financial year, a total of two onshore and 41 offshore wells were drilled in the basin, with the discovery of one new pool on Barrow Island.

Eight offshore new-field wildcat wells were drilled in the Browse Basin by Shell Australia Limited, the majority of which were in the Greater Cornea area. Following Shell's Cornea Field discovery in the Browse Basin, an extended drilling program commenced during 1998–99, but results of the exploration and appraisal drilling were well below expectations and the Cornea prospect is no longer considered to be a giant field.

In the Bonaparte Basin, five new-field wildcat wells (four offshore and one onshore) were drilled compared to six last financial year, and two development wells were drilled. The Buffalo Oil Field in WA-260-P, offshore Bonaparte Basin, is projected to come on-stream by the end of 1999 and a production-well drilling program is currently under way. BHP expects the field to produce 3.5 million cubic metres of oil over a three-year period.

No offshore drilling took place in the Canning and Perth Basins.

Onshore

The level of onshore drilling activity in Western Australia is at its lowest level this decade, with only five new-field wildcat wells, one extension well, and one development well drilled in 1998–99. Onshore seismic acquisition remains at very low levels compared with the 1980s.

The lack of activity in onshore exploration was particularly evident in the Canning Basin, which was once a highly active exploration area. The Canning Basin may be one of the most underrated basins in Australia, considering the potential of its petroleum systems. Only one exploration well was drilled, Lake Hevern-1, which had minor gas shows and was plugged and abandoned. However, there is some promise for more active exploration in the future. New Standard Exploration has applied for five exploration permits in the southern Canning Basin.

Onshore drilling in the Bonaparte Basin remained very low, with only one well drilled. This was Vienta-1, which discovered potentially economic gas.

The only activity in the Perth Basin was the acquisition of 375 line km of onshore seismic data, and drilling of one exploration well. No offshore work was carried out in the basin, but a large permit offshore in the northern Perth Basin was granted to Premier Oil.

The Mid West gas pipeline came on-stream in August 1999, with gas from the North West Shelf to supply mining areas in the Mid West region of the State, particularly the Windimurra vanadium mine.

Of concern to industry in the granting of new onshore titles is Native Title and the lengthy process required for the Right to Negotiate process, and the accompanying uncertain outcomes. Although new Commonwealth legislation has been brought in to assist in improving the Native Title process, a number of issues remain unresolved and continue to hinder onshore exploration and development activities.

The Geological Survey of Western Australia continued with its petroleum initiatives projects that focus on the underexplored interior basins (Officer and Canning Basins) and western margin of Western Australia (onshore Southern Carnarvon and Perth Basins). Drilling of Empress 1 and 1A in the Savory Sub-basin has led to significant improvements in the understanding of potential Neoproterozoic petroleum systems of the Officer Basin, and a 2000-m stratigraphic well, Vines 1, is being drilled in the Waigen Sub-basin (Officer Basin). Drilling in the Southern Carnarvon Basin has confirmed the Woodleigh structure as a large bolide–impact feature. Shallow drilling in the Coolcalalaya Sub-basin indicated that Upper Carboniferous and Lower Permian strata with low organic yields are more widely distributed than previously thought.

Coal

Production from Wesfarmers' new Premier opencut coal mine near Collie, which opened in early 1998, is being expanded to a rate of 4.1 Mtpa following the completion of the new Collie A power station in early 1999. The coal is sub-bituminous steaming coal, typically with 6–7% ash, and a specific energy content of 20 MJ/kg. Most of the coal mined by Wesfarmers Coal Ltd is used for raising steam to generate power, but it is also used in cement manufacturing, brickmaking, and in direct-reduction processes in the mineral sands and nickel industries.

The feasibility of working the large O'Sullivan lignite deposit, located between Esperance and Norseman, was advanced during the year. The lignite layer averages 20 m in thickness and lies about 20 m below the surface, and formed within Tertiary palaeochannels. The proposal is for a three-stage process of recovering kerogen and naturally occurring hydrocarbons to produce oil, in situ burning of the lignite to produce steam for power generation, and in situ bacterial oxidation of the remaining lignite to produce methane and humic acid. BHP Minerals explored the lignite – oil shale during the early 1980s, and the deposit is now being evaluated by a consortium that includes Yinnex NL and Australian Power and Energy Corporation.

Uranium

The activities of Paladin Resources NL and Acclaim Uranium NL has seen exploration expenditure for uranium total $2.1 million during 1998–99, but this only continues the minimal levels of uranium exploration seen in Western Australia for the last twenty years. Exploration expenditure for uranium during the period 1979–1988 was at levels of $10–14 million annually.

Exploration by Paladin Resources NL focused on Manyingee (90 km south of Onslow) and Oobagooma (70 km north-northeast of Derby). These deposits have the potential to be mined using the in situ leach method. Combined, they represent global resources of the order of 14 000 – 20 000 t of U_3O_8 at grades in the range 0.12 – 0.14% U_3O_8. Manyingee is possibly the most advanced in situ leach project in Australia, after Beverley and Honeymoon in South Australia, and during 1998–99 Paladin Resources NL commenced a full environmental, engineering, metallurgical, and hydrogeological review.

Acclaim Uranium NL is assessing three calcrete-style deposits (Nowthanna, Lake Maitland, and Millipede/Abercromby), but it would be Lake Maitland, with its high-grade core and better lateral continuity, that is more likely to be mined first.

Speciality metals

Tantalum

The tantalite sector was a star performer for minerals in 1998–99 with record sales, strong profitability for the sole producer Sons of Gwalia Ltd, and a substantial boost in resources at Wodgina in the Pilbara. The record production of 927 862 pounds was all from Greenbushes and Wodgina. Sons of Gwalia is the global leader in tantalite production (about 50% of primary tantalum concentrates produced), and it is benefitting from sustained demand due to growth in hand-held electronic instruments including mobile phones, laptop computers, video cameras, and pager systems. The company expects tantalum sales to be sustained at over one million pounds per year. All future production from the company has been sold to its prime customers Cabot Corporation and the Bayer Group. During 1999, Sons of Gwalia Ltd increased resources at Wodgina from 5.5 million pounds of contained Ta_2O_5 to 31 million pounds of contained Ta_2O_5. Sons of Gwalia Ltd believes that there is sufficient tantalite at Wodgina and Greenbushes to last around 50 years at planned production levels.

Titanium–zircon

In a major development during the year (December 1998), Westralian Sands merged with RGC to form Iluka Resources Ltd, which has become the world's second-largest producer of heavy mineral sands. The group produces a combined 2.35 Mtpa of titanium minerals, rutile, zircon, and ilmenite. Heavy mineral concentrates and synthetic rutile are produced at Eneabba/Narngulu and Capel. The merger will undoubtedly lead to some rationalization of the titanium industry in Western Australia, with Iluka already announcing that the Capel mine and synthetic-rutile plant would close. Even before the merger, RGC announced that it was closing its processing plant at Eneabba in a move to slash annual operating costs by about $15 million. RGC also plan to cut output from the Narngulu synthetic-rutile plant near Geraldton by 25% in response to the weaker mineral sands market.

Another disappointing event was the closure of BHP's Beenup mineral sands mine in February 1999 (the mine opened in January 1997). The mine suffered hefty losses resulting from a range of technical problems, including high clay content of the ore that impacted on management of tailings, and the mine's inability to reach satisfactory levels of production.

Industrial minerals

Gypsum

During 1998–99, Western Australia produced 1.22 Mt of gypsum valued at $21.6 million, an increase of 290% (by quantity) from that produced in 1997–98. This dramatic increase is from a full year's contribution of mining the Lake MacLeod deposit, which began production in June 1997. All gypsum mined from Lake MacLeod is exported to markets mostly in Japan.

Cape Peron Gypsum Pty Ltd, a subsidiary of Shark Bay Resources Pty Ltd, proposes to mine gypsum from the Cape Peron gypsum deposit, located 37 km north of Denham. The company proposes an opencut operation with an anticipated mining rate of 750 000 tpa for a period of over 18 years.

Limestone

A major development during the year was the announcement of a merger between the competitors Cockburn Cement Ltd and Swan Cement Ltd under a $311 million restructuring of the listed cement group Adelaide Brighton Ltd. The London-listed Rugby Group will fold its wholly owned Cockburn Cement into Adelaide Brighton for $230 million, and in return take a 55% stake in the South Australian company. This restructuring of Adelaide Brighton will result in massive rationalization, probably involving one or more plant closures in Australia, such as the wet-cement plant at Geelong, and cutting capacity at Cockburn's Munster plant by 100 000 tpa. In Western Australia, the merger will result in eliminating duplication and increase efficiencies by combining Cockburn Cement and Swan Cement's operations at Kwinana, Munster, and Malaga. The two companies together, at present, have the capacity to produce around 2.1 Mt or more of cement clinker from facilities at Kwinana, Dongara, and Cape Range.

Manganese

Sovereign Resources NL is proceeding with a $78 million electrolytic manganese dioxide (EMD) and manganese sulfate project in the Pilbara, following positive results from feasibility studies completed during early 1999. The financial model was based upon production of 10 000 tpa of manganese sulfate and an initial production of 15 000 tpa of EMD, over a 20-year life. The plant, to be built near Port Hedland, is planned to open by mid-2000. The main markets for the products are in Australia, North America, and Europe. Sovereign also aims to capture approximately 5% of the international EMD market, which has grown consistently due to the increasing demand for alkaline and button cell batteries. Although initially planning to source manganese ore from its Ant Hill deposit, Sovereign Resources now has an option agreement over 45 000 tpa of unbeneficiated fine manganese ore produced by Consolidated Minerals Ltd from the Woodie Woodie manganese mine.

This project has greatly assisted the restructured Consolidated Minerals Limited, which restarted mining at Woodie Woodie in May 1999. Consolidated Minerals also signed a contract for a trial shipment of 30 000 t of lump ore to a steelmaker in Japan, and there are further contracts in place with buyers in Japan, China, and Europe. The manganese ore from Woodie Woodie mine is highly regarded because of its low phosphorous, low iron, and moderate silica content, which makes the material ideal for blending.

Talc

A major development during the year was the plan by WMC Ltd to build an $11 million talc mill at Three Springs, 150 km southeast of Geraldton. The new mill will have an initial capacity of 35 000 – 45 000 tpa. At present, talc from Three Springs is mined and exported in lump for processing at the company’s mill in Amsterdam. The move to process talc in Western Australia is due to a favourable market outlook, particularly in South East Asia. The mill at Three Springs will supply markets in South East Asia and Australia, and will use processing technology developed in Europe to transform the fine-grained Three Springs talc into high-value products for paper coating applications.

Precious minerals

Diamond

Expenditure on diamond exploration in 1998–99 totalled $25.6 million, a decrease of $6.2 million (20%) from 1997–98. Despite fewer dollars being spent in exploration for the year, encouraging results were obtained at Blina–Ellendale (west Kimberley), Beta Creek (north Kimberley), and in the east Pilbara. In addition, mineable reserves at Argyle were increased.

Australia’s only commercial production of diamond in 1998–99 was from the AK1 lamproite pipe and alluvial operations at Argyle. Production in 1998–99 was 35.91 million carats (Mct), a fall of 7.13 million carats (16.58%) from the 43.04 million carats in 1997–98. During the year, the Argyle Diamond Mines Joint Venture Partners (Rio Tinto 56.8%, Ashton 38.2%, and Western Australian Diamond Trust 5%) revised reserves for the AK1 openpit to 71.6 Mt at 2.7 carats per tonne, extending the anticipated mine life to 2006, which is about four years longer than previous estimates. Stage one of a major pit expansion is underway and stage two of the pit cutback will start towards the latter part of 2000. The Argyle Diamond Mines Joint Venture Partners entered farm-in agreements with Striker Resources NL and Australian Kimberley Diamonds NL covering about 5000 km^2 of tenements in the King George River area. A major airborne geophysical survey was flown over this area in 1998.

In the Ellendale and Blina project areas of the west Kimberley, Kimberley Resources NL found two lamproite pipes (Kimberley 1 and 2) at Blina in 1997, but work since then has outlined an additional 16 new lamproite pipes (Kimberley 3–18). Laboratory studies on samples collected from the newly discovered pipes continue, but, to date, both microdiamonds and macrodiamonds have been discovered in seven out of the 13 pipes tested.

Striker Resources NL continued on-ground exploration in the north Kimberley in 1998–99, with most work focused on Ashmore. To mid-1999, the Ashmore pipes have produced 676 microdiamonds totalling 4.684 carats, including fragments of a 2.4 carat stone. A bulk sampling program is planned to process sufficient material for a representative parcel of between 2000 and 5000 carats to facilitate diamond valuation and geostatistical analysis of the population. Results from this study will assist in determining whether the pipes can support a commercial mining operation. Site works have commenced at Ashmore and a total of 130 km of road access from Carson River Station to Beta Creek was re-established.

In the east Pilbara, there was keen interest in the kimberlitic Brockman dyke, which spans a series of tenements north of Nullagine held by Stockdale, Lynas Gold NL, Haoma Mining NL, and a group of prospectors. Diamonds have now been reported from six areas along the dyke over a 3.4 km strike length, but the dyke is recognizable over a strike length of about 30 km.

Acknowledgements

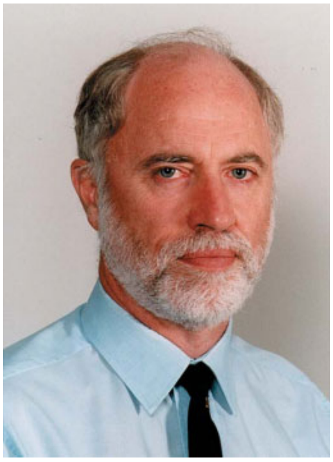
This article is compiled from public information, and relies heavily on company reports to the Australian Stock Exchange (ASX). Unless otherwise stated, data on mineral exploration expenditure used in this article were obtained from the Australian Bureau of Statistics (ABS), Catalogue 8412.0, ‘Actual and expected private mineral exploration’. The geological context and most of the localities mentioned in this report can be found in the ‘Western Australian atlas of mineral deposits and petroleum fields 1999’, published by the Geological Survey of Western Australia. Information on estimated mineral resources (excluding petroleum) is maintained within the Department’s MINEDEX database. Details of mineral production are from data supplied by producers to the Department of Minerals and Energy, under the requirements of the Mining Act 1978 and the Petroleum Act 1967, or from company reports to the ASX.

Inside the GSWA

Staff profiles

John Backhouse

John Backhouse resigned from the Geological Survey of Western Australia on 25 November 1998, 30 years to the day he joined the Palaeontological Section in 1968. By the time he left, he had served under five Directors, compiled more than 1000 internal reports, and written several major publications on Western Australian palynology (which is the study of acid-insoluble microfossils, including spores and dinoflagellate cysts). His publications include a seminal work on the Late Jurassic and Early Cretaceous palynology of the Perth Basin, and substantial contributions to the understanding of Western Australian Permian successions, particularly of the Collie Coal Basin.



John was recruited to the Geological Survey of Western Australia in 1968 after answering an advertisement in the journal Nature. Born and raised in Blackburn in northern England, John has never completely lost his Lancashire accent. His early introduction to geology was on high school trips led by an elderly geography teacher who was a frustrated geologist. Field excursions, mostly consisting of forced marches through cold driving rain across bleak moors to examine Carboniferous fossil localities, failed to dampen his enthusiasm for geology (although his attitude towards field-work may have been coloured by these early experiences). He enrolled at the University College of Wales, in Aberystwyth, graduating with BSc (Hons) in geology in 1966. Although Aberystwyth had strict Presbyterian mores, John was cheered to discover about 30 pubs within walking distance of the town centre, and that geological field trips to 'wet' counties compensated for Sunday closing.

After three years in Wales, the attractions and distractions of London proved irresistible, and John moved to University College, London, where he gained his M.Sc. in micropalaeontology in 1967. It was here that Bill Chaloner introduced him to palynology and John examined one of the first Permian samples from the North Sea, and in a brief career as a research assistant in late 1967, produced palynological evidence for Tournaisian sedimentation north of the Mercian Highlands barrier in central England.

John migrated from the United Kingdom to Australia in November 1968; one of the last people to experience a three-week 'cruise' on a £10 passage. He found Perth teeming with British migrants, many working for GSWA, which in those days was scattered through several buildings in Francis Street. In his early years in Perth he shared a series of 'bachelor pads' with other GSWA geologists. Few who frequented the newly constructed Mineral House have forgotten the notorious 'Bagot Road parties'.

These were the days of rapid expansion and the push to obtain complete geological coverage of Western Australia at 1:250 000 scale under Joe Lord's regime. Most geologists either spent long field seasons mapping, or weeks as site geologists for drought-relief drilling, but John's specialist work kept him chained to the microscope (or so he claimed for much of his career). His antipathy to field work may have had something to do with a short spell as a well-site geologist, and a field trip to the Kimberley with Phil Playford. Whatever the reason, John's field excursions have been mainly limited to Rottnest Island, or short trips to the South West region or Carnarvon Basin. Initially he worked on foraminifers, but in April 1971, he took over palynological work when Barry Ingram resigned, and has continued to work in this field for the last 28 years of his career.

John's main interest is in Mesozoic spores and dinoflagellates, and his comprehensive documentation of Jurassic and Cretaceous palynomorphs of the Perth Basin culminated in the completion of a part-time PhD at the University of Western Australia in 1984. John then turned his attention to a detailed systematic and biostratigraphic description of Permian rocks from the Collie, Perth, Carnarvon, and Canning Basins. John's extensive studies of Western Australian sedimentary basins today underpin much of the stratigraphic correlation used for petroleum exploration, but the initial impetus was provided by GSWA's extensive groundwater investigations to secure Perth's water supply. The success of this program owes much to the high-resolution stratigraphic palynology provided by John.

For a while John worked on Quaternary sediments from Rottnest Island, and compiled a series of illustrated reports that reviewed all palynomorph taxa from the Jurassic, Cretaceous, and Tertiary strata of Western Australia. His cultivated persona of absent-minded professor is highly selective — while he has difficulty remembering the name of his colleagues, he never seems to forget the name of a fossil.

John was appointed as Senior Palaeontologist in 1992. In the last 15 years, John diversified into regional reviews of petroleum wells to support basin studies. He worked mainly at basin or sub-basin scale, using high-resolution palynology for regional correlation. This approach has provided much valuable data for GSWA's Western Margin petroleum initiative program.

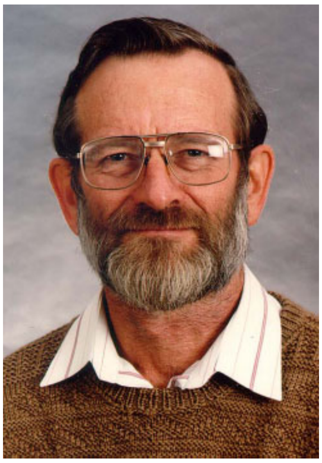
John married Liz Panegyres in 1983, acquiring an instant extended Greek family in the process. In earlier years he was often to be found at the Helena Valley fruit farm he shared with John Watt and others, but these days his cultivation efforts are confined to his home garden, and to his interest in bonsai. As his two children, Anastasia and Harry, grew older, John took up junior soccer coaching, and he still serves on the committee. He also acted as assistant editor to the Australian Journal of Earth Sciences for many years.

When John first began work at GSWA, Western Australian palynology was in its infancy. Exploration of the North West Shelf had hardly begun, and systematic descriptions of most fossil species that now play a vital role in stratigraphic correlation did not exist. For a while, Western Australian Petroleum (WAPET), based in Perth, was at the cutting edge of world dinoflagellate biostratigraphy, and other petroleum companies used biostratigraphy extensively for correlation. Despite the early start made on Western Australian basins by the local petroleum industry, John was always disturbed to find how little of the high-quality palynology carried out had ever been properly documented and published. He frequently expressed concern that much of the collective knowledge would be lost through company downsizing and obsessive secrecy, and saw his role as a Survey palynologist to act as a custodian and interpreter of those data.

John is well aware of the length of time needed to hone palynological skills, and is consequently troubled by the lack of recruits to the discipline to eventually replace those who, like himself, trained over 30 years ago. Although his initial plan on leaving GSWA was to become a consultant palynologist for North West Shelf exploration, he has been persuaded to become a part-time Senior Research Fellow at the University of Western Australia. In this new role John hopes to address the problems of taxonomic and biostratigraphic documentation, and help train a new generation of biostratigraphers.

Ian Williams

Ian's 35 years with the Geological Survey of Western Australia makes him our longest serving geologist. He joined the Regional Geology Section of the Geological Survey in 1964, and for the last three years he has been a key member of the Pilbara Craton project.



Ian's interest in geology was first sparked when, as a nine year old, he accompanied his father on prospecting trips around New South Wales. Fascinated by the minerals and rocks he found, he started a collection, and has never looked back. About half a century of collecting later, he has established an extremely impressive mineral and rock collection which takes up a large part of his Gooseberry Hill home and gardens.

After gaining a First Class Honours degree at the University of Sydney in 1961, Ian accepted a position of Field Geologist with New Consolidated Gold Fields (Australia) Pty Ltd., and commenced his professional career in New South Wales and Queensland. Since 1964, his geological mapping with GSWA has taken him to all parts of Western Australia, except the South West and Eucla-Warburton regions. Apart from his extensive first-hand knowledge of the geology of many of these areas, his memory for the people and events of these areas is truly prodigeous.

Ian has made a major contribution to the success of the Geological Survey. Not only has he mapped too many areas to list here, but he can lay claim to a number of important 'firsts'. For example, in 1968 he organized and led the first in a series of popular GSWA safari-style public field excursions to describe and explain our geological mapping. Although well attended, this first excursion on the KURNALPI 1:250 000 sheet was well and truly eclipsed when he led the 1971 EDJUDINA 1:250 000 sheet excursion which, held during the height of the nickel boom, attracted a convoy of 92 vehicles and more than 200 people! Drawing on his experience with helicopter surveys undertaken jointly with the Bureau of Mineral Resources (now the Australian Geological Survey Organisation), in 1975 Ian also led GSWA's first independent helicopter mapping program. In just one month, this resulted in the successful mapping of extensive tracts of remote country across six 1:250 000 sheets in the Rudall–Nabberu region.

Ian has been involved in some of the most exciting discoveries made by GSWA. For example, in 1969 he found the Edjudina Meteorite, a bronzite chrondrite, about 30 cm across, and now in the Western Australian Museum. Later, his mapping of the Mount Narryer area contributed to the discovery of Western Australia's oldest rocks, and some of the oldest minerals (zircons) found on Earth. On subsequent mapping projects, his keen powers of observation resulted in the discovery of the 'chain of beads' (some of the earliest evidence of fossil seaweeds) in the Precambrian Stag Arrow Formation, and evidence of Proterozoic glaciation in what was until recently referred to as the Savory Basin. His ongoing interest in minerals led to his 1977 discovery of the new copper mineral moolooite, on Mooloo Downs Station in the Gascoyne region, and later to the discovery of the first Australian occurrence of jiangshinite ($MgMn_7.3H_20$).

Ian and his wife Anne have two children, Chris and Sarah, and three grandchildren.

Brian Moore

Born and raised in Perth, Brian enlisted in the Royal Australian Air Force (RAAF) in 1956. He qualified as a Motor Transport Fitter and enjoyed postings to many Air Force bases within Australia, as well as serving two and a half years at Butterworth Air Base, Malaysia. During his time in the RAAF, Brian was employed in a variety of positions relating to the to the maintenance, overhaul, and servicing of ground support equipment. Prior to his discharge, after 22 years service, he attained the rank of Warrant Officer in charge of a major Engineering Maintenance Squadron in Sydney.

Brian commenced work with the Geological Survey of Western Australia as a Stores and Transport Assistant in 1978. He was responsible for GSWA's vehicle fleet, associated field equipment, and the publication store, which at that time was located in Morley. The field support and expanded publication store is currently located in Carlisle, and Brian's responsibilities have increased to encompass the Department's communications system, and training of personnel in aspects of field safety. Brian and his staff instruct new field personnel in aspects of using four-wheel drive vehicles in the field, including 'hands-on' training in tyre changing and techniques, procedures in high-frequency radio communications, vehicle winching, first aid, and so on. As supervisor of Stores and Transport, Brian enjoys the challenge and the variety of work at GSWA's Carlisle depot, and believes that the support and safety of all field staff is paramount to the efficient and trouble-free operation of any field trip.

Brian and his wife Maria were married in 1960 and have two daughters and three grandchildren. They live in the Swan Valley and enjoy the open spaces and tranquil rural atmosphere of this beautiful, grape growing area. In the early part of his RAAF career, Brian enjoyed playing football, badminton, and table tennis, but these days his interests lie in fishing and the occasional caravan trip.

Suzanne Dowsett

Suzanne was born and educated in the United States of America. After graduating with a degree in Fine Arts from the Mississippi State College for women, she decided she would visit Australia for two years. After some research and following a recommendation, she arrived in Perth in October 1966 and a few weeks later found work in the Mines Department.

Suzanne's employment in the department has been in two parts. The first was from 1966 to 1970, where she was involved with the various aspects of geological map production. The second phase began in 1984 when she returned as a contractor, then entering into a job-sharing situation, before once again taking up a full-time position. During this period her duties were spread across most branches of the Surveys and Mapping Division. She eventually found her way back into geological mapping and began working in the publications section in 1989 — just in time to witness the begining of the computer era.

It was with great trepidation that Suzanne started working with computers, but within a very short time she became very efficient in its use, and these days cannot believe how we managed without them.

Outside of work Suzanne has many and varied interests, being a member of the W.A. Quilters Association, the Heritage Roses of Australia Society, the Cottage Gardeners' Circle and the W.A. Insect Study Group. Her other interests include reading, art, music, and early American and Australian antiques. With all these other interests Suzanne has still found time, with husband Dan, to make extensive renovations to their home.

There is a touch of irony to Suzanne's story — her daughter Leah has an ongoing fascination with long trips to America.

Obituary

Joseph Henry Lord, 1919–1999

Joe Lord passed away on 15 January 1999. Joe was Director of the Geological Survey from 1961 to 1980, and will be fondly remembered as the father of the modern Geological Survey of Western Australia.

Joseph Henry Lord was born in Salisbury, England, in 1919 and arrived in Western Australia with his parents in 1920. He was educated at Christ Church Grammar School, where he was school captain in his final year and an enthusiastic sportsman, playing Australian Rules football, cricket, and tennis. In 1941 he graduated from the University of Western Australia with a Bachelor of Science majoring in geology. Immediately upon graduation, Joe joined the RAAF and saw war service in Darwin and New Guinea as a Meteorological Officer, attaining the rank of Flight Lieutenant.

At the end of the Second World War, Joe began his geological career, joining GSWA in 1946 as a Geologist Class 2. Joe worked in many parts of Western Australia while with the Survey, but his most notable achievement was the location and delineation of the extensive coal reserves of the Muja Sub-basin of the Collie Basin.

Joe resigned from GSWA in 1953 to take up a position with the Commonwealth Bureau of Mineral Resources, and later with New Consolidated Goldfields of Australia Pty Ltd overseeing geological exploration throughout Australia.

In December 1960, Joe rejoined GSWA and on Matt Ellis's retirement six months later, assumed the role of Director, Geological Survey Branch. He set about a major reorganization and expansion of GSWA, recruiting geologists from Australia, New Zealand, Canada, and the United Kingdom. Over the 20 years he led the Survey, Joe succeeded in developing it into a modern scientific organization with enthusiastic, high-calibre staff.

It was during this time that the extensive natural resources of Western Australia were being developed: commercial oil had been discovered at Barrow Island; the Pilbara iron-ore mines were opening; nickel had been discovered at Kambalda; and the mineral sands industry was booming. Competition from private enterprise for experienced geologists was keen, and 20 of Joe's 51 geologists resigned, attracted by the substantially higher salaries being offered in industry.

Arguably, the two most outstanding achievements of GSWA were initiated during these difficult times. On the eve of Joe's retirement in 1980, fieldwork for the systematic geological mapping of the whole State at 1:250 000 scale was completed — 163 map sheets covering an area larger than most countries. Such basic geoscientific knowledge is essential to industry explorers.

The second main achievement was the provision of secure water supplies throughout Western Australia. Joe developed a competent team of hydrogeologists, whose work delineated extensive groundwater resources in the Perth region and most other regional centres of the State.

On his retirement as Director of the Geological Survey in 1980, Lord set up and initially directed the Western Australian Minerals and Petroleum Research Institute (WAMPRI; later to become the Minerals and Energy Research Institute of Western Australia — MERIWA). This Institute has been responsible for arranging funding and research of mineral and petroleum projects throughout Western Australia to the value of around $27.5 million.

Joe Lord was also a founding chairman of Geoconferences (WA) Inc. — a non-profit organization dedicated to the promotion of geoscience, and to the support of young geoscientists in the early stages of their careers. Joe held executive positions in several learned societies, including the Geological Society of London, Geological Society of Australia, Australasian Institute of Mining and Metallurgy, and Royal Society of Western Australia.

There is no doubt that Joe Lord's contribution to the understanding of the geoscientific framework of Western Australia has had a significant impact on ensuring that the mineral and petroleum industries continue to underpin the economy of Western Australia.

Staff list
(30 June 1999)

BLIGHT, David (Director)

Regional Geoscience Mapping Branch

GRIFFIN, Tim (General Manager)
TYLER, Ian (Acting Chief Geoscientist)

Bangemall Basin
MARTIN, David
THORNE, Alan

Earaheedy/Glengarry Basins
ADAMIDES, Nicos
HOCKING, Roger
JONES, Amanda
PIRAJNO, Franco

Eastern Goldfields
GROENEWALD, Bruce
PAINTER, Matthew
ROBERTS, Ivor

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

Southern Gascoyne Complex
OCCHIPINTI, Sandra
SHEPPARD, Steve

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

Geochemical Mapping
COKER, Julian [1]
McGUINESS, Sally
MORRIS, Paul
PYE, Karen
SANDERS, Andrew

Lennard Shelf
PLAYFORD, Phillip

Geochronology
NELSON, David

Geophysics
HOWARD, David
WATT, John

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

Map Production and GIS
BANDY, Stephen
BRIEN, Cameron
BURDEN, Phillip
COLDICUTT, Shaun
COLLOPY, Sean

[1] consultant or fee for service support

DAWSON, Brian
FLETCHER, Greg
FOX, Alistair
FRANCOIS, Annick
GREEN, Ellis
GREENBURG, Kay
HAMILL, Sammy
JOSE, Geoffrey
KIRK, John
KUKULS, Liesma (Les)
LADBROOK David
LENANE, Tom
LOAN, Geoff
PRAUSE, Michael
McCABE, Marian
TAYLOR, Peter
THEEDOM, Erica
VICENTIC, Milan
WALLACE, Darren
WILLIAMS, Brian

Data Integration
GOZZARD, Bob
DOWNING, John

Mineral and Petroleum Resources Branch

ROGERSON, Rick (General Manager)

Petroleum Initiative Basin Studies
APAK, Sukru (Neil)
BLUNDELL, Kelvin
CARLSEN, Greg
CROSTELLA, Angelo[1]
DE LEUW, Lorraine
GHORI, Ameed
IASKY, Robert
IRIMIES, Felicia
MOORS, Henry
MORY, Arthur
SHEVCHENKO, Sergey
STEVENS, Mark

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

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

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

Palaeontology
GREY, Kath

Library
CHEUNG, Eunice
CROSS, Robert
KNYN, Brian

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

Special Projects
GOSS, Andrew

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

Statutory Exploration Information Group
ARATHOON, Claudette
ARDEN, Lorraine[1]
BELL, Ann
BROWN, Brad
DALY, Matthew
DODD, Fiona
ELLIS, Margaret
EMMS, Rosie
FETHERSTON, Michael
FITTON, Ann
HAWORTH, Jeffrey
HUGHES, Bernard
KARNIEWICZ, George
LESIAK, Irena
LOPEZ, Annabelle
MASON, Jan Sandra
McCORQUODALE, Fiona
McGORRIN, Yvonne
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Staff movements (1 July 1998 to 30 June 1999)

Internal transfer
CAREW, Eugene — to Stores and Transport

Internal reclassifications
EVANS, Elaine — to Level 2
MIKUCKI, Jenny — to Level 6
SMITHIES, Hugh — to Level 6
WATT, John — to Level 5

Commencements
BELL, Ann
BROWN, Bradley
DAY, Lyn
DODD, Fiona
EMMS, Rosie
FITTON, Ann
FLETCHER, Greg
HALL, Glennis
KING, Jonathon
MARNHAM, Jodi
McGUINESS, Sally
MOORS, Henry

Resignations
COPP, Iain
DOMBROWSKI, Peter
FAULKNER, Joan
JONES, Katherine
KING, Jonathon
MATHEWS, Leon
MYERS, John
VAN BURGEL, Gerrit
YAZIN, Raza

Retirements
BACKHOUSE, John

Transfer in
DALY, Mathew — from Chemistry Centre

Transfers out
LOPEZ, Annabelle — to Chemistry Centre
SAINT, Joan — to MTD

Casual and Fee for service
ARDEN, Lorraine
BELL, Ann
BUI, Dac Dung
COKER, Julian
CROSTELLA, Angelo
DAY, Lyn
D'ERCOLE, Cecilia
EMMS, Rosie
FITTON, Ann
FRANCHITTO, Angelo
GARDNER, Yasmine
GORDEN, Nyree
GUTTRIDGE, Sandra
HARRISON, Samantha
HOSKING, Pat
JOCKEL, Fergus
LENNOX-BRADLEY, Shaun
MacKAY, Anthony
McGUINESS, Sally
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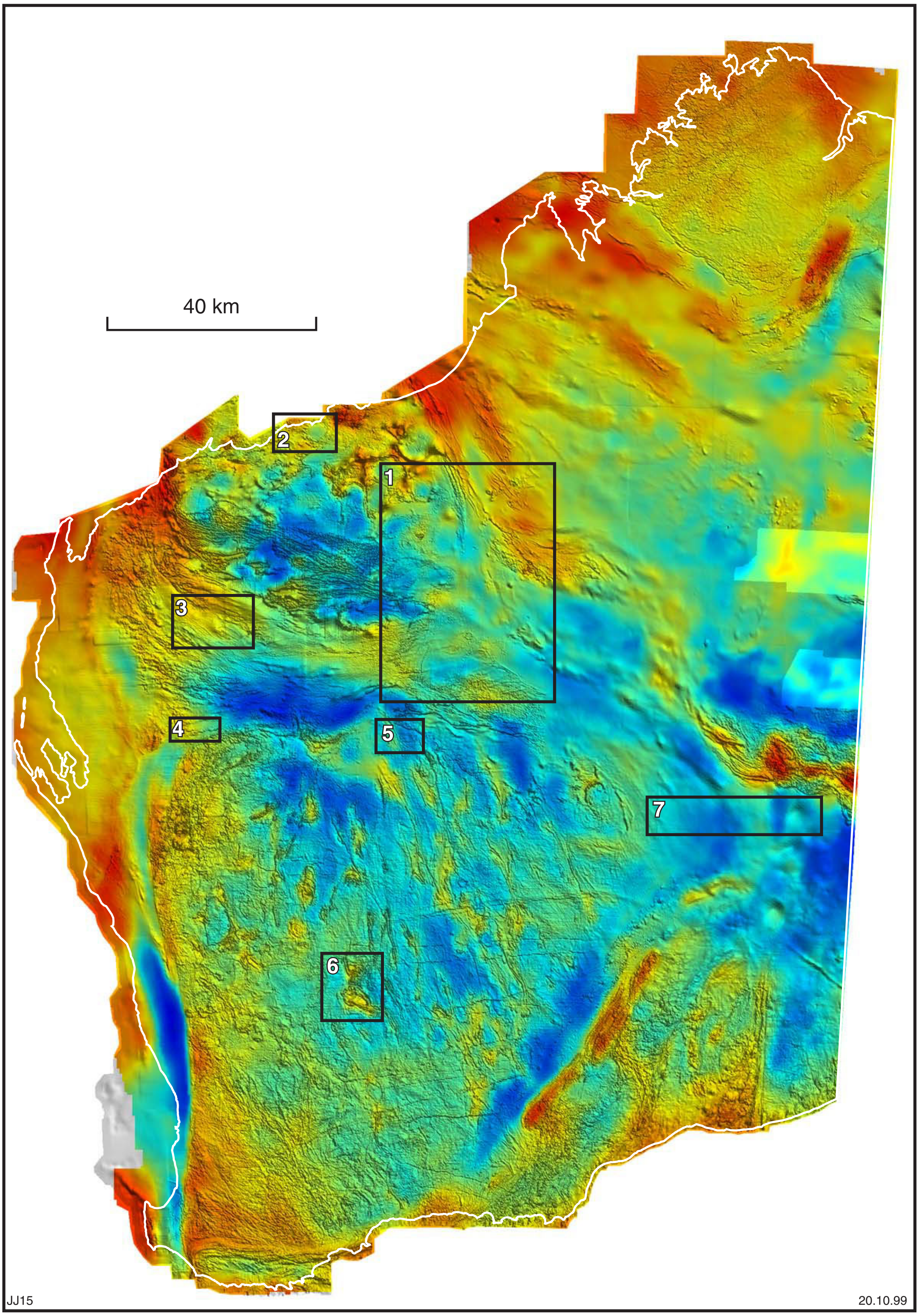

Map of Western Australia showing the locations discussed in the seven technical papers on the following pages. Pseudo-colour Bouguer gravity image and grey-scale Total Magnetic Intensity. Blue = gravity low; TMI highlights structural information. Data courtesy of Australian Geological Survey Organisation

Technical papers

Neoproterozoic successions of the northwestern Officer Basin: a reappraisal

by L. Bagas[1], K. Grey, R. M. Hocking, and I. R. Williams

Abstract

Stratigraphic units previously assigned to the Savory Group of the Savory Basin are a continuation of the Officer Basin succession. Continuing to use 'Savory Basin' as a separate structural entity cannot be justified, and the area is here referred to as the northwestern Officer Basin. The Savory Group, the main fill of the former Savory Basin, comprises two main packages of sedimentary rocks separated by a 150 to 200 m.y. hiatus. The name Savory Group is, therefore, no longer tenable and is replaced by new terminology. The name Sunbeam Group is introduced for the older package, which is approximately 800 m.y. old. The name Boondawari Formation is retained for an approximately 600 m.y. old, partly glacigenic formation. The overlying package, previously the upper Savory Group, is here named the Disappointment Group. The group excludes the Durba Sandstone, at the top of the succession.

KEYWORDS: Centralian Superbasin, Officer Basin, Savory Basin, Savory Group, Sunbeam Group, Boondawari Formation, Disappointment Group, Proterozoic, stratigraphy.

The northwestern part of the Officer Basin extends between the Archaean Pilbara and Yilgarn Cratons to about 100 km east of Newman (Fig. 1). The area was originally regarded as the eastern part of the Mesoproterozoic Bangemall Basin (Williams et al., 1976; Muhling and Brakel, 1985), although Grey (1978) suggested a younger age based on stromatolites. It was elevated to separate basin status, as the Savory Basin, with the discovery firstly of an unconformity apparently within the Bangemall Group, and secondly of glacigene sedimentary rocks that confirmed the Neoproterozoic age of the rocks above the unconformity (Williams, 1987). The basin's contents were named the Savory Group (Williams, 1992).

Williams (1992, p. 9 and 92) suggested that the rocks in the Savory Group were deposited in a marginal sag basin that developed along the Palaeoproterozoic to Mesoproterozoic Capricorn Orogen, the site of a collision between the Archaean Pilbara and Yilgarn Cratons at c. 1.84 Ga. Biostratigraphic and lithostratigraphic similarities between the Savory, Officer, and Amadeus Basins lead to the conclusion that all are, in part, coeval and probably linked under Phanerozoic rocks (Grey, 1978, 1995; Williams, 1992, p. 9). Walter and Gorter (1994), Walter et al. (1995), and Grey (1995) have made correlations between the major Neoproterozoic basins of central Australia and suggested that deposition commenced in a single large sag basin, the Centralian Superbasin, after about 850 Ma. The Centralian Superbasin includes the Officer, Savory, Amadeus, Ngalia, and Georgina (part only) Basins.

This intracratonic superbasin was disrupted internally by a central uplift during the Paterson Orogeny (or Petermann Ranges Orogeny of central Australia; Walter et al., 1995), between 560 and 525 Ma. Separate depocentres then formed in each of the basins. Walter and Gorter (1994) and Walter et al. (1995) recognized four major successions in the superbasin, referred to as Supersequences 1 to 4, which could be correlated between individual basins using sequence stratigraphy, biostratigraphy, isotope chemostratigraphy, seismic interpretation, magnetostratigraphy, and limited radiometric dating. Phanerozoic rocks in the Officer Basin (Table Hill Volcanics and above) were included in the Gunbarrel Basin by Hocking et al. (1994).

Status of the Savory Basin

Bagas et al. (1995) proposed that the Tarcunyah Group, in the northeastern part of the area (Fig. 1), is a correlative of the lower part of the Savory Group. They further proposed that the Tarcunyah and the lower Savory Groups are also equivalent to Supersequence 1 of the Centralian Superbasin (Walter et al., 1994; Walter et al., 1995), and are part of the Officer Basin, rather than components of a separate basin. Detailed seismic interpretation by Perincek (1996) improved this

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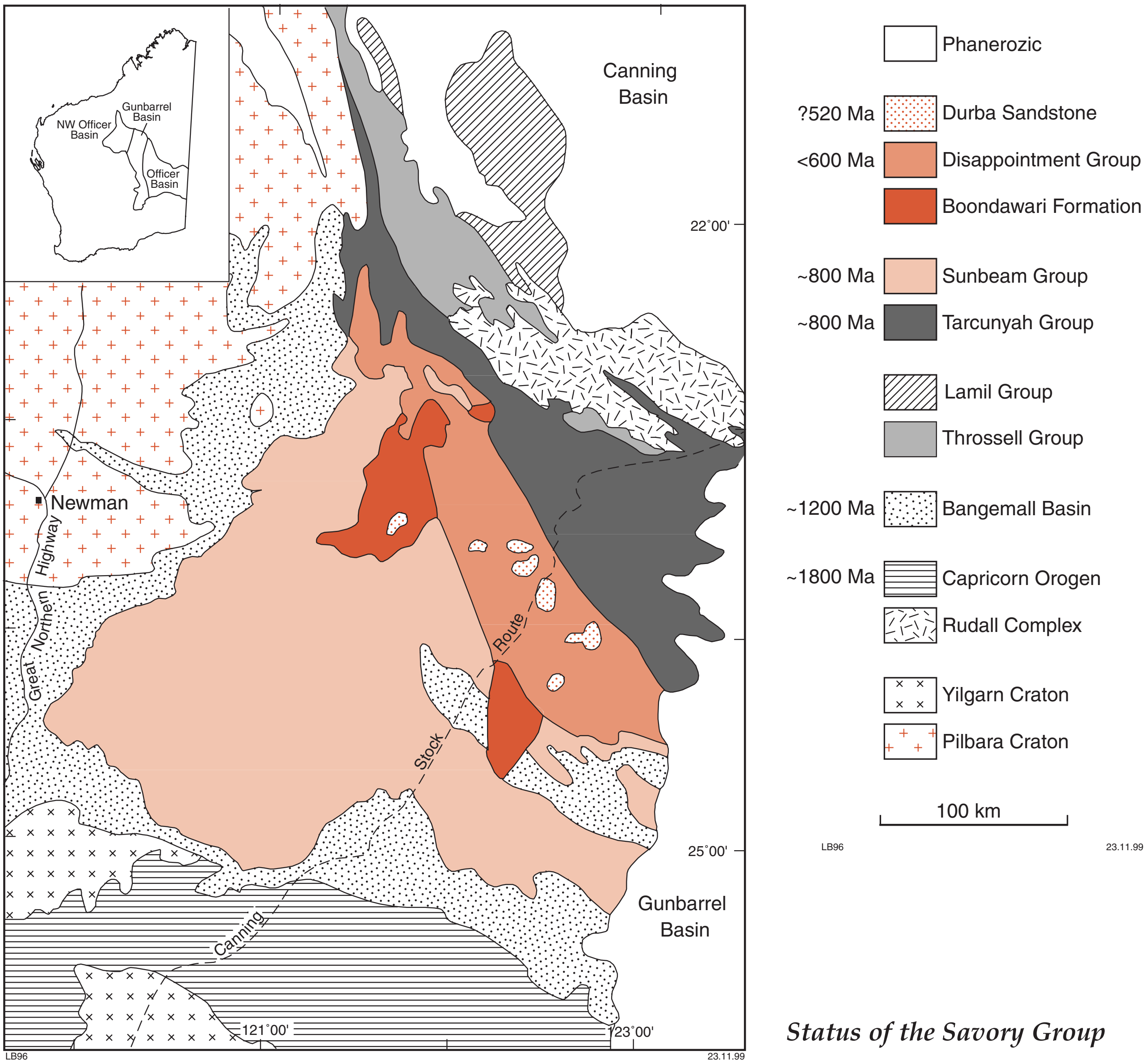

Figure 1. Regional setting of the northwestern part of the Officer Basin

correlation, which has since been further strengthened using stromatolites and palynology (Grey and Cotter, 1996; Grey and Stevens, 1997; Stevens and Grey, 1997; Grey, unpublished data).

These correlations led recent workers to use the name Savory Sub-basin to indicate its status as a sub-component of the Officer Basin (Grey and Cotter, 1996; Grey and Stevens, 1997; Stevens and Grey, 1997; Stevens and Carlsen, 1998). However, it is not strictly a sub-basin, but simply a northwestern preserved part of the Officer Basin where there is no Phanerozoic cover. The terms Savory Basin and Savory Sub-basin are here abandoned, although Savory region remains a useful geographic reference to the area where Neoproterozoic rocks are exposed. Its subdivisions (Wells and Blake Sub-basins, Trainor Platform) are retained as tectonic subdivisions of the Officer Basin, and have similar status to sub-divisions such as the Gibson and Yowalga Sub-basins (Hocking et al., 1994). The name Wells Sub-basin is here revised from Wells Foreland Basin to remove genetic-model implications.

Status of the Savory Group

The presently understood Savory Group (Williams, 1992) includes two major successions separated by a hiatus of 150 to 200 m.y. (million years), and the Durba Sandstone (Walter et al., 1995; Bagas et al., 1995). The recognition of this hiatus requires that the two successions be separated, and the name Savory Group be abandoned.

The stratigraphic names used for the remainder of the Officer Basin in Western Australia cannot be used in the former Savory Basin because precise correlations between constituent formations are still uncertain. Phanerozoic cover between the two areas obscures the Neoproterozoic succession. Nor can the terminology for the Tarcunyah Group, to the northeast, be extended to the lower (older) succession in the former Savory Group because the two are geographically separated either by a younger (upper) succession, or by faulting (Williams, 1992). Consequently, separate new names are proposed for the lower succession (Sunbeam Group, after Sunbeam Creek on TRAINOR*), and the upper succession (Disappointment Group, after Lake Disappointment on GUNANYA) of the former Savory Group. The Durba Sandstone is ungrouped, above the Disappointment Group; and the Boondawari Formation lies between the Sunbeam and Disappointment Groups. The Sunbeam Group may include an unconformity at the base of the Spearhole Formation (Fig. 2), possibly due to the marginal setting of the Savory region. If present, it is minor and is here ignored for lithostratigraphic purposes.

Geological setting and correlation

The mid- to late-Neoproterozoic (850–544 Ma) rocks of the Savory region (northwestern Officer Basin) unconformably overlie, or are in faulted contact with, the Mesoproterozoic Bangemall Group to the west and south, and older parts of the Palaeoproterozoic to Neoproterozoic Paterson Orogen in the northeast (Williams and Bagas, in press). These Neoproterozoic rocks continue eastwards beneath Phanerozoic sedimentary and volcanic rocks of the Gunbarrel Basin (Hocking et al., 1994) into the Officer Basin of central Australia (Perincek, 1996). There are two inliers in the region, the Oldham and Ward Inliers. Rocks in these inliers may correlate with the Collier and Edmund Subgroups of the Bangemall Group, or with the Throssell Group of the Yeneena Supergroup (Hocking, Grey and Bagas, unpublished data).

The Paterson Orogen has three subdivisions: the Palaeoproterozoic Rudall Complex, the Mesoproterozoic to Neoproterozoic Yeneena Supergroup, and the Neoproterozoic Tarcunyah Group (Bagas et al., 1995). The Yeneena Supergroup is a redefinition of the 'Yeneena Group' of Williams et al. (1976), and comprises the Mesoproterozoic to Neoproterozoic Throssell and Lamil Groups (Williams and Bagas, in press). The Karara Formation, previously regarded as younger than the Yeneena Group, was recently included in the Neoproterozoic Tarcunyah Group (Bagas et al., 1995).

Similar rock types are present in the approximately 800 m.y. old Tarcunyah and Sunbeam Groups (Figs 1 and 2). Both groups contain a basal sandstone and conglomerate; the Googenhama Formation, and the Glass Spring Formation and its lateral equivalents, respectively (Fig. 2). Carbonate units of the Mundajini, Skates Hills, Waters, and Waroongunyah Formations overlie the basal sandstone succession in the Tarcunyah and Sunbeam Groups. These carbonates contain the *Acaciella australica* Stromatolite Assemblage (characteristic of the Browne Formation of the Officer Basin, the Bitter Springs Formation of the Amadeus Basin, and the Yackah beds of the Georgina Basin; Stevens and Grey, 1997; Hill et al., in press), and the *Baicalia burra* Stromatolite Assemblage (characteristic of the Kanpa Formation of the Officer Basin, and the Burra Group of the Adelaide Rift Complex; Preiss, 1987; Walter and Veevers, 1997; Hill et al., in press). The stromatolite assemblages are consistent with a Supersequence 1 age. In the Adelaide Rift Complex, the *Acaciella australica* Assemblage occurs stratigraphically below the 802 ± 10 Ma Rook Tuff (Fanning et al., 1986), while the *Baicalia burra* Assemblage occurs above it. Furthermore, both the Sunbeam and Tarcunyah Groups contain red beds, siltstone, shale, and significant intervals of evaporites, intercalated with stromatolitic carbonates. This lithological association is characteristic of Supersequence 1 throughout much of the Centralian Superbasin (Walter et al., 1995).

The younger Brownrigg, Yandanunyah, Wongarlong, and Nooloo Formations in the Tarcunyah Group do not have direct correlatives in the Sunbeam Group (Fig. 2), although they may correspond to the Hussar and Kanpa Formations to the southeast. Both the Tarcunyah Group and more northerly exposures of the Sunbeam Group underwent folding and faulting during the Paterson Orogeny prior to, or partly contemporaneous with, the deposition of the unconformably overlying Disappointment Group (Williams, 1992; Bagas et al., 1995).

Supersequence 2 is apparently absent in Western Australia, indicating a significant break in deposition of between 150 and almost 200 m.y. (Grey et al., 1999). This period marks uplift and erosion associated with firstly the Areyonga and then the Souths Range Movements in central Australia (Walter et al., 1995). It also corresponds to the Blake Movement (Williams, 1992), which affects the Sunbeam Group and, to a lesser extent, the Tarcunyah Group.

In addition to the date of c. 800 Ma inferred from stromatolite correlations, the age of deposition of the Tarcunyah and Sunbeam Groups is constrained by the unconformably overlying glacigenic rocks of the Boondawari Formation (Supersequence 3). These are retained as a separate formation, but they may well be subdivided and raised to group status in the future. They are correlated with the Marinoan glaciation of the c. 600 Ma Supersequence 3 (Walter et al., 1994; Bagas et al., 1995; Grey, 1995).

The Boondawari Formation is unconformably overlain by the sandstone succession of the McFadden, Tchukardine, and Woora Woora Formations, here collectively called the Disappointment Group. The group was deposited in the Wells Sub-basin during the onset of tectonism (Williams, 1992) associated with the c. 550 Ma Paterson Orogeny (as redefined by Bagas and Smithies, 1998). This sandstone succession is a probable correlative of the c. 580–544 Ma (Walter and Veevers, 1997) latest Supersequence 3 or early Supersequence 4 of the Centralian Superbasin. The Durba Sandstone overlies the Disappointment Group, and may be separated from it by a significant disconformity.

Conclusions

This reappraisal of the lithostratigraphy and tectonic history of the Officer Basin provides a clearer understanding of the Neoproterozoic

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

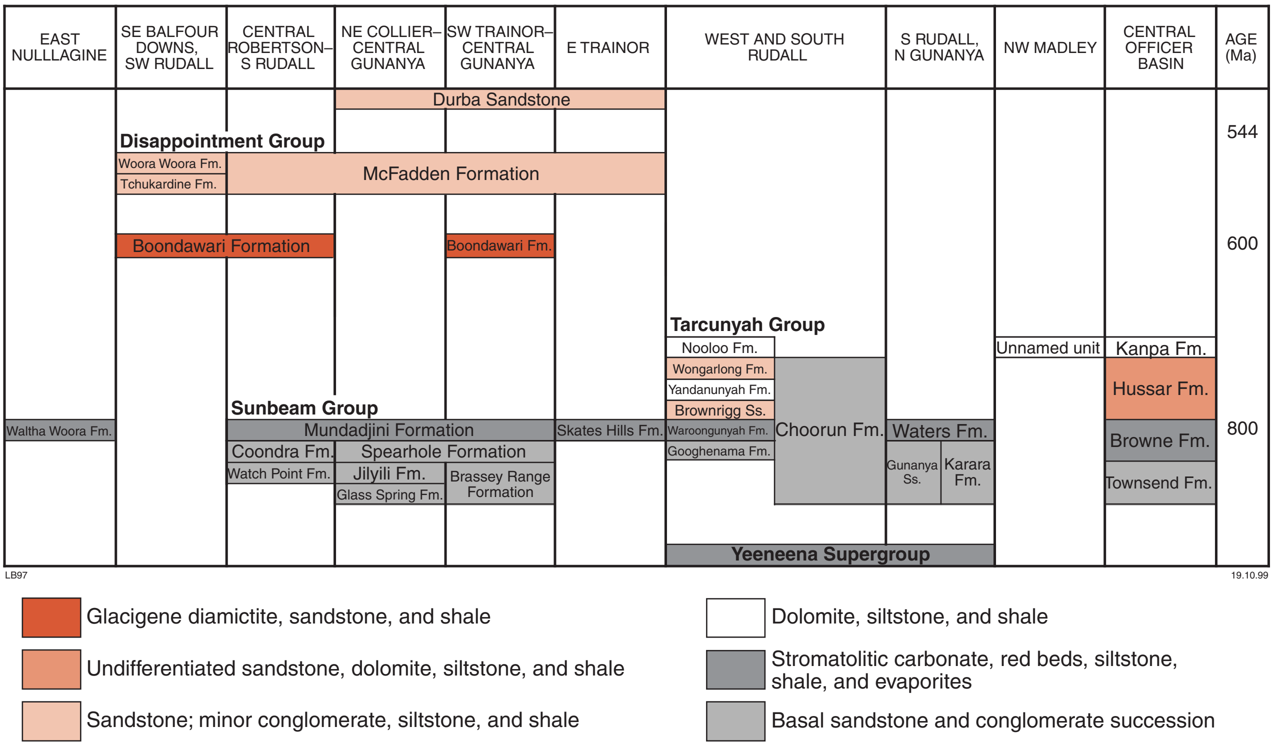

Figure 2. Generalized stratigraphic correlations between the Tarcunyah and Sunbeam Groups of the northwestern Officer Basin, and parts of the central Officer Basin. Column headings are areas within standard 1:250 000 map sheets, except for the more general central Officer Basin

history of Western Australia. Firstly, the former Savory Basin is subsumed within the Officer Basin, and the name Savory Sub-basin is dropped entirely. Secondly, a significant unconformity is recognized within the 'Savory Group', so that the name is abandoned and replaced by the names Sunbeam and Disappointment Groups, with the Boondawari Formation and Durba Sandstone as ungrouped units. The Sunbeam Group is part of Supersequence 1 of the Centralian Superbasin. The Boondawari Formation is part of Supersequence 3 and has lateral equivalents ranging from the Olympic Formation/Pioneer Sandstone to the Julie Formation in the Amadeus Basin. The Disappointment Group is part of latest Supersequence 3 or earliest Supersequence 4, as tentatively suggested by Walter and Gorter (1994), and is a probable lateral equivalent of the Arumbera Sandstone of the Amadeus Basin. Furthermore, the Sunbeam Group is here correlated with part of the former Yeneena Group (the Tarcunyah Group; Fig. 2), making the Tarcunyah Group part of the Officer Basin. This in turn allows correlation with the Centralian Superbasin. The Centralian Superbasin is thus extended to the northwest to include the areas covered by the Tarcunyah Group and former Savory Group.

Appendix 1

Sunbeam Group (*new name*)

Derivation of name: After Sunbeam Creek (Lat. 24°55'S, Long. 122°18'E) on TRAINOR.

Distribution: The constituent formations are the Glass Spring, Jilyili, Brassey Range, Watch Point, Coondra, Spearhole, Mundadjini, and Skates Hills Formations. The group is exposed on southeast BALFOUR DOWNS, eastern ROBERTSON, southwest GUNANYA and TRAINOR, western MADLEY, northeast BULLEN and NABBERU, northern STANLEY, and northwest HERBERT.

Lithology: Sandstone, siltstone, conglomerate, shale, mudstone, dolomite, stromatolitic dolomite, and evaporite.

Thickness: About 5500–6000 m.

Relationships and boundary criteria: The Sunbeam Group unconformably overlies, or is in faulted contact with, various Mesoproterozoic units of the Bangemall Basin (Martin et al., 1999), including the Scorpion, Collier, and Manganese Groups around the northwestern, western, and southern margins, and the rocks in the Oldham and Ward Inliers. It is a lateral equivalent of the oldest part of the Officer Basin succession (Supersequence 1) to the east, and the Tarcunyah Group to the northeast of the Disappointment Group as defined here. In the northeast, it is unconformably overlain or in faulted contact with the Boondawari Formation and the Disappointment Group, as defined here. Permian rocks along the eastern margin unconformably overlie it.

Age and evidence: The main evidence for the age of the Sunbeam Group is the presence of the *Acaciella australica* Stromatolite Assemblage in the Skates Hills Formation. By correlation with other parts of the Centralian Superbasin, the Sunbeam Group has an age of slightly older than 800 Ma (Grey, 1995; Grey and Stevens, 1997). Palynological samples support the age of the group (Grey and Stevens, 1997). It is older than the overlying Boondawari Formation, which contains diamictite and cap dolomite of Marinoan age (Walter et al., 1995).

Synonymy: The Sunbeam Group was previously the older part of the Savory Group.

References: Williams (1987, 1992, 1994); Williams and Tyler (1991); Grey (1995); Grey and Stevens (1997).

Notes: The recognition of a 150 to 200 m.y. hiatus between the Skates Hills Formation and the Boondawari Formation necessitates the abandonment of the former Savory Group. The Sunbeam Group includes stratigraphic units below the Boondawari Formation that are equivalent in age to Supersequence 1 of the Centralian Superbasin.

Disappointment Group *(new name)*

Derivation of name: After Lake Disappointment (Lat. 23°30'S, Long. 122°40'E) on GUNANYA.

Distribution: The constituent formations are the McFadden, Tchukardine, and Woora Woora Formations. The group is exposed on southeast BALFOUR DOWNS, southwest RUDALL, TRAINOR, and western MADLEY.

Lithology: Sandstone, siltstone, and conglomerate

Thickness: About 1500–1800 m.

Relationships and boundary criteria: The group overlies, or is in faulted contact with, the Mesoproterozoic Manganese Group of the Bangemall Basin, the Sunbeam Group, and the Boondawari Formation. In the northeast, it is in faulted contact with, or unconformably overlies, the Tarcunyah Group.

Age and evidence: There is no direct evidence for the age of the Disappointment Group, but it overlies the Marinoan diamictite and cap dolomite of the Boondawari Formation and is therefore probably a lateral equivalent of either upper Supersequence 3 or Supersequence 4 of the Centralian Superbasin. It is associated with the onset of tectonism (Williams, 1992) during the c. 550 Ma Paterson Orogeny (Bagas and Smithies, 1998).

Synonymy: The Disappointment Group was previously the youngest part of the Savory Group.

References: Williams (1987, 1992, 1994); Williams and Tyler (1991); Bagas et al. (1995); Bagas and Smithies (1998).

Notes: The Disappointment Group includes most younger units of the former Savory Group that unconformably overly both the Sunbeam Group and the Boondawari Formation. They are equivalent in age to the upper part of Supersequence 3 or to Supersequence 4 of the Centralian Superbasin, but may be separated from the Durba Sandstone by a significant hiatus.

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High-Mg diorite from the Archaean Pilbara Craton; anorogenic magmas derived from a subduction-modified mantle

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

Abstract

Archaean high-Mg diorite (sanukitoid), hitherto described only from Canadian Archaean provinces, is identified in the Mallina Basin of the Pilbara Craton, Western Australia, where it intrudes the metasedimentary rocks in a late-tectonic, extensional setting associated with felsic alkaline magmatism. High-Mg diorite is characterized by unusually high Mg# (~60), Cr, and Ni for Archaean felsic rocks. The suggested source for these rocks is mantle, metasomatized by a tonalitic melt possibly derived from subducted oceanic crust. However, while subduction appears a necessary precursor, a direct relationship between high-Mg diorite and subduction is negated by the late- to post-tectonic setting. The Pilbara high-Mg diorite suite is a result of remelting of a metasomatized subcrustal source, during a c. 2950 Ma thermal event that probably represented either a plume or lower crustal delamination. Archaean terrains that contain high-Mg diorite also display independent evidence of subduction. These rocks are absent from the eastern part of the Pilbara Craton, where evidence for a post-3440 Ma subduction history is contentious. A spatial relationship between high-Mg diorite and gold mineralization may reflect a common structural control.

KEYWORDS: Archaean, magnesium diorite, granitoid, Pilbara Craton

Archaean high-Mg diorite was first described from the Superior Province of Canada by Shirey and Hanson (1984), who referred to it as 'Archaean sanukitoid' because of geochemical similarities to Miocene high-Mg andesite (sanukite) of the Setouchi volcanic belt in Japan. High-Mg diorite shows higher Mg#[3] (>60) and significant enrichments in Cr and Ni, as well as large ion lithophile elements (LILE e.g. Ba, Sr), compared to most other Archaean igneous rocks of comparable silica content (55–60 wt%). It is parental, via a process of fractional crystallization, to rocks in the compositional range of granodiorite and (rarely) monzogranite, in which these compositional features persist and clearly distinguish this 'high-Mg diorite series' from other Archaean granites. Estimates that these rocks may comprise up to 25% of the Superior Province, and compositional similarities to average Archaean crust, have led to the suggestion that their origin is an important factor in evaluating Archaean crustal evolution (Sutcliffe et al., 1990; Stern and Hanson, 1991; Kelemen, 1995).

We have identified a series of intrusions in the Mallina Basin of the Pilbara Craton (Fig. 1) that together form a high-Mg diorite suite. Like their Canadian counterparts, they intruded a late- to post-tectonic (anorogenic) setting. One pluton, the Peawah Granodiorite, is dated at 2948 ± 5 Ma (Nelson, 1996), and the remainder show intrusive or structural relationships (or both) consistent with a similar emplacement age. The suite was emplaced before voluminous, K-rich, crustally derived syenogranite and monzogranite at c. 2935 Ma, but synchronous with the alkaline Portree Granitoid Complex. In this paper, we briefly document field, petrographic, and geochemical features of the Pilbara high-Mg diorite suite, and discuss their petrogenesis, their significance in terms of crustal evolution, and conclude with some observations related to their possible economic significance.

Regional geology

The granite–greenstone terrane of the Pilbara Craton can be divided into eastern, central, and western components on the basis of distinct structural styles and stratigraphy, and the temporal patterns of granite intrusion. Tonalite–trondhjemite–granodiorite

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3 $Mg^{\#} = Mg^{2+}/(Mg^{2+}+Fe_{Total})\times100$ with Fe_{Total} as Fe^{2+}.

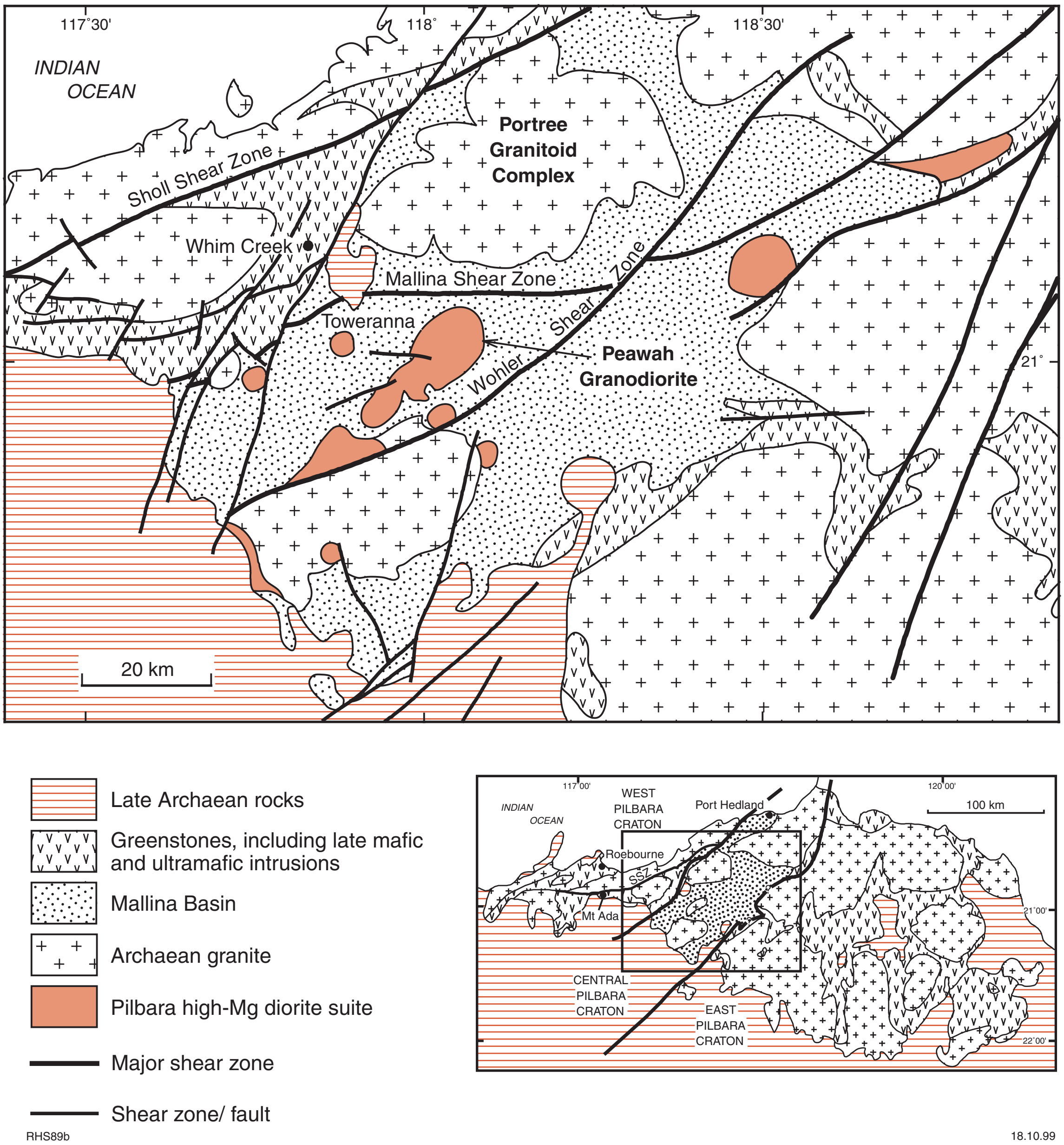

Figure 1. The geology of the central part of the Pilbara granite–greenstone terrane

(TTG)* is a significant but not dominant component of the overall felsic magmatism in the craton (Champion and Smithies, 1998). The older (c. 3600 to 2850 Ma), eastern part of the craton is dominated by large, ovoid, domal, granitoid complexes and enveloping greenstones (Fig. 1). Here, intrusion of TTG, possibly representing juvenile continental crust, was restricted to the period before c. 3420 Ma, thus being essentially confined to the older portions of the Shaw (Bickle et al., 1993) and Mount Edgar (Collins, 1993) Granitoid Complexes. In contrast, the western part of the region is characterized by linear, north-easterly trending outcrop patterns (Fig. 1), with younger and episodic TTG magmatism at c. 3260 Ma, 3100–3120 Ma, and 2990 Ma. The remaining felsic intrusive rocks in the eastern and western parts of the craton include tonalites, trondhjemites, and granodiorites, and later monzogranites and syenogranites. These have higher K_2O (Fig. 2), Y and Yb, lower Al_2O_3, and usually lower La/Yb and Sr, and complex zircon inheritance patterns compared to TTG. They are interpreted to result from low-pressure partial melting, probably of earlier TTG crust (Champion and Smithies, 1998).

* Our use of TTG equates with the high-Al rocks of Barker (1979), characterized at SiO_2 of 70 wt% by Al_2O_3 >15 wt%, low K_2O, low Yb (<1 ppm), high La/Yb (generally >30), Sr and Ba both >500 ppm, and Na_2O/K_2O >1.

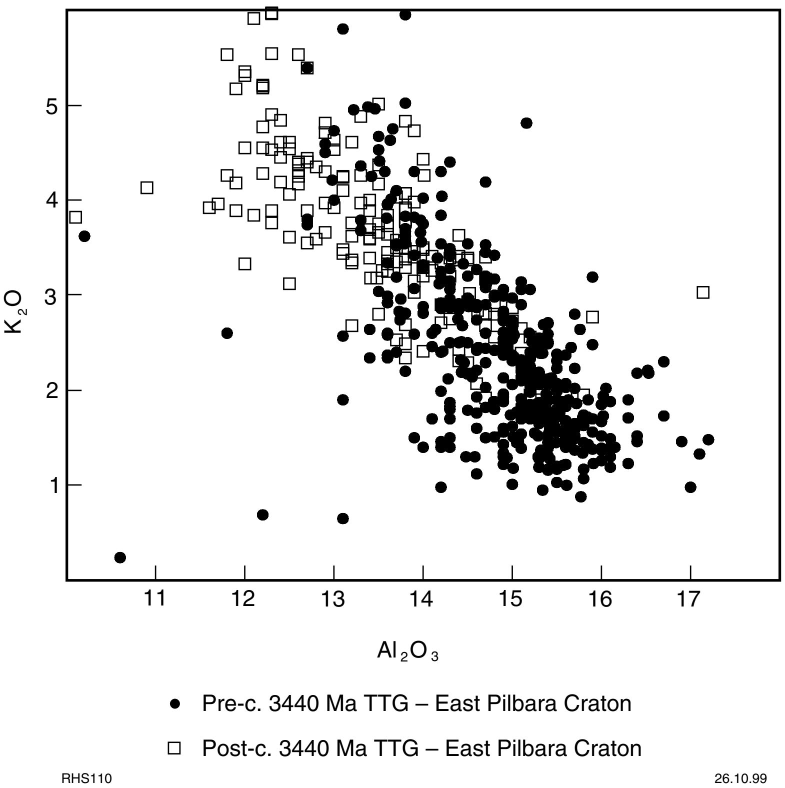

Figure 2. Compositional variation diagram showing the generally more potassic composition of the younger (post-c. 3400 Ma) TTG rocks of the eastern part of the Pilbara Craton

The eastern and western parts of the northern Pilbara Craton are separated by the thick and extensive turbiditic deposits of the c. 3015 to 2940 Ma Mallina Basin, which forms the bulk of the central part of this region (Fig. 1). No TTG outcrops in this region. The high-Mg diorite suite and the alkaline Portree Granitoid Complex intruded the Mallina Basin at c. 2950 Ma and represent virtually the entire exposed products of magmatism of that age. Both suites of rocks intruded the basin at a subvolcanic level, during a second phase of basin extension and deposition that does not appear to be related to subduction. Intrusions that form the high-Mg diorite suite together define an east-northeasterly trending belt that extends for over 200 km (Fig. 1), and parallels the long axis of the Mallina Basin. Late, K-rich granites, which intruded at c. 2935 Ma, are also focused on this central region, and become less voluminous to the west and east.

High-Mg diorite suite

Petrography

The rocks of the Pilbara high-Mg diorite suite range from diorite and monzodiorite through to granodiorite and rare monzogranite. Mesocratic granodiorite dominates within all intrusions of the suite. Plagioclase is the main constituent. Hornblende is the dominant mafic mineral, commonly with cores of either diopside, or actinolite after clinopyroxene. Biotite commonly mantles hornblende. Some samples of diorite also contain bronzite as discrete subhedral grains or as anhedral cores to clinopyroxene phenocrysts. One conspicuous feature of the high-Mg diorite suite is the presence of common, mostly ovoid, enclaves up to 1 m long, which represent the earlier crystallized parts of the magma.

Geochemistry

According to Stern and Hanson (1991), the essential characteristics of least fractionated high-Mg diorite (i.e. with <60 wt% SiO_2) include MgO >6 wt%, $Mg^\#$ >60, Ni and Cr each >100 ppm, Sr and Ba each >500 ppm, and high Na_2O, K_2O, light rare-earth elements, and La/Yb. The least fractionated rocks of the Pilbara high-Mg diorite suite approximate these compositions, with $Mg^\#$ between 55 and 62, SiO_2 as low as 59 wt%, and up to 224 ppm Cr (Fig. 3) and 120 ppm Ni. The rocks of the Pilbara high-Mg diorite suite vary in silica content (Fig. 3) between approximately 59 and 70 wt%, with high $Mg^\#$ (>60 to 40). The rocks show moderate concentrations of Na_2O and K_2O, from 3.5 to 4.8 wt% and 1.7 to 3.3 wt% respectively. High $Mg^\#$ are accompanied by high concentrations of Cr (up to 210 ppm), Ni (up to 100 ppm) and V (up to 110 ppm). Amongst the LILE, the concentrations of Sr and Ba are high (Sr of 300–950 ppm; Ba of 450–1600 ppm), but show no clear correlation with silica or $Mg^\#$, or with each other. Chondrite-normalized La/Yb ratios increase from approximately 18 to 53 with decreasing $Mg^\#$, largely reflecting decreasing concentrations of the heavy rare-earth elements. No Eu anomaly is observed throughout the range of silica contents.

A comparison of the Pilbara high-Mg diorite suite with TTG from the eastern part of the Pilbara Craton shows that both groups have distinctively high LILE and low Nb, Ta, Y, and Yb concentrations, even though the Pilbara high-Mg diorite suite has lower SiO_2, and higher $Mg^\#$, MgO, Cr, and Ni. Notable exceptions are some c. 3.45 Ga tonalite gneisses from the Shaw Granitoid Complex (Bickle et al., 1993), which appear to lie compositionally between the high-Mg diorite series and TTG (Fig. 4).

Petrogenesis

A fundamental tenet of igneous petrology is that partial melting cannot produce a liquid with a higher $Mg^\#$ than the source (Wilson, 1993). The low $Mg^\#$ of crustal rocks suggests that they cannot be a source for high-Mg diorite. This is true even for Archaean basalt, including those of the Pilbara Craton, which typically have $Mg^\#$ <60 (Glikson et al., 1986). The source for high-Mg diorite must have

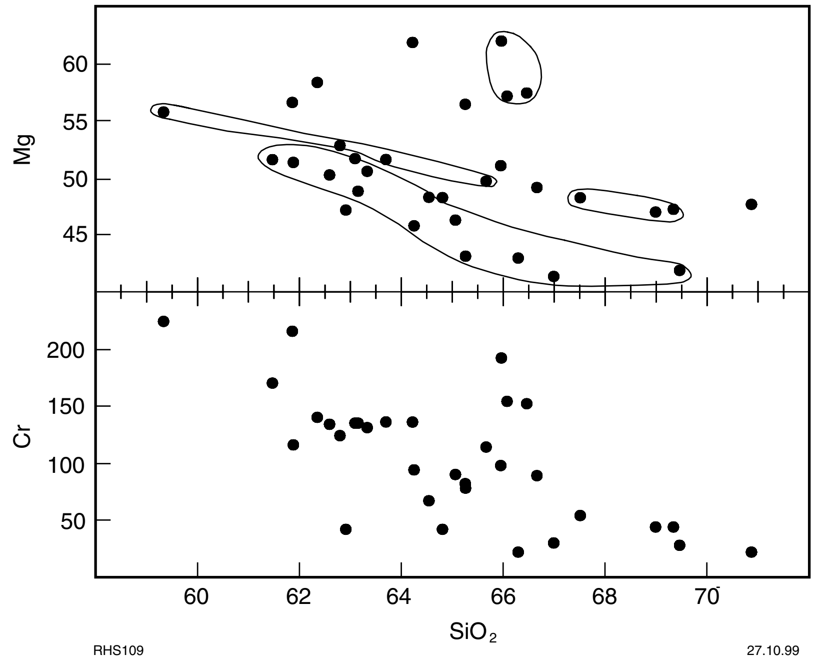

Figure 3. Compositional variation diagram for rocks of the Pilbara high-Mg diorite suite. Groups represent individual intrusions

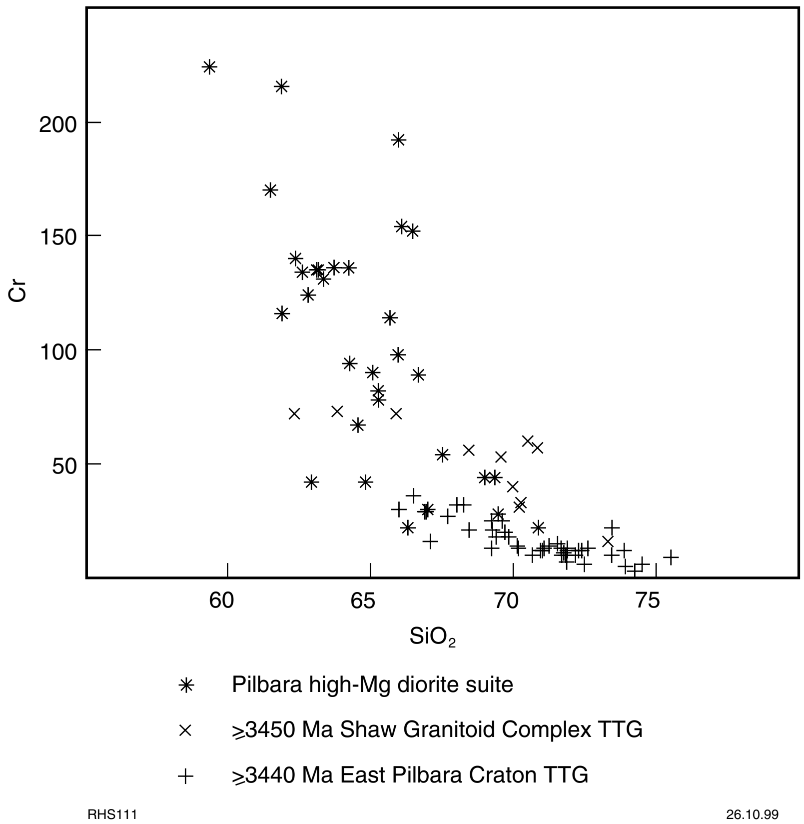

Figure 4. Compositional variation diagram comparing old (≥3450 Ma) TTG rocks of the Shaw Granitoid Complex with other TTG rocks from the eastern part of the Pilbara Craton and with rocks of the Pilbara high-Mg diorite suite

incorporated material with higher $Mg^{\#}$, such as mantle. However, this is unlikely to occur via crustal contamination of a mantle melt, as high-Mg diorite typically has higher LILE concentrations than most crustal material (Stern et al., 1989). Similarly, for the Pilbara high-Mg diorite suite, the fact that some intrusions with higher SiO_2 have higher $Mg^{\#}$ than intrusions with lower SiO_2 (Fig. 3) also suggests that crustal contamination of mantle-derived melt is not a viable mechanism. High LILE concentrations in high-Mg diorite are also accompanied by depletions in Nb, Ta and TiO_2, imparting a distinctive subduction zone signature on the rocks, and suggesting LILE enrichment of a mantle source in an arc environment (Pearce, 1982).

Shirey and Hanson (1984) recognized the compositional similarities between high-Mg diorite and Miocene high-Mg andesite – mantle melts related to active subduction, and accordingly postulated melting of a subduction-modified mantle source. Extending this idea further, Drummond et al. (1996) suggested that high-Mg diorite may form via contamination of Archaean TTG, produced through partial melting of subducting oceanic crust, with mantle peridotite. Archaean TTG is a close *compositional* analogue of Phanerozoic adakite (dacitic magmas with low Cr and Ni, and high LILE and La/Yb ratios) that is produced via melting of subducted hot, young, oceanic crust. Interaction of ascending adakite melt with peridotite is postulated to cause an increase in $Mg^{\#}$, Cr, and Ni, and a decrease in SiO_2, but also essentially preserves the adakite trace-element characteristics (Yogodzinski et al., 1995).

If subduction occurred in the Archaean, the calculated high ancient geotherms suggest that slab melting should have resulted, and may have been a common mechanism for production of Archaean adakitic (TTG) rocks (Martin, 1994). Primitive TTG commonly has slightly higher $Mg^{\#}$, Cr and Ni than experimental melts of basalt under the appropriate pressure and temperature (P/T) conditions (Rapp, 1997), and this perhaps provides evidence for limited interaction between TTG and peridotite, and a priori, for subduction. However, models that compare high-Mg diorite to orogenic high-Mg andesite, and to TTG of possible subduction origin, ignore the anorogenic setting of high-Mg diorite.

Heat flow models (Abbott, 1991) and P/T regimes required for TTG generation (Martin, 1994) suggest that flat subduction is the most appropriate subduction model for the Archaean. In view of the transitional geochemistry of TTG and high-Mg diorite, and the evidence for limited interaction between TTG and peridotite, we suggest that ascending TTG derived from subducted oceanic crust locally ascends through, interacts and, in places, accumulates within mantle wedged between flat subducted oceanic crust and the base of the continental crust. Later remelting of the localized and now strongly metasomatized relict mantle, and metasomatized portions of the adjacent lower crust, could produce high-Mg diorite and alkali granite respectively. Tectonic processes that may cause this remelting include plume tectonics and lower crustal delamination. Both processes would be expressed at the surface by extension, and it is interesting to note that the Pilbara high-Mg diorite suite was intruded along the axis of the extensional Mallina Basin, during a regional thermal event lacking evidence for coeval subduction, and was shortly followed (c. 2935 Ma) by high-K magmatism related to extensive crustal recycling.

It should also be noted that although itself typically anorogenic in setting, high-Mg diorite is found in Archaean terrains that do preserve good independent evidence of subduction, for example the Slave and Superior Provinces of Canada (Davis et al., 1994) and the central and western parts of the Pilbara Province (Ohta et al., 1996). The virtual restriction of TTG to the early (pre-3420 Ma) history of the eastern part of the craton, and the corresponding absence of high-Mg diorite is interesting, and may reflect post-3420 Ma crustal evolution dominated by processes other than subduction.

Possible economic significance

The intrusional locus of the Pilbara high-Mg diorite suite parallels the axis of the Mallina Basin, the site of numerous old and recent gold discoveries. At least one of the intrusions, at Toweranna, approximately 16 km south-southeast of Whim Creek, is mineralized by late, fracture-controlled veins, and at least one other intrusion is within the Mallina Shear Zone, the site of numerous gold discoveries. It is notable that compositionally similar mafic rocks form a very minor component of the Archaean Yilgarn Craton, and appear to be preferred granite hosts for gold mineralization, for example Granny Smith, Liberty, Lawlers, and Porphyry (Champion, 1997). The fact that mineralization appears to post-date intrusion, in both the Yilgarn and Pilbara Cratons, negates a direct genetic link, but it is clear that these small-volume, subcrustally derived magmas are focused into major crustal structures, and represent favourable structural or chemical (or both) traps for gold mineralization.

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A provisional revised stratigraphy for the Bangemall Group on the EDMUND 1:250 000 sheet

by D. McB. Martin[1], A. M. Thorne, and I. A. Copp

Abstract

Five different stratigraphic schemes for the Bangemall Group rocks on EDMUND have been published since 1968. Recent GSWA mapping has highlighted the fact that none of the existing schemes adequately reflects the observed field relationships. A revised stratigraphy for the Bangemall succession on EDMUND is presented in which the Bangemall Group is elevated to supergroup status, and the component Edmund and Collier Subgroups are raised to group level. Two newly defined units, the Blue Billy and Muntharra Formations, are recorded within the Edmund Group. In addition, the boundaries between previously recognized formations within this group have been redefined in certain cases.

KEYWORDS: Bangemall Group, Bangemall Supergroup, Edmund Subgroup, Edmund Group, Collier Subgroup, Collier Group, stratigraphy, Proterozoic

Introduction

Fine-grained siliciclastic and carbonate sedimentary rocks of the Mesoproterozoic Bangemall Group (Fig. 1) unconformably overlie metamorphosed Palaeoproterozoic sedimentary and igneous rocks of the Capricorn Orogen (Myers, 1990), and are overlain by strata of the Neoproterozoic–Palaeozoic Officer Basin (Perincek, 1996; Williams, 1992). The age of the Bangemall Group is poorly constrained; deposition is thought to have occurred between about 1.64 and 1.00 Ga. (Nelson, 1995; Williams, 1990). The Bangemall Group hosts Western Australia's largest Pb–Cu–Ba deposit (Abra), as well as minor gold and base metal mineralization (Cooper et al., 1998a).

Previous stratigraphic subdivisions of the Bangemall Group (Daniels, 1969; Chuck, 1984; Muhling and Brakel, 1985; Williams, 1990; Cooper et al., 1998a) have been complicated by the presence of lateral facies changes within, and gradational relationships between, the various units, resulting in inconsistent stratigraphic nomenclature for different geographical areas. Furthermore, there are significant disagreements between authors on the basic stratigraphic subdivision of the group, particularly with regard to definition of subgroups (Fig. 2).

One of the aims of the current systematic 1:25 000-scale geological mapping program is to simplify the stratigraphic nomenclature for the Bangemall Group and to resolve some of the problems related to regional correlation within it. In this paper, we present a provisional revised stratigraphy based on detailed mapping on the eastern part of EDMUND*, and also on work carried out by GSWA during a study of the mineral occurrences and exploration potential of the Bangemall Basin (Cooper et al., 1998a).

The Bangemall Supergroup

On EDMUND and adjacent parts of TUREE CREEK and MOUNT EGERTON, there is strong evidence for at least a two-fold subdivision of the Bangemall Group into an older Edmund Subgroup and a younger Collier Subgroup (Cooper et al., 1998a), with the Collier Subgroup being equivalent to the Mucalana Subgroup of Muhling and Brakel (1985) and Williams (1990). The results of a regional compilation of 1:100 000-scale Landsat TM imagery of the Bangemall Group (Cooper et al., 1998b), and mapping carried out during the present study, suggest that the Edmund and Collier Subgroups are separated by a significant unconformity. This break has resulted in the basal Collier Subgroup being juxtaposed against units of the Edmund Subgroup, which range in stratigraphic height from the Devil Creek Formation to the Coodardoo Formation (Fig. 2). The presence of this regional unconformity within the succession is the basis for elevation of the Bangemall Group to supergroup status, and

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

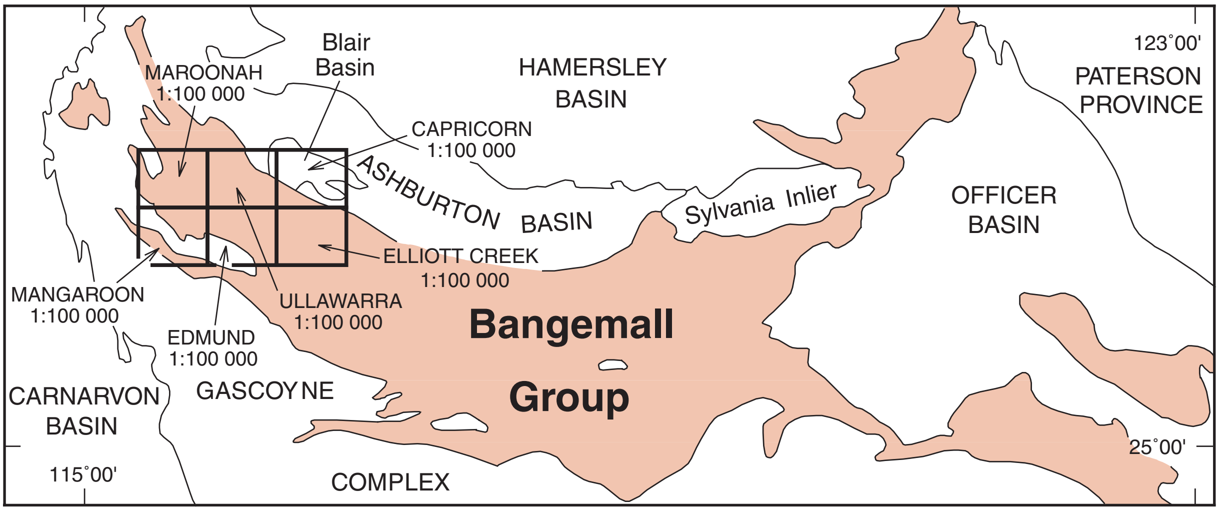

Figure 1. Distribution of the Bangemall Group in Western Australia, and location of the E*DMUND 1:250 000 sheet and constituent 1:100 000 sheets*

Daniels (1969)		Muhling and Brakel (1985)		Chuck (1984)		This study	
Kurabuka Formation	Bangemall Group	Kurabuka Formation	Mucalana Subgroup	Kurabuka Formation	Dooley Subgroup	Ilgarari Formation	Collier Group
		Mt Vernon Sandstone		Mt Vernon Sandstone		Calyie Formation	
Fords Creek Shale		Fords Creek Shale		Fords Creek Shale		Backdoor Formation	
Coodardoo Fm.		Coodardoo Formation	Edmund Subgroup	Coodardoo Formation		Coodardoo Formation	Edmund Group
Curran Formation		Curran Formation		Curran Formation		Ullawarra Formation	
Ullawarra Formation		Ullawarra Formation		Ullawarra Formation			
		Nanular Sandstone		Nanular Sandstone			
Devil Creek Fm.		Devil Creek Formation		Devil Creek Fm.		Devil Creek Formation	
Discovery Chert		Discovery Chert		Discovery Chert	Flory Subgroup	Discovery Formation	
Kiangi Creek Fm.		Jillawarra Formation		Jillawarra Formation		Muntharra Formation	
		Kiangi Creek Formation		Kiangi Creek Fm.		Kiangi Creek Formation	
Irregully Formation		Irregully Formation		Cheyne Springs Fm.		Cheyne Springs Fm.	
						Blue Billy Formation	
				Gooragoora Sandstone		Gooragoora Formation	
				Irregully Formation	Weegarinna Subgroup	Irregully Formation	
		Mt Augustus Sandstone, Tringadee and Coobarra Formations		Tringadee Formation			

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Figure 2. Historic development of stratigraphic nomenclature for the Bangemall Group on E*DMUND and adjacent areas. The chronological arrangement of stratigraphic schemes is because Chuck (1984) drew heavily on a pre-publication copy of Muhling and Brakel (1985). Chuck's (1984) stratigraphic relationships for the Jillawarra Formation are based on his map and text description, rather than his table 7*

the Edmund and Collier Subgroups to group level.

Edmund Group

The Edmund Group unconformably overlies Palaeoproterozoic rocks of the Capricorn Orogen and is unconformably overlain by the Collier Group. On EDMUND, the Edmund Group has a maximum thickness (excluding dolerite sills) of about 3900 m. Our proposed revisions to the stratigraphy of Daniels (1969) are based on the work of Chuck (1984), although two new units have been proposed whereas others have been redefined. In all, ten formations are recognized, which in ascending order are: the Irregully, Gooragoora, Blue Billy, Cheyne Springs, Kiangi Creek, Muntharra, Discovery, Devil Creek, Ullawarra, and Coodardoo Formations. The most significant problems with the previous stratigraphic nomenclature are in the definition and correlation of units below the Discovery Formation (Fig. 2).

The Irregully Formation is the lowermost unit of the Edmund Group on EDMUND and unconformably overlies Palaeoproterozoic rocks of the Ashburton and Capricorn Formations, and igneous and metamorphic rocks of the Gascoyne Complex. Daniels (1970) and Muhling and Brakel (1985) subdivided the Irregully Formation into nine members, but Chuck (1984) and Copp (1998) redefined the formation to include only the lowermost major carbonate unit (Wongida Dolomite Member), together with a thin, locally developed basal siliciclastic unit (Yilgatherra Member). The basal sandstone and shale unit has so far not been named on EDMUND, but may be equivalent to the Tringadee Formation of Chuck (1984) and Muhling and Brakel (1985). Palaeocurrent directions in these localized sandstone units are towards the south and southeast.

Following Chuck (1984), the Gooragoora Sandstone Member is elevated to formation status, and renamed the Gooragoora Formation. The Gooragoora Formation has sharp, conformable contacts with the underlying Irregully Formation and the overlying Blue Billy Formation, and ranges in thickness from 10 to 150 m on EDMUND. Contrary to the definition of Chuck (1984), the Gooragoora Formation is lithologically and palaeoenvironmentally distinct from the Irregully Formation and is relatively heterogeneous in composition, consisting of sandstone and siltstone locally interbedded with significant amounts of carbonate (Table 1). Palaeocurrent directions in the principal sandstone units are towards the southeast.

The Gooragoora Formation is overlain by a pyritic carbonaceous siltstone unit that forms the newly proposed Blue Billy Formation. This formation is broadly equivalent to the Wannery, Chubilyer, Weewoddie, and Yeelingee Members of Daniels (1970), and the lower part of the Jillawarra Formation of Chuck (1984). The formation varies in thickness from 30 to 500 m and in places contains lenticular bodies of thick-bedded, massive quartz sandstone. The upper part of the Blue Billy Formation is transitional with the conformably overlying Cheyne Springs Formation, with the boundary being marked by a gradational change from siltstone to interbedded siltstone and planar-laminated dolomite.

The Cheyne Springs Formation was first defined by Chuck (1984) and is probably equivalent to the Warrada Dolomite Member of Daniels (1970). The Cheyne Springs Formation outcrops on the northeastern and western parts of EDMUND, where it ranges in thickness from 50 to 300 m. Typically, the formation consists of planar-laminated and cross-laminated dolomite, interbedded with siltstone, dolomitic siltstone, and minor fine-grained sandstone.

A laterally persistent unit of thick-bedded quartz sandstone and siltstone (Terrys Camp Member) marks the base of the overlying

Table 1. Proposed lithostratigraphy of the Bangemall Supergroup

Formation	*Lithologies*	*Thickness (a) (m)*	*Basal contact*
Collier Group			
Ilgarari	siltstone, numerous dolerite sills	680	sharp
Calyie	massive to cross-bedded sandstone	130	interfingering
Backdoor	planar-laminated siltstone, minor sandstone and chert	1500	?unconformity
Edmund Group			
Coodardoo	turbidite sandstone and minor siltstone	200	gradational
Ullawarra	planar-laminated siltstone, minor sandstone, numerous dolerite sills	100–650	sharp
Devil Creek	dolomitic breccia, dolograinstone, dolomudstone, minor stromatolites	85–200	sharp
Discovery	silicified carbonaceous mudstone and siltstone, minor sandstone and conglomerate at the base	50–70	sharp
Muntharra	dolomudstone and siltstone	30–50	?sharp
Kiangi Creek	planar-laminated siltstone and turbidite sandstone	200–550	?erosional
Cheyne Springs	interbedded laminated dolomudstone, siltstone, and minor sandstone	50–300	gradational
Blue Billy	pyritic carbonaceous siltstone, minor sandstone	30–500	sharp
Gooragoora	siltstone, sandstone, and minor dolomite	10–150	sharp
Irregully	dolomite (locally stromatolitic), minor sandstone and conglomerate	350–1 200	angular unconformity

NOTE: (a) Thicknesses, which exclude dolerite sills, are from measured sections and estimates from aerial photographs

Kiangi Creek Formation on EDMUND. This contact is marked locally by a thin conglomerate bed and appears to represent a disconformity with the underlying Cheyne Springs Formation. The bulk of the Kiangi Creek Formation consists of siltstone and interbedded turbidite sandstone, and varies in thickness from 200 to 550 m. Palaeocurrents in this formation are directed towards the southwest on the southeastern part of EDMUND, and towards the northwest on the northwestern part of the map sheet.

Carbonate strata between the Kiangi Creek and Discovery Formations have been assigned to the Muntharra Formation, which is equivalent to the upper part of the Jillawarra Formation of Chuck (1984). The Muntharra Formation is best exposed north of Strama Bore on Irregully Creek, where it consists mainly of non-stromatolitic dolomite and dolomitic mudstone. The lower and upper contacts of the Muntharra Formation are sharp.

Siliceous deposits of the Discovery Formation (formerly the Discovery Chert) have long been recognized as an important stratigraphic marker in the Bangemall succession. However, recent mapping has shown that in many cases the siliceous character of this unit appears to be secondary, indicating replacement of rocks ranging from carbonaceous siltstone to sandstone and conglomerate. Chuck (1984) noted that the results of drilling in the Mount Palgrave area suggest that silicification in that area is a surface enrichment of a much less siliceous black shale. In view of this compositional heterogeneity, we propose that this unit be renamed the Discovery Formation.

The Devil Creek Formation is 85–200 m thick and has a sharp, conformable contact with the underlying Discovery Formation. The Devil Creek Formation consists of dolograinstone and dolomudstone, which are locally stromatolitic and are interbedded with massive dolomitic conglomerate on the northeastern part of EDMUND. Siltstones and minor sandstones of the Ullawarra Formation conformably overlie the Devil Creek Formation and were considered to be a facies equivalent of this carbonate unit by Chuck (1984) and Muhling and Brakel (1985). The Nanular Sandstone of Chuck (1984) and Muhling and Brakel (1985) has not been recognized on EDMUND (Table 1). In addition, the Curran Formation, which gradationally overlies the Ullawarra Formation, is demoted to member status and included within the Ullawarra Formation. Palaeocurrent directions in the Ullawarra Formation are towards the northwest.

The Coodardoo Formation is the uppermost unit in the Edmund Group and has a transitional, conformable contact with the underlying Ullawarra Formation. The formation is about 200 m thick on EDMUND, and comprises thick-bedded turbidite sandstone and minor siltstone.

Collier Group

On EDMUND, the Collier Group was previously known as the Mucalana Subgroup (Muhling and Brakel, 1985; Williams, 1990), but was incorporated into the Collier Subgroup by Cooper et al. (1998a). In keeping with the original stratigraphic subdivision of the Collier Subgroup, the Fords Creek Shale (basal Mucalana Subgroup) has been renamed the Backdoor Formation. Similarly, the Calyie Formation, which consists of sandstone and siltstone, replaces the Calyie and Mount Vernon Sandstones. The Kurabuka Formation is renamed the Ilgarari Formation. Thicknesses and lithological data for components of the Collier Group are given in Table 1.

Problems in regional correlation

Two main problems exist with previous regional correlations within the Bangemall Supergroup that are especially applicable to EDMUND. The first relates to the definition of the Irregully Formation, as used by Daniels (1969) and Muhling and Brakel (1985), in which all carbonate units below the Kiangi Creek Formation were included in the Irregully Formation. This usage was modified by Chuck (1984) and Copp (1998), who redefined the Irregully Formation to include only the lowermost carbonate unit and the associated basal siliciclastic rocks.

The second problem concerns the identification and correlation of the Jillawarra Formation (Fig. 2), which was first defined by Brakel and Muhling (1976) and later included in the stratigraphic scheme of Chuck (1984). Muhling and Brakel (1985) considered the Jillawarra Formation to be partly a lateral equivalent of the Kiangi Creek Formation, but also correlated it with the Backdoor Formation of their Collier Subgroup. Alternatively, Chuck (1984) considered the Jillawarra Formation to overlie the Kiangi Creek Formation, but to also be laterally equivalent to, and interfinger with, all stratigraphic units down to the top of the Irregully Formation. In this sense, all argillaceous strata between the Irregully and Discovery Formations were mapped as Jillawarra Formation. Because of these conflicting views, the name Jillawarra Formation is not used in our present scheme, these rocks being assigned instead to three separate units: the Blue Billy, Kiangi Creek, and Muntharra Formations.

A consequence of Muhling and Brakel's (1985) correlation of the Jillawarra and Backdoor Formations was that they considered all units between the Jillawarra Formation and Fords Creek Shale to be laterally equivalent. No such correlation is implied by our stratigraphic scheme, since we assign the Backdoor Formation and rocks equivalent to the Jillawarra Formation to the Collier and Edmund Groups respectively.

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The nature of c. 2.0 Ga crust along the southern margin of the Gascoyne Complex

by S. Sheppard[1], S. A. Occhipinti, I. M. Tyler, and D. R. Nelson

Abstract

The southern part of the Gascoyne Complex consists of foliated and gneissic granites of the Dalgaringa Supersuite, as well as pelitic and calc-silicate gneisses of the Camel Hills Metamorphics, the protoliths of which were deposited between c. 2025 and c. 1960 Ma. The Dalgaringa Supersuite mainly consists of 2005–1975 Ma foliated and gneissic tonalite, granodiorite, and monzogranite. SHRIMP U–Pb dating has not yet found any trace of Archaean rocks of the Yilgarn Craton in the southern Gascoyne Complex. The complex may have formed as a convergent continental margin above a northwesterly dipping subduction zone before it was accreted to the Yilgarn Craton at c. 1960 Ma during the Glenburgh Orogeny.

KEYWORDS: Proterozoic, structural terranes, granite, geochronology, Gascoyne Complex, Dalgaringa Supersuite, Camel Hills Metamorphics, Glenburgh Orogeny

Introduction

Granites and high-grade metamorphic rocks of the Gascoyne Complex are an important part of the Capricorn Orogen, a major tectonic zone formed during collision of the Archaean Yilgarn and Pilbara Cratons in the Palaeoproterozoic (Fig. 1). However, tectonic models for the Gascoyne Complex have been hampered by a lack of reliable geochronological data. The timing of granite intrusion, deformation, and metamorphism are poorly constrained.

Williams (1986) suggested that the southern part of the Gascoyne Complex consisted mainly of reworked Archaean gneisses of the Yilgarn Craton. Myers (1990) interpreted the southern part of the Gascoyne Complex as para-autochthonous Yilgarn Craton interleaved with Proterozoic rocks (his Zone B). He suggested that the Errabiddy Shear Zone (Fig. 1) marks the boundary between para-autochthonous Yilgarn Craton to the north, and unreworked Yilgarn Craton to the south. The granitic gneisses in the southern part of the Gascoyne Complex were interpreted as Archaean because they are similar in appearance to gneisses in the Narryer Terrane of the Yilgarn Craton, and because they have Sm–Nd chondritic model ages of 2700–2500 Ma (Fletcher et al., 1983). However, reconnaissance SHRIMP U–Pb dating by Nutman and Kinny (1994) failed to identify reworked Archaean crust in the southern Gascoyne Complex.

Remapping of the ROBINSON RANGE* and GLENBURGH 1:250 000 map sheets in 1997 and 1998, as part of the Southern Gascoyne Complex Project, combined with SHRIMP U–Pb zircon geochronology (Nelson, 1998, 1999), confirms that rocks of the Yilgarn Craton are not present north of the Errabiddy Shear Zone in the mapped area (Fig. 1). Instead, the crust along the southern margin of the Gascoyne Complex mainly, or entirely, formed between 2005 and 1975 Ma. Furthermore, this crust was deformed and metamorphosed at medium to high grade up to 150 million years before collision of the Yilgarn and Pilbara Cratons between 1840 and 1800 Ma (Tyler et al., 1998; Occhipinti et al., 1998).

The rocks in the southern part of the Gascoyne Complex are divided into three main stratigraphic units. These are 2005–1975 Ma granitic gneiss and granite of the Dalgaringa Supersuite, Palaeoproterozoic medium- to high-grade metasedimentary rocks of the Camel Hills Metamorphics, and 1830–1800 Ma granite and pegmatite dykes and plugs. In addition, two episodes of deformation and medium- to high-grade metamorphism that occurred between 1985 and 1945 Ma are collectively referred to here as the Glenburgh Orogeny. The 1830–1800 Ma granites are related to the Capricorn Orogeny (Occhipinti et al., 1998) and not discussed here.

In the following sections, sample numbers refer to samples analysed by Nelson (1999) unless otherwise referenced. The raw data and concordia plots for these samples are

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* Capitalized names refer to standard map sheets.

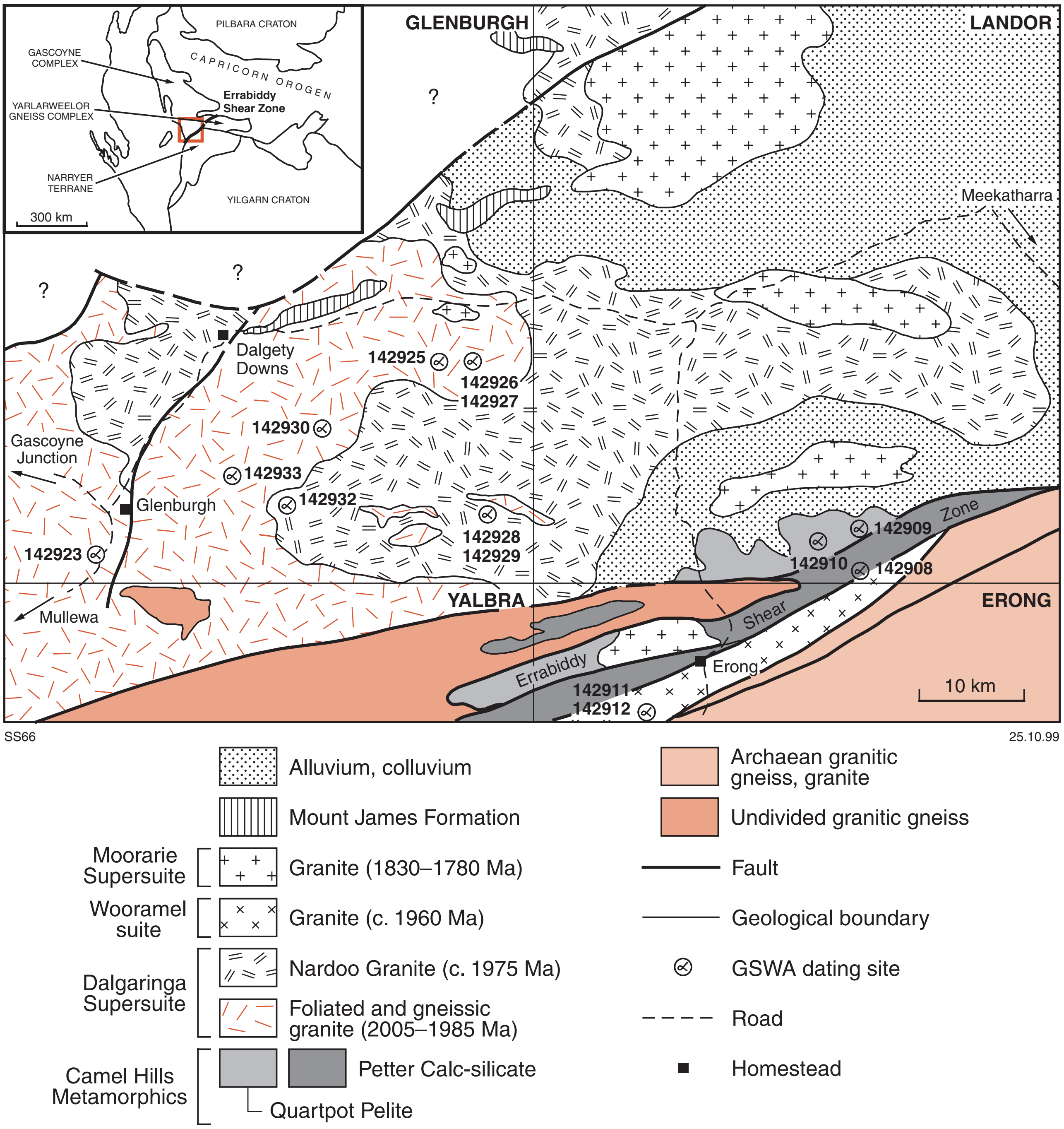

Figure 1. Simplified geology of the southern margin of the Gascoyne Complex on the GLENBURGH *1:250 000 map sheet. The names of the 1:100 000 map sheets are also shown*

contained in the same publication. Locations of the dated samples are shown on Figure 1.

2005–1975 Ma Dalgaringa Supersuite

The Dalgaringa Supersuite consists of massive, foliated, and gneissic granites dated at 2005–1975 Ma. The supersuite comprises two episodes of magmatism, which are separated by a deformation and high-grade regional metamorphic event. The two episodes consist of 2005–1985 Ma foliated to gneissic tonalite to monzogranite, and c. 1975 Ma tonalite and granodiorite plutons.

2005–1985 Ma foliated and gneissic granite

Foliated and gneissic granites outcrop in a wide, easterly to east-northeasterly trending belt on the southern part of the GLENBURGH 1:100 000 map sheet (Fig. 1). The rocks range from strongly deformed and completely recrystallized, foliated and gneissic granite in zones of high strain, to statically recrystallized granites with intrusive relationships preserved in areas of low strain.

The most abundant, and oldest, rock type so far identified is a grey, fine- to medium-grained, foliated to gneissic tonalite. The rock commonly has a banded appearance owing to the presence of heterogeneously deformed pegmatite veins and dykes (Fig. 2a). In low-strain zones the rock is a medium-grained, even-textured biotite–quartz diorite or tonalite. Although this rock type resembles Archaean mesocratic granitic gneiss in the Narryer Terrane (Occhipinti et al., 1998; Sheppard and Swager, 1999), two samples of tonalite and quartz diorite (GSWA 142926 and 142933) on GLENBURGH gave SHRIMP U–Pb zircon dates for igneous crystallization of 2002 ± 2 Ma and 1989 ± 3 Ma respectively.

The tonalite is commonly interlayered tectonically with subordinate fine- to medium-grained, foliated biotite monzogranite and lesser leucocratic tonalite to form a composite gneissic granite unit. In areas of low strain, preserved igneous relationships show that the monzogranite intruded the tonalite. However, locally preserved net-vein textures imply that there is little age difference between the two rock types. A sample of the biotite monzogranite (GSWA 142927) gave a date for igneous crystallization of 1999 ± 5 Ma. This age is indistinguishable from that of tonalite sample GSWA 142926, which has been net-veined by the monzogranite. The tonalite has also been extensively intruded by sheets of medium- to coarse-grained biotite granodiorite and monzogranite, one of which (GSWA 142925) was dated at 2002 ± 3 Ma.

All of the above rock types are intruded by veins and sheets of medium- to coarse-grained biotite monzogranite or syenogranite, and pegmatite. The sheets are up to several metres thick, and locally contain up to 30% or more of the foliated and gneissic granites. Two of the sheets were dated. One of these, a foliated monzogranite (GSWA 142923), was re-sampled from site NP 19 of A. P. Nutman (1996, pers. comm.) and gave a date of 1987 ± 4 Ma, within error of the c. 1990 Ma age reported by Nutman and Kinny (1994). Sample GSWA 142930 from a foliated biotite pegmatite was dated at 1994 ± 2 Ma.

Nardoo Granite

The 2005–1985 Ma foliated and gneissic granites were intruded by a large pluton of biotite(–hornblende) tonalite and granodiorite. This intrusion, known as the Nardoo Granite, is equivalent to the gneissic biotite–hornblende granodiorite of the Dalgety Gneiss Dome of Williams (1986). The Nardoo Granite consists of weakly to strongly foliated or locally gneissic tonalite and granodiorite (Fig. 2b). The

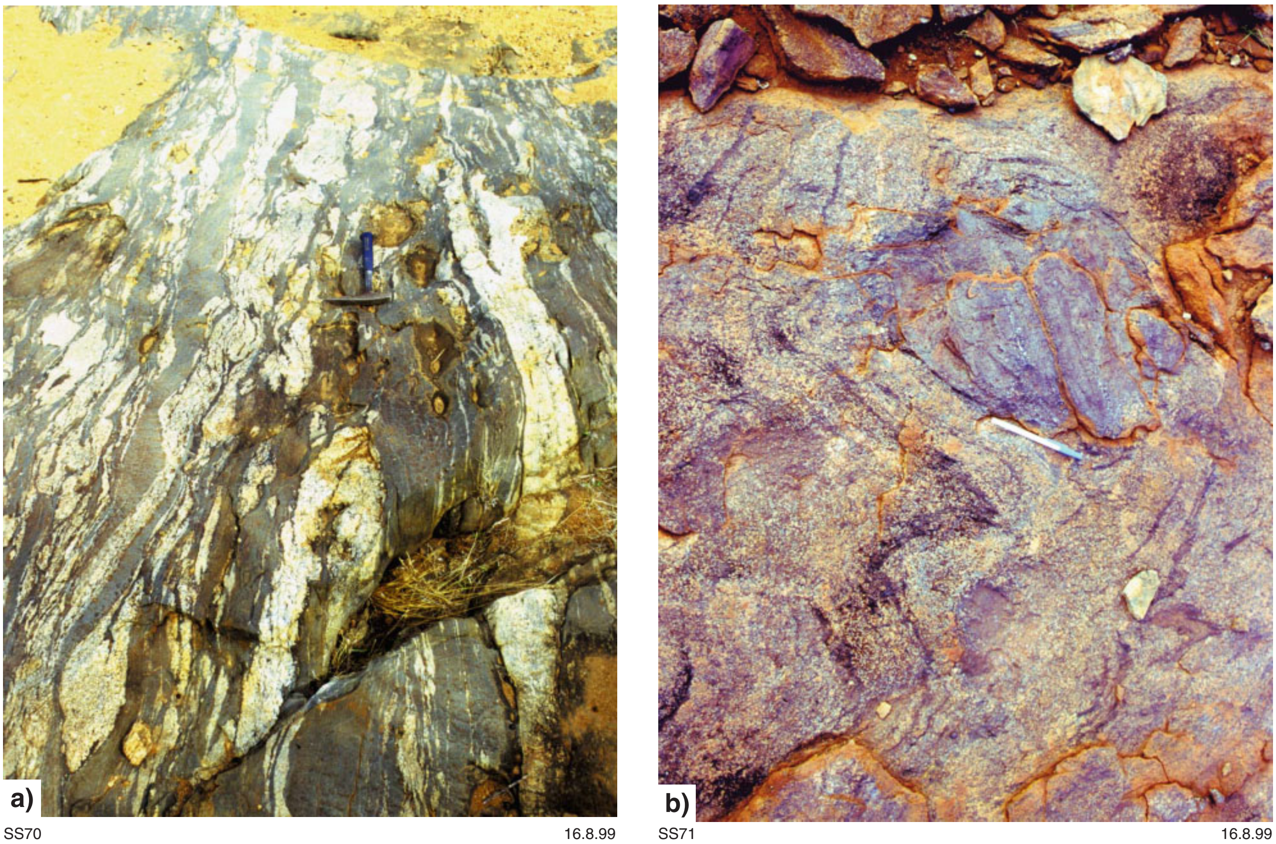

Figure 2. a) Pegmatite-banded tonalite gneiss in creek pavement about 500 m east of sample site GSWA 142933; b) Foliated granodiorite of the Nardoo Granite with an inclusion of low-strain tonalite gneiss, about 6 km east-southeast of sample site GSWA 142932

margins of the intrusion are commonly more strongly deformed than the core, and the contact with the surrounding gneissic tonalite to monzogranite is not sharp. The contact is marked by inclusions and rafts of the gneissic tonalite to monzogranite in the Nardoo Granite, and decreasing numbers of veins and sheets of Nardoo Granite intruded into the country rock.

The Nardoo Granite consists of two mappable rock types: a medium-grained, porphyritic biotite–hornblende tonalite, and a medium-grained, even-textured or weakly porphyritic leucocratic biotite granodiorite. Contacts between the two are generally sharp, but in places the two rock types grade into each other. In low-strain zones, irregular veins and dykes of granodiorite have consistently intruded the tonalite. Nevertheless, the tonalite and granodiorite are the same age; a sample of the tonalite (GSWA 142932) gave a date of 1977 ± 4 Ma, while a sample of the granodiorite (GSWA 142928) was dated at 1974 ± 4 Ma.

The Nardoo Granite has a different composition to the potassic granites which are typical of much of the Palaeoproterozoic in Australia (Wyborn et al., 1992). On mantle-normalized diagrams these potassic granites have pronounced high La and Ce contents, Ba and Sr 'troughs', and little or no depletion in Y relative to Na (Fig. 3). In contrast, the Nardoo Granite is similar to Phanerozoic granites from convergent margin settings, in having lower La and Ce contents, no Ba 'trough', and a marked Y depletion (Fig. 3). The two samples of the Nardoo Granite plotted show a small Sr 'trough', although many other samples do not.

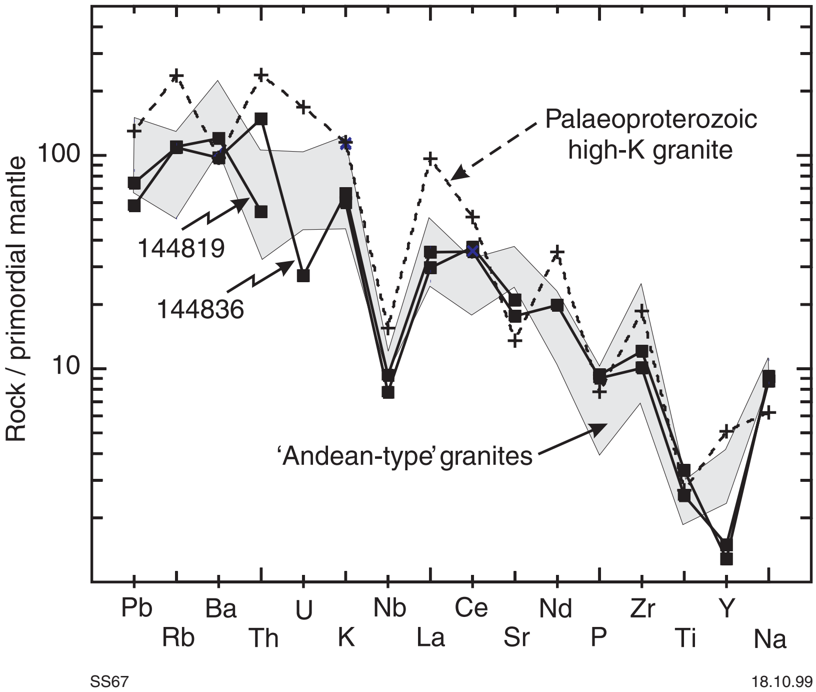

Figure 3 Mantle-normalized plot comparing the Nardoo Granite (GSWA 144819 and 144836) with Andean-type granites from the Cretaceous Coastal Batholith of Peru (Atherton and Sanderson, 1985) and the Eocene Coast Batholith of Alaska (Arth et al., 1988). The Palaeoproterozoic high-K granite is from the Paperbark supersuite in the Halls Creek Orogen (GSWA 113401; Sheppard et al., 1997). The low U contents in the Nardoo Granite are a secondary feature; the U content in GSWA 144819 is below the detection limit.

Camel Hills Metamorphics

Medium- to high-grade metasedimentary rocks, referred to here as the Camel Hills Metamorphics, outcrop in a belt about 150 km long between Archaean rocks of the Narryer Terrane and Palaeoproterozoic granitic gneiss and granite of the Gascoyne Complex (Fig. 1). These metasedimentary rocks were previously included within the Morrissey Metamorphic Suite (Williams, 1986). The Camel Hills Metamorphics is subdivided into the Quartpot Pelite and the Petter Calc-silicate.

The Quartpot Pelite consists of pelitic schist and migmatitic pelitic gneiss, with minor amounts of interlayered quartzite, calc-silicate schist and gneiss, and amphibolite. SHRIMP U–Pb zircon data were obtained for two samples of migmatitic pelitic gneiss (sample GSWA 142905, Nelson, 1998; sample GSWA 142910, Nelson, 1999). The youngest zircon ages in each sample are c. 1960 Ma, which have been obtained from rims and cores with very low Th/U ratios. Although one of the authors (Nelson, 1998, 1999) has interpreted these as detrital zircons, their Th/U ratios suggest that they grew during the high-grade metamorphism that produced partial melting of these rocks. Zircons between 2025 and 2550 Ma dominate the detrital zircon populations, with a small contribution in one sample (GSWA 142910) from zircons older than 2600 Ma in age. The maximum depositional age is thus constrained to c. 2025 Ma.

The Petter Calc-silicate is composed of calc-silicate schist or gneiss and interlayered quartzite, and minor pelitic schist or migmatitic pelitic gneiss and amphibolite. The maximum depositional age for a quartz-rich calc-silicate gneiss on the LANDOR 1:100 000 map sheet (sample GSWA 142908) of 1944 ± 5 Ma is only provided by a single detrital zircon grain. The bulk of the zircons are 2700–2600 Ma in age, with a small number older than 3000 Ma. These ages imply that the Petter Calc-silicate had a different provenance to the Quartpot Pelite.

Glenburgh Orogeny

The oldest fabric in the southern Gascoyne Complex is a regionally extensive gneissic layering in the 2005–1985 Ma gneissic tonalites and monzogranites, which is cut by sheets of the Nardoo Granite. Inclusions of pegmatite-banded gneissic tonalite and monzogranite are abundant in the Nardoo Granite (Fig. 2b). Therefore, the Nardoo

Granite was intruded after deformation and regional metamorphism that took place between c. 1985 and c. 1975 Ma.

Inclusions of gneissic tonalite and monzogranite in the Nardoo Granite are commonly folded about an axial surface parallel to a penetrative foliation in the Nardoo Granite. This foliation is cut by a dyke of biotite monzogranite that has been dated at 1945 ± 14 Ma (sample GSWA 142929). In the migmatitic pelitic gneiss of the Camel Hills Metamorphics, widespread high-grade metamorphism and partial melting were dated at c. 1960 Ma. Therefore, the rocks in the southern part of the Gascoyne Complex were also deformed and metamorphosed at medium to high grade at c. 1960 Ma, after intrusion of the Nardoo Granite. The second deformation and metamorphism was concomitant with intrusion of monzogranite plutons of the Wooramel suite into the northwest margin of the Yilgarn Craton at c. 1960 Ma (Fig. 1; sample GSWA 142911, Nelson, 1998; sample GSWA 142912, Nelson, 1999).

The two deformation and regional metamorphic events identified here are much older than the Capricorn Orogeny. The two events are referred to as the Glenburgh Orogeny (Occhipinti et al., 1999).

Discussion

Our mapping and SHRIMP geochronology support the suggestion of Nutman and Kinny (1994) that the southern Gascoyne Complex probably formed a terrane separate from the Yilgarn Craton until c. 1960 Ma. No evidence has been found along the southern margin of the Gascoyne Complex for reworked Archaean rocks of the Yilgarn Craton.

The nature and age of the basement to the southern Gascoyne Complex is unclear, but there are indications that it is continental crust of latest Archaean to early Palaeoproterozoic age. Nutman and Kinny (1994) reported an age of c. 2500 Ma for a sample of banded gneiss in the Carandibby Inlier, which is part of the Gascoyne Complex, about 60 km to the west-southwest of Dalgety Downs Homestead (Fig. 1). In addition, detrital zircons identified in two migmatitic pelitic gneiss samples from the Quartpot Pelite may reflect the age of the basement. These zircons give ages of 2025–2550 Ma, and are younger than dated rocks from the northwestern part of the Yilgarn Craton, which are all older than 2600 Ma.

The preponderance of tonalite and granodiorite in the Dalgaringa Supersuite is in contrast to most Palaeoproterozoic batholiths in northern Australia, which are dominated by monzogranite and granodiorite. In addition, the Nardoo Granite shares some of the characteristics of Phanerozoic subduction-related granites (Fig. 3). The Dalgaringa Supersuite may thus represent the product of convergent margin magmatism developed on early Palaeoproterozoic crust that subsequently collided with the passive margin of the Yilgarn Craton. The presence of c. 1960 Ma granites intruded into the northern margin of the Yilgarn Craton, and c. 1945 Ma granite dykes in the southern part of the Gascoyne Complex, suggests that the southern part of the Gascoyne Complex was accreted by this time. The early Palaeoproterozoic tectonic history of the Gascoyne Complex may be dominated by processes of subduction and terrane accretion before final collision of the Yilgarn and Pilbara Cratons during the Capricorn Orogeny between 1840 and 1800 Ma (Tyler et al., 1998; Occhipinti et al., 1998).

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Geology and alteration of the Merrie greenstone belt

by T. R. Farrell[1] and N. G. Adamides

Abstract

The Archaean Merrie greenstone belt is located at the northern end of the Eastern Goldfields Province in the Yilgarn Craton. The belt contains a large syncline with a lower sequence of mafic and ultramafic rocks, and an upper sequence of felsic and sedimentary rocks. The belt has been deformed and metamorphosed to lower amphibolite facies adjacent to the greenstone margin, and greenschist facies in the centre. Alteration of the greenstones post-dates regional metamorphism and deformation. Mafic rocks are typically overprinted by patchy epidote alteration and quartz–epidote veins, or by diffuse biotite alteration adjacent to networks of pyrite-filled fractures (or both). Alteration took place at 410–430°C, under low-fluid CO_2 concentrations (X_{CO_2} <0.18), and resulted in the net addition of potassium. Alteration was either not intense enough, or occurred at fluid CO_2 levels that were too low, for the development of carbonate-bearing alteration.

KEYWORDS: Archaean, greenstone, metamorphism, hydrothermal alteration

The Merrie (or Cunyu) greenstone belt lies about 90 km north of Wiluna, on the northern edge of the Archaean Yilgarn Craton. The belt is poorly exposed and, in the past, the geology and structure were necessarily inferred from limited outcrop and low-resolution aeromagnetic data. In this paper, we present a revised interpretation of the structure, metamorphism, and alteration of the Merrie belt, with emphasis on the mineralogy and $T–X_{CO_2}$ conditions of alteration. This interpretation is based on recent 1:100 000-scale geological mapping, new aeromagnetic data, and petrographic work on drillhole samples.

Geological setting

The Eastern Goldfields Province (Griffin, 1990) is characterized by elongate, north to northwesterly trending greenstone belts and extensive areas of monzogranite and gneiss. The Merrie greenstone belt (Fig. 1) contains a sequence of deformed supracrustal rocks dominated by basalt (with thin units of ultramafic rock and minor gabbro), with less abundant overlying felsic and sedimentary rocks. The belt is flanked by poorly exposed granitoid rocks (mainly monzogranite), and unconformably overlain in the north by sedimentary rocks of the Proterozoic Yerrida and Earaheedy Basins. A major tectonic lineament, the Merrie Range Fault (Fig. 1; Myers and Hocking, 1998), lies to the east, and a possible splay off this fault runs along the eastern margin of the belt.

Stratigraphy and structure

The Merrie belt is poorly exposed and the sparse surface outcrops are deeply weathered. For this reason, most of the information on the geology of the belt has been derived from sampling of exploration drillholes. An aeromagnetic image of the area (Fig. 2) shows that the belt contains a large fold, outlined by thin units of high magnetic intensity that are interpreted to be ultramafic bodies (no banded iron-formation was identified in surface outcrops). Liu (1997), and Myers and Hocking (1998) interpreted this fold as an anticline. However, on the basis of way-up directions from poorly preserved pillow structures in metabasalt, it is interpreted here to be a syncline. This is consistent with the absence of granite in the core of the structure (common in antiformal greenstone belts, Myers, J. S., 1999, pers. comm.), and is further supported by geophysical modelling (Adamides, in prep.). Mafic rocks (dominantly metabasalt with subordinate, thin ultramafic units, and minor metagabbro, amphibolite and chlorite schist) dominate the outer, stratigraphically lower, parts of the syncline. Metamorphosed felsic and sedimentary rocks are interpreted from surface geology and drillhole information to occupy the upper part of the sequence in the centre of the syncline (Fig. 1). Weakly deformed, metamorphosed hornblende diorite was identified in one drillhole in the core of the syncline.

The Merrie belt is heterogeneously deformed, and zones of strongly deformed rock typically alternate with zones of little or no deformation. A zone of intense deformation is present along the faulted eastern margin of the belt. Most rocks in the belt have a weak to moderate, subvertical, north-northwesterly

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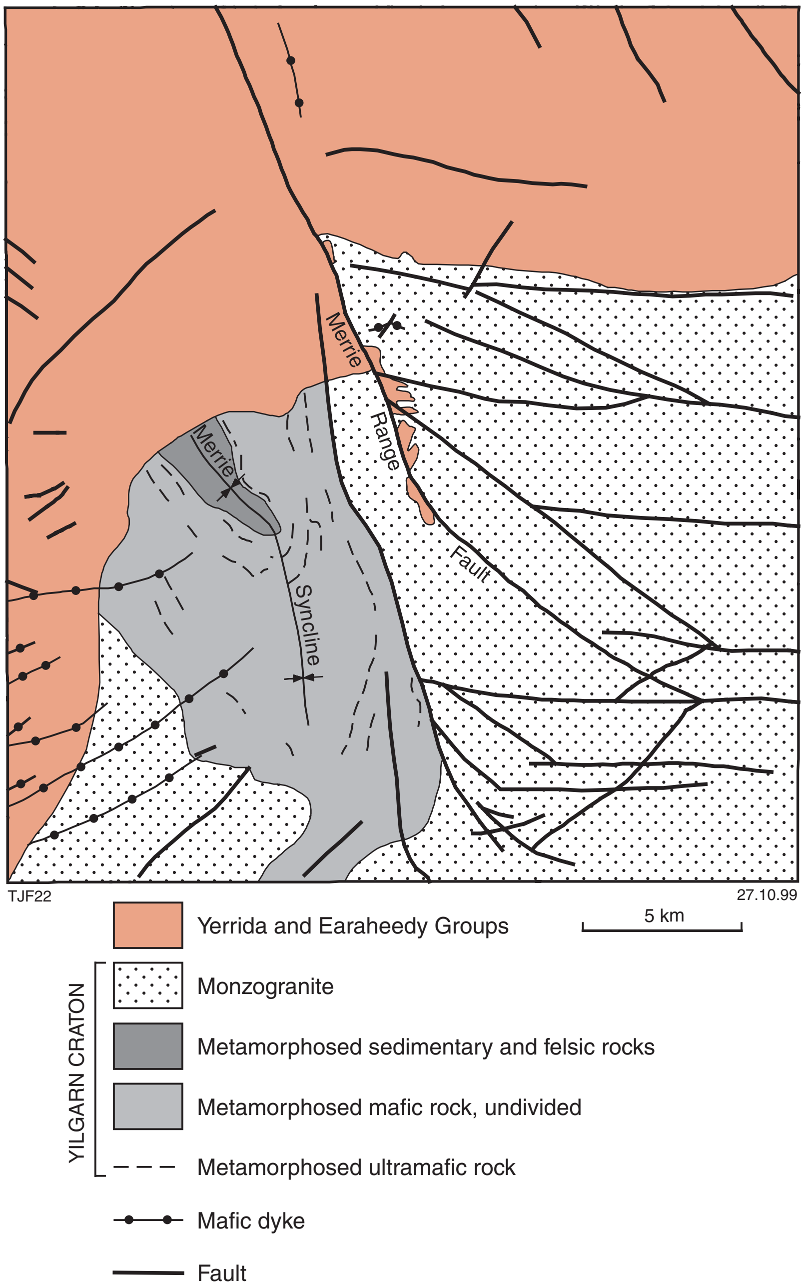

Figure 1. Interpreted geology of M*ERRIE* *showing the location of the Merrie greenstone belt*

trending foliation, defined mainly in mafic rocks by the preferred orientation of chlorite. A sub-horizontal mineral lineation is present in more highly strained zones, and a fine crenulation is also present in chlorite-rich mafic rocks.

Metamorphism

In common with other greenstone belts in the Eastern Goldfields Province (Myers and Swager, 1997), the Merrie belt has a narrow higher grade zone (amphibolite facies) along the margins, and a low-grade zone (greenschist facies) covering most of the central part of the belt.

In the amphibolite-facies zone, mafic rocks contain mineral assemblages that include hornblende and Ca-plagioclase. In contrast, in the low-grade zone, medium- to coarse-grained mafic rocks (metagabbro and metadolerite) contain lower greenschist-facies assemblages of actinolite–albite(–epidote). Metabasalt commonly contains vesicles filled by quartz(–epidote) and chlorite (Fig. 3a). The groundmass in these rocks is typically composed of a fine-grained mixture of quartz, actinolite, albite, and chlorite. Intermediate rock types (?meta-andesite) were also identified, in some cases with relict plagioclase phenocrysts (Fig. 3b). Metamorphosed ultramafic rocks consist of various proportions of intimately intergrown chlorite, tremolite, anthophyllite, and talc.

Metamorphosed felsic porphyritic or volcaniclastic rocks (Fig. 3c), encountered in drillholes in the centre of the belt, typically have a recrystallized matrix of fine-grained, interlocking quartz and albite enclosing fragments of subhedral or embayed quartz, sericitized plagioclase, and, in some cases, felsic lithic fragments and relict white mica.

Metasedimentary rocks contain the assemblage quartz–actinolite–epidote–leucoxene (probably from the breakdown of detrital iron–titanium minerals). They are interpreted to be sedimentary in origin on the basis of a layering defined by the alternation of quartz- and epidote-rich domains, and the absence of any relict igneous textures.

The stability of Ca-plagioclase in mafic rocks close to the margin of the belt indicates a temperature greater than about 450–500°C in the amphibolite facies zone. In low-grade mafic rocks in the centre of the belt, the presence of chlorite–albite–actinolite(–epidote) indicates lower greenschist facies — probably at a temperature of 350–400°C (cf. Liou et al., 1985).

Hydrothermal alteration

The metamorphic mineral assemblages are overprinted by later veins and zones of hydrothermal alteration, particularly adjacent to crosscutting fractures. The most abundant alteration minerals are biotite, epidote, and quartz. Hydrous Fe-oxides (after ?pyrite) are present in some veins, and carbonates are usually scarce. Strongly epidotized rocks typically contain abundant

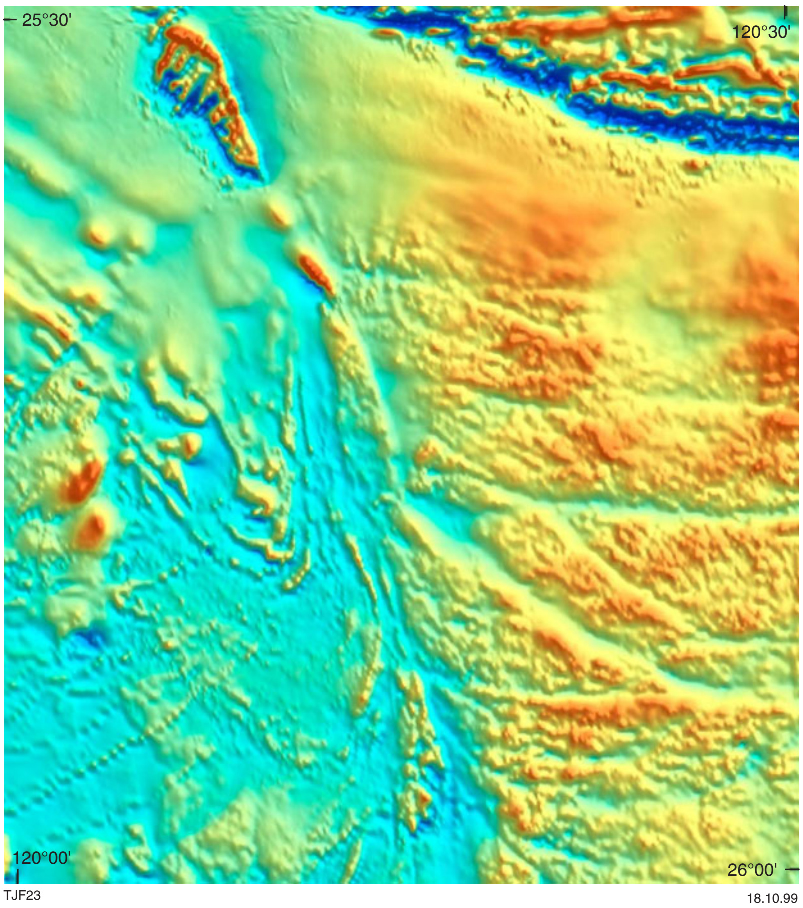

Figure 2. Total magnetic intensity aeromagnetic image of MERRIE*. Note the fold structure in the Merrie greenstone belt defined by thin highly magnetic units*

fine-grained epidote, and are cut by veins containing quartz and epidote (Fig. 3d).

Biotite is a conspicuous alteration mineral in many of the mafic rocks, and its presence is interpreted to be evidence of K-metasomatism. Biotite typically occurs in broad alteration haloes surrounding veins and fractures, commonly in association with fine-grained epidote. In strongly altered rocks, the biotite alteration is pervasive. Biotite is also present as an alteration product around the margins of actinolite crystals, as well as being retrogressively altered to chlorite.

The altered mafic rocks are commonly cut by an irregular network of fractures and thin veins that contain hydrous Fe-oxides (?limonite–goethite). The Fe-oxides in these veins are probably the product of weathering and oxidation of former pyrite. A biotite alteration halo typically envelopes the veins. In some samples, these (former) pyrite veins cut across quartz–epidote veins, and are therefore interpreted to be late in the paragenetic sequence. In all cases, the pyrite veins cut across the foliation and the vein minerals are undeformed.

The opaque minerals are usually broken down to leucoxene and, with progressive alteration, a transition is observed through to microcrystalline titanite, and rarely, to well-crystallized rutile. The presence of finely dispersed microcrystalline titanite throughout many altered rocks suggests that there was localized mobility of titanium during alteration.

Discussion

Alteration in the Merrie belt is interpreted to have taken place after the main regional deformation events (D_1–D_3, Farrell, 1997). This is based on the observation that the pyrite veins with associated biotite haloes are undeformed and cut across the main foliation, coupled with the random orientation of individual biotite crystals. Biotite is not a typical component of unaltered metamorphosed mafic rocks in the Eastern Goldfields Province, and its abundance in the Merrie belt is probably due to K-metasomatism, possibly related to fluids released during the crystallization of late granitoid intrusions (cf. McNaughton et al., 1993). In addition, biotite has not been reported from alteration zones at Jundee–Nimary (Phillips et al., 1998a, 1998b; Byass and Maclean, 1998) and Wiluna (Chanter et al., 1998) to the south. The presence of biotite in the Merrie belt suggests that alteration occurred at a higher temperature than in either of these two deposits.

Figure 4 shows some of the relevant mineral equilibria and the interpreted conditions of alteration in the Merrie belt on a T–X_{CO_2} diagram. The coexistence of epidote–chlorite–biotite–albite–quartz, along with the absence of Ca-plagioclase, limits the temperature to approximately 410–430°C for greenschist facies rocks (neglecting the effect of Fe^{2+} substitution for Mg) — slightly higher than indicated for regional metamorphism. The stable coexistence of epidote–biotite also indicates a low X_{CO_2} (0 – 0.15), which is consistent with the low carbonate content of the altered mafic rocks. This is also confirmed by the scarcity of rutile, which indicates that the CO_2 content of the fluid was only locally high enough (X_{CO_2} 0.15 – 0.18) to cause the breakdown of titanite.

These values of X_{CO_2} are broadly similar to typical values for lode-gold deposits in the Yilgarn Craton (0.05 – 0.25; Witt, 1991; Mikucki and Ridley, 1993). However, alteration in the Merrie belt is distinctly different in style to the alteration reported from gold deposits in the northern part of the Yandal and Agnew–Wiluna belts. The sequence at Jundee–Nimary (Byass and Maclean, 1998; Phillips et al., 1998a,b) is broadly similar to that in the Merrie belt (dominated by mafic rocks with thin units of ultramafic rock and subordinate

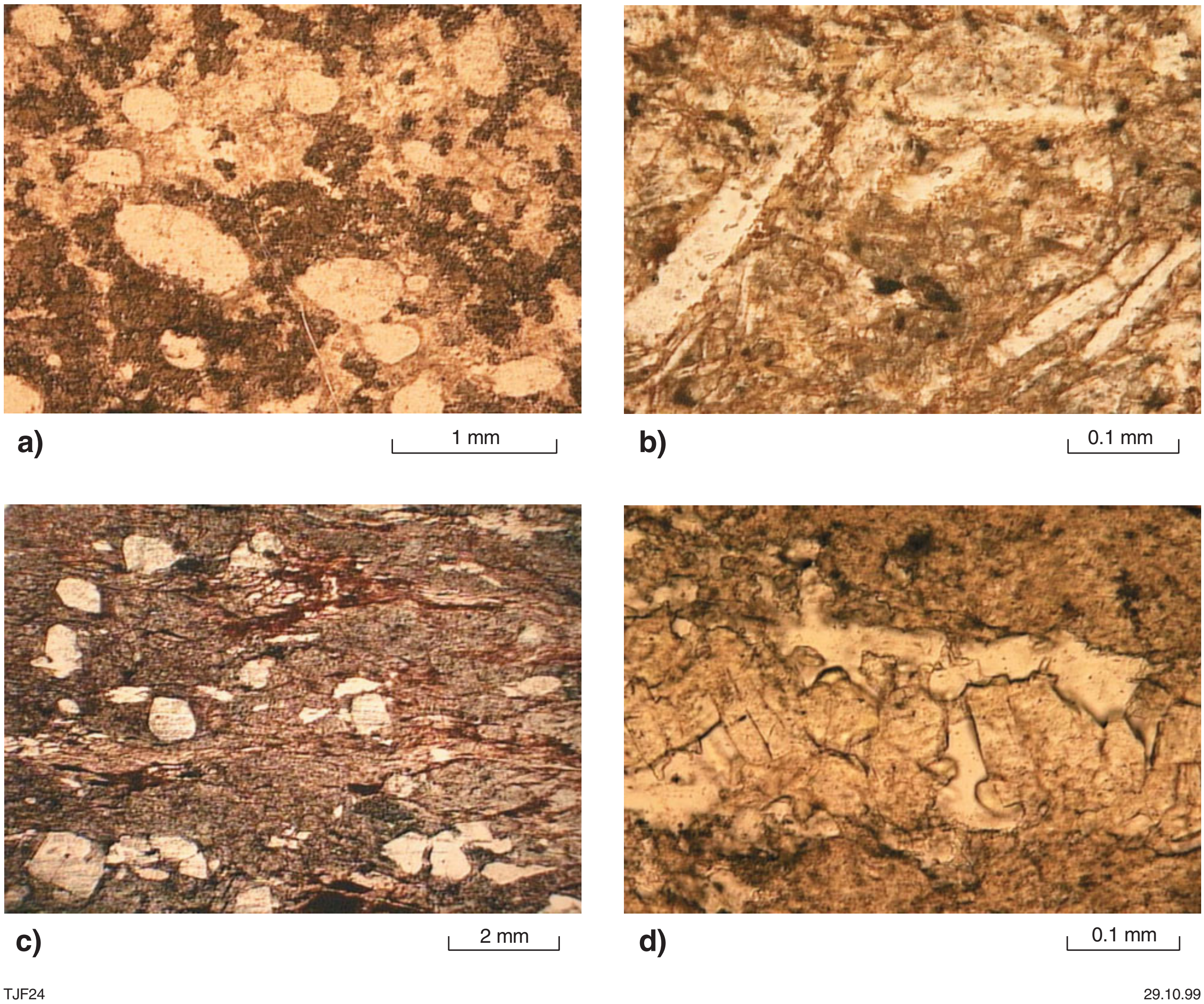

Figure 3. Textures of rock types of the Merrie greenstone belt
a) Relict vesicular texture in metamorphosed mafic lava. Vesicles are filled by quartz. The matrix of the rock is predominantly composed of actinolite, with patchy epidote alteration (dark areas). Plane polarized light. GSWA 152869
b) Plagioclase-phyric, epidotized intermediate rock, probably meta-andesite. The matrix is composed of epidote, biotite, and albite. Plane polarized light. GSWA 152875a
c) Typical felsic volcaniclastic rock, with relict subhedral and embayed quartz grains in a foliated fine-grained matrix. Plane polarized light. GSWA 152894
d) Epidote–quartz vein in fine-grained mafic rock. Plane polarized light. GSWA 152877

amounts of felsic porphyry), but the mineralization is associated with quartz–carbonate–sulfides(–chlorite –muscovite) alteration. Mineralization in the Bulletin deposit at Wiluna (Chanter et al., 1998) is associated with sericite–carbonate (–chlorite) alteration. The important difference to the Merrie belt is that carbonates are abundant in proximal alteration zones in both deposits, and in many other low-T (<450°C) lode-gold deposits in the Yilgarn Craton (Witt, 1991; Mueller and Groves, 1991; Mikucki and Ridley, 1993). The general absence of carbonates in the Merrie belt suggests that, either the sampled rocks are from areas of distal (weak) alteration at reduced X_{CO_2} (cf. Witt, 1991), or that the fluid CO_2 content was too low to stabilize carbonates.

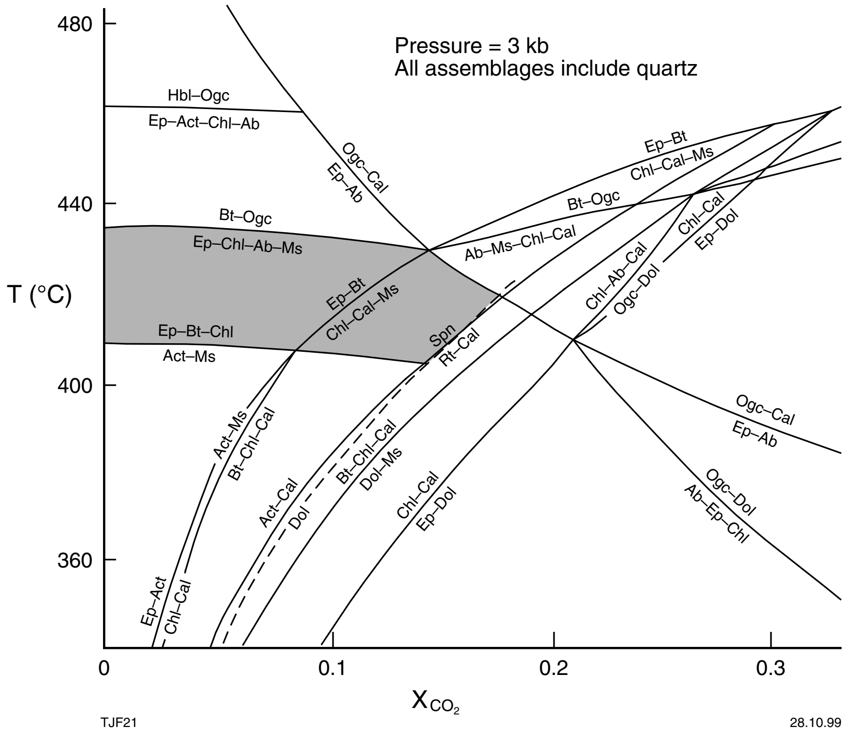

Figure 4. ***Isobaric T–X_{CO_2} diagram showing relevant mineral equilibria in the system K_2O–Na_2O–CaO–MgO–Al_2O_3–SiO_2–H_2O–CO_2 (modified from Clark et al., 1986). Temperature–X_{CO_2} conditions for alteration in the Merrie belt are indicated by the shaded area. Minerals: Ab = albite, Act = actinolite, Bt = biotite, Chl = chlorite, Cal = calcite, Dol = dolomite, Ep = epidote, Hbl = hornblende, Ms = muscovite, Ogc = oligoclase, Rt = rutile, and Spn = sphene***

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Structural evolution of the Marda–Diemals area, Southern Cross Province

by J. E. Greenfield[1] and S. F. Chen

Abstract

Initial basin formation (D_e) and deposition of the Marda–Diemals greenstones took place at c. 3.0 Ga. The first recognizable deformation event (D_1) was north–south compression that resulted in easterly trending recumbent folds and ductile strike-slip movement along major shear zones. During the waning stages of D_1, the formation of a restricted sedimentary basin (Diemals Formation), extrusion of a calc-alkaline volcanic succession (Marda Complex), and the intrusion of the Pigeon Rocks Monzogranite are inferred to have occurred penecontemporaneously at c. 2.73 Ga. Upright, northerly trending folds that overprint D_1 structures formed during D_2 east–west compression. During late D_2, westward-directed differential compression reoriented D_2 structural trends and reactivated the major shear zones. Post-dating all these structures are conjugate north-northeasterly trending dextral and east-southeasterly trending sinistral brittle faults.

KEYWORDS: Archaean, granite, greenstone, geological structure, Yilgarn Craton.

The Southern Cross Province (Griffin, 1990) of the Yilgarn Craton is characterized by strongly deformed, lenticular greenstone belts. Greenstone lithologies are dominated by mafic–ultramafic volcanic successions intercalated with banded iron-formation (BIF) units, and intruded by voluminous monzogranites. The Marda–Diemals area (Fig. 1) contains the key elements of a structural model based on recent geological mapping of the JOHNSTON RANGE* (Wyche et al., in prep.), LAKE GILES (Greenfield, in prep.), BUNGALBIN (Chen and Wyche, in prep.), and JACKSON (Riganti and Chen, in prep.) 1:100 000 sheets.

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* Capitalized names refer to standard map sheets

Geological setting

The Marda–Diemals greenstone belt is a wide, arcuate tectonic unit (Fig. 1) containing a lower, mafic-dominated sequence, and an upper sequence of felsic volcanic and clastic sedimentary rocks. It contains three distinct, ovoid granitoid plutons — the Pigeon Rocks and Butcher Bird Monzogranites, and the Chatarie Well Granite (Fig. 1). The Pigeon Rocks Monzogranite has a SHRIMP U–Pb zircon age of 2729 ± 4 Ma (Nelson, 1999). There is also a lenticular granite–gneiss body, the Rainy Rocks Monzogranite (Fig. 1), which has a SHRIMP U–Pb zircon age of 2678 ± 14 Ma (Dalstra, 1995).

Lower greenstones

The lower greenstone sequence comprises a basal quartzite overlain by high-Mg basalt and ultramafic rocks, followed by tholeiitic basalt, and two major units of BIF and chert intercalated with mafic and ultramafic volcanic and intrusive rocks. Felsic intrusive and pyroclastic rocks outcrop locally, but their absolute position within the stratigraphy is not clear. A minimum age for the lower greenstone sequence is provided by a SHRIMP U–Pb zircon age of 3023 ± 10 Ma for an intrusive quartz–feldspar porphyry at Deception Hill (Fig. 1; Nelson, 1999). This age is within error of a SHRIMP U–Pb zircon age of 3013 ± 16 Ma for a thin felsic unit, interpreted as volcanic, within the greenstones near Jackson Homestead (Dalstra, 1995).

Upper greenstones

A major unconformity separates the lower greenstone sequence from an upper greenstone sequence comprising the Diemals Formation and the Marda Complex.

The Diemals Formation (Walker and Blight, 1983) is a thick sequence of heterogeneously deformed, clastic sedimentary rocks. The formation is present in a roughly triangular basin with sharp, faulted contacts on its western and southeastern margins, and an unconformity on the northern margin (Fig. 2). The western margin has been metamorphosed up to greenschist facies; however, most of the formation has undergone very low grade metamorphism. The sequence changes upwards, from silty argillite interbedded with polymictic conglomerate, to coarse-grained quartz arenite. Common sedimentary structures include graded bedding and cross-bedding.

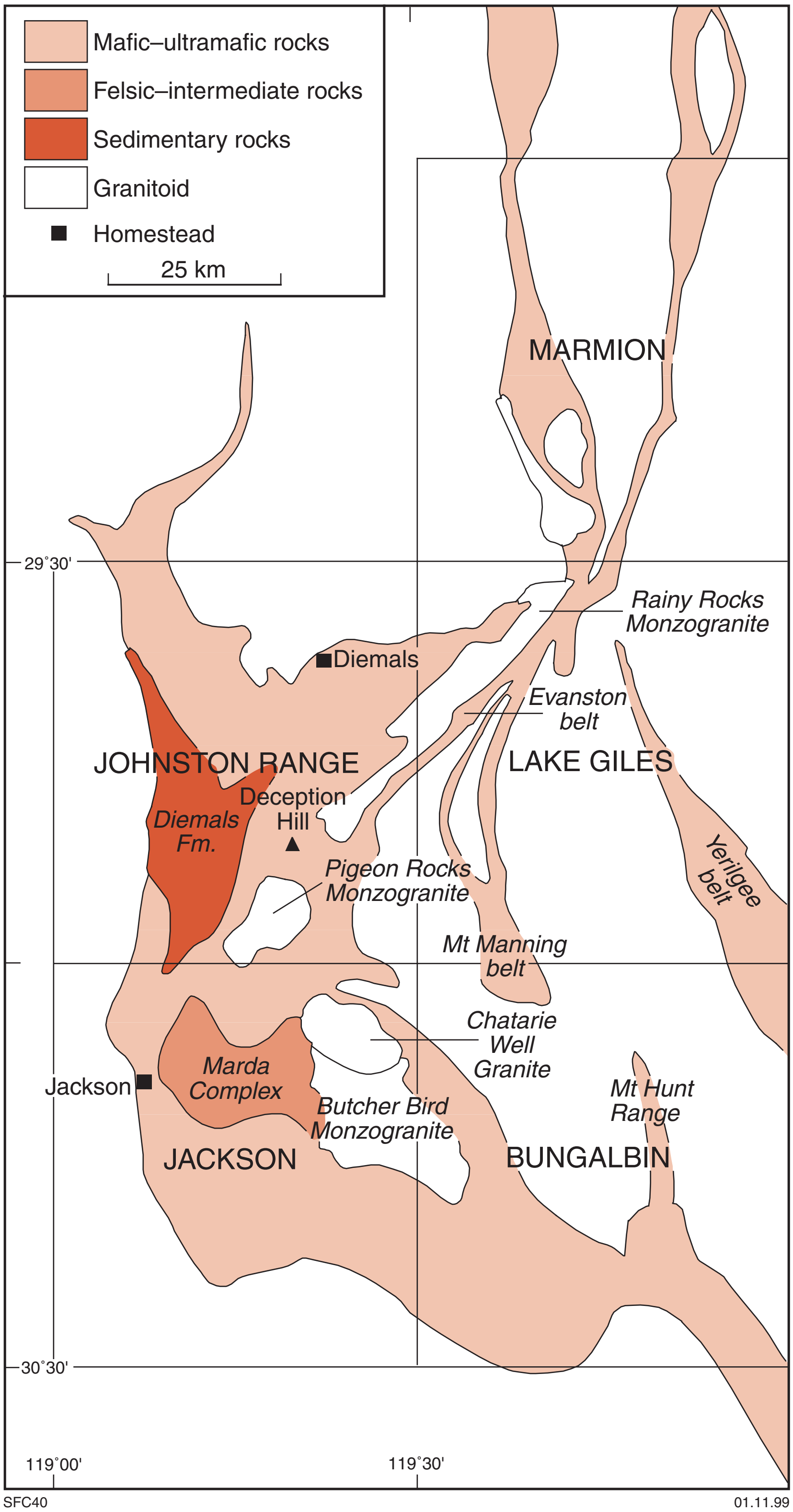

Figure 1. Locality map showing the central Southern Cross Province and localities described in the text

The conglomerates contain mainly BIF and vein-quartz clasts, but there are also granitoid boulders in the north. BIF in clasts has been tightly to isoclinally folded prior to reworking. The greenstone clasts are inferred to be locally derived, and suggest the Diemals Formation was deposited in a restricted basin.

The calc-alkaline Marda Complex (Hallberg et al., 1976; Chin and Smith, 1983) contains a range of extrusive acid to intermediate rock types. Pidgeon and Wilde (1990) obtained a conventional zircon U–Pb age of 2735 ± 2 Ma from fragmental rhyolite. Hallberg et al. (1976) examined the geochemistry of the Marda Complex, and inferred a magmatic source unrelated to the mafic volcanics that underlie the complex. They interpreted the complex as being at least partly subaerial. Intercalated sedimentary units along the northwestern margin may be correlated with the upper units of the Diemals Formation, suggesting that the Diemals Formation and the Marda Complex may have been coeval.

Structure

Early fold structures (D_1/F_1)

The earliest recognized structures are tight to isoclinal folds, ranging from centimetre-scale, rootless, isoclinal folds defined by quartz-rich layers in BIF to kilometre-scale, isoclinal folds that have been overprinted by F_2 (Fig. 2).

In the Evanston belt (Fig. 1), F_1 folds are refolded by large-scale F_2 folds into isoclinal folds that plunge steeply (doubly) to the northwest and southeast. In the northern Diemals area, repetition of BIF units has been recognized for approximately 2 km across strike. This is interpreted as being the result of D_1 faulting and folding that has been refolded by kilometre-scale upright F_2 folding (Fig. 2). A regional-scale, gently inclined D_1 antiform east of the Butcher Bird Monzogranite (Fig. 2) is refolded by open, kilometre-scale F_2 folds.

Before F_2, the F_1 folds were northerly verging and easterly trending, and gently inclined to recumbent, with shallowly plunging axes. Other than D_1 repetitions of BIF units, there appears to be no regional-scale D_1

disruption of the stratigraphy of the Marda–Diemals greenstones.

Regional-scale fold structures (D_2/F_2)

D_2 fold structures are dominated by megascale, upright, open to tight folds that trend northerly in the northwest, and northeasterly to southeasterly in the east and south (Fig. 2). Asymmetric S- and Z-folds are recognized on the limbs of regional-scale folds. They may be up to hundreds of metres in wavelength, but are more commonly at smaller (<1 m) scales.

The limbs of F_2 folds are typically steeply dipping. The axes of antiforms and synforms in the northwest have moderate to steep plunges to the south, whereas those in the northeast plunge moderately to the northeast. This pattern is repeated in the Evanston, Mount Manning, and Yerilgee belts, where poles to bedding have great circle distributions that indicate a general plunge to the northeast and northwest (Fig. 2).

S_2 fabrics associated with D_2 high-strain zones are pervasive and penetrative, but are mostly restricted to shear zones on greenstone margins. F_2 axial planar fabrics have developed under greenschist- to amphibolite-facies conditions, and regional metamorphism is interpreted to be syn-D_2 (Dalstra, 1995).

Late brittle faults

North-northeasterly and east-southeasterly trending conjugate brittle faults cut across all fold structures. North-northeasterly trending faults dominantly produce dextral offsets up to 200 m, whereas east-southeasterly trending faults are sinistral with offsets less than 50 m. The fault zones contain narrow quartz veins, with or without magnetite, and although up to 30 m wide, are commonly less than 5 m.

Major easterly trending aeromagnetic lineaments, possibly fractures filled by Proterozoic mafic dykes, cut across the brittle faults (Fig. 3).

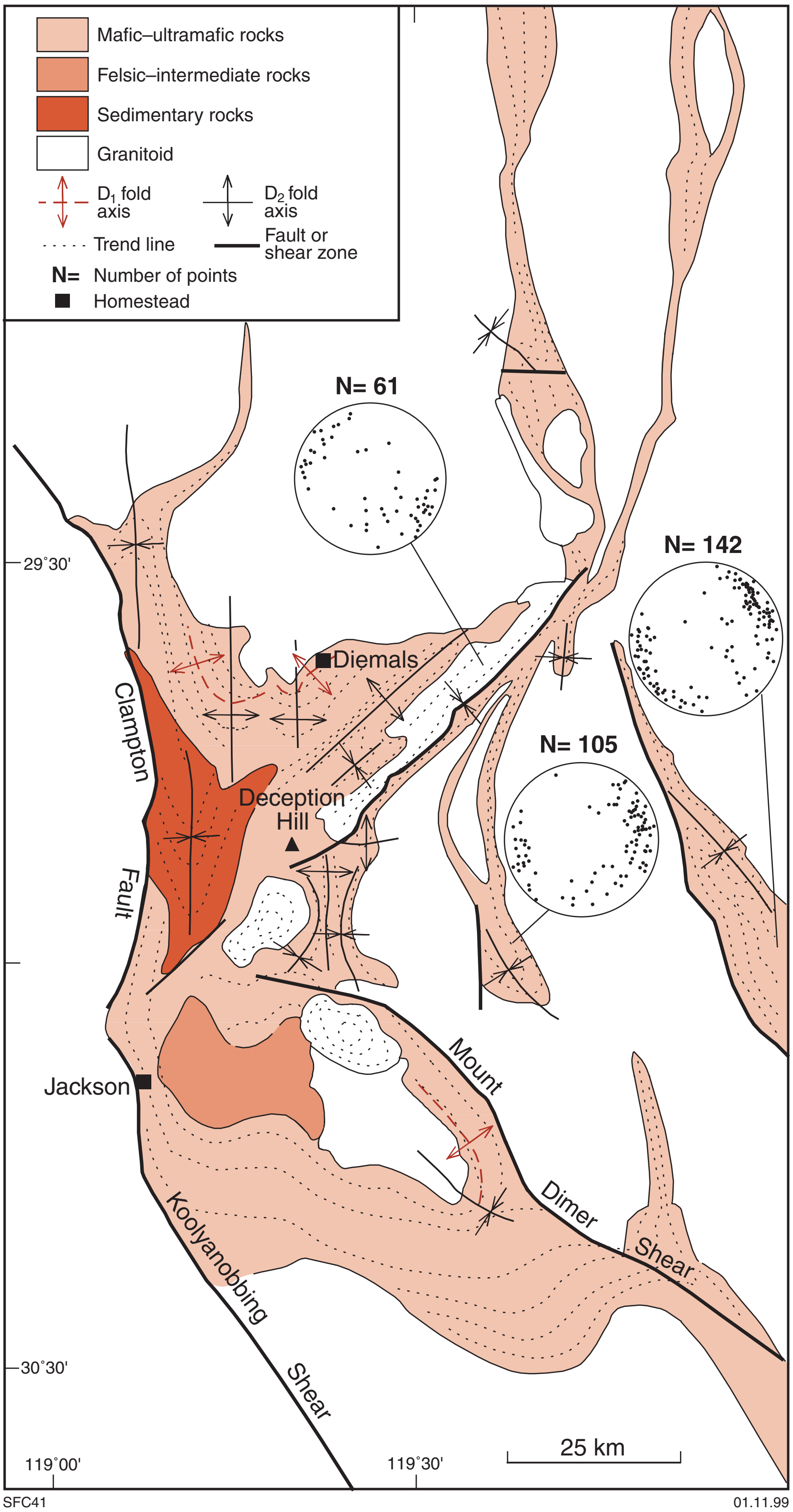

Figure 2. Major structural components of the central Southern Cross Province. Equal-area stereonet projections show poles to bedding for the Evanston, Yerilgee, and Mount Manning greenstone belts

Major shear zones

The Koolyanobbing Shear is a northwesterly trending, crustal-scale

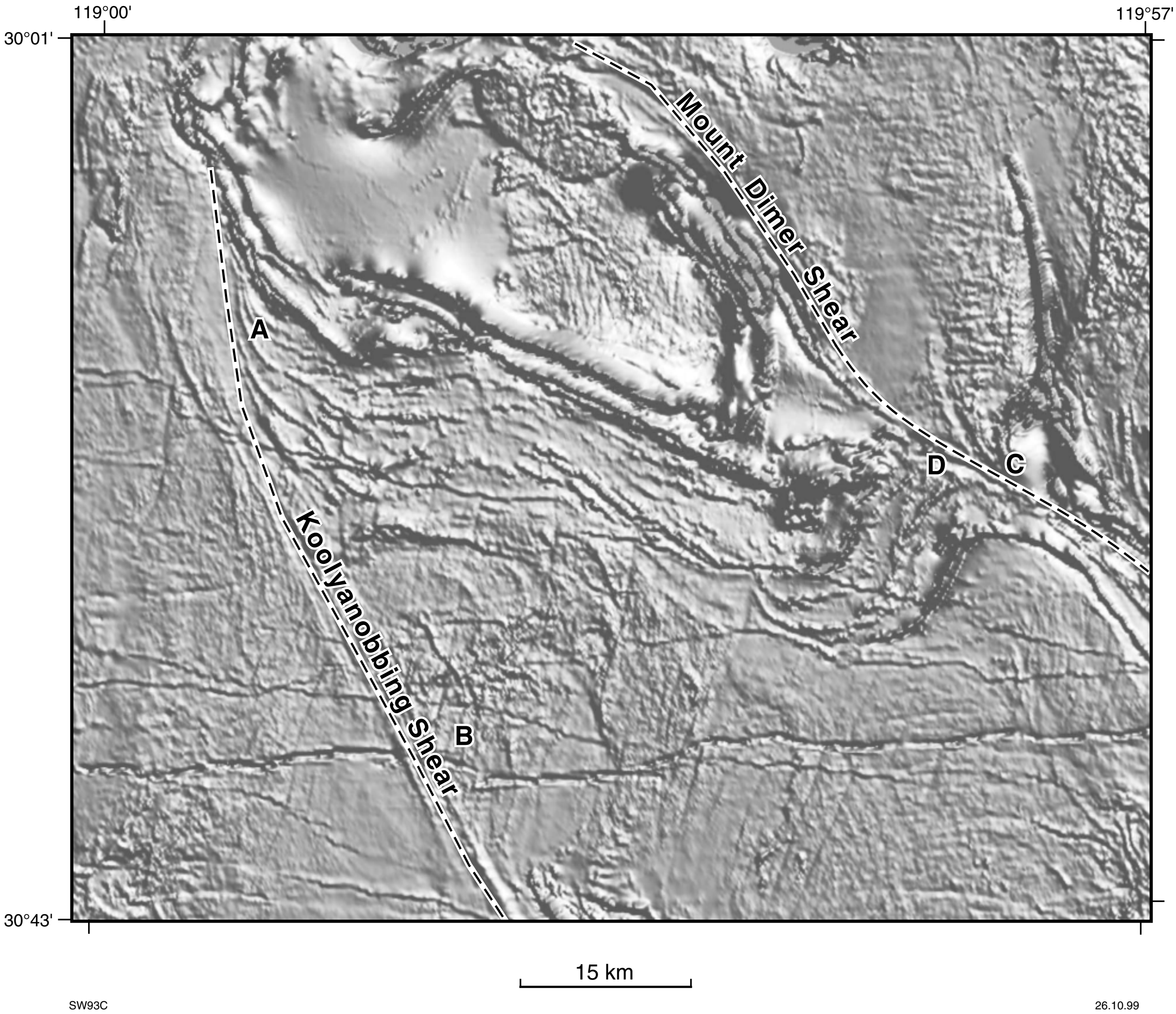

Figure 3. Total magnetic intensity image of the central Southern Cross Province. Dashed lines highlight interpreted shear zones. Letters indicate localities of interpreted movement sense along shear zones: A = dextral drag into the Koolyanobbing Shear; B = sinistral movement sense along the Koolyanobbing Shear; C = sinistral drag into the Mount Dimer Shear; D = dextral drag into the Mount Dimer Shear. Image derived from Kevron Geophysics multi-client data and used with permission

ductile shear zone (Fig. 2), 6–15 km wide (Libby et al., 1991), and approximately 450 km long. Strain increases towards the centre of the structure. Shallow-plunging mineral lineations and kinematic indicators (S–C, C–C´ fabrics) suggest dominantly sinistral transcurrent movement. However, at least one well-exposed pavement contains dextral S–C fabrics (Libby et al., 1991). Similarly, aeromagnetic images show ambiguous, large-scale kinematic indicators on the Koolyanobbing Shear. Dextral drag is inferred from tapering greenstone units south of the Marda Complex, whereas sinistral drag of granitoid is inferred farther to the south (Figs 2 and 3).

Libby et al. (1991) interpreted a continuation of the Koolyanobbing Shear north of Jackson, coinciding with the Clampton Fault (Fig. 2). However, aeromagnetic data suggest the Koolyanobbing Shear terminates west of the Marda Complex (Fig. 3). In the Clampton area, the Clampton Fault consists of a 200 m-wide easterly dipping zone of sheared quartz veins at the granite–greenstone contact. Dalstra (1995) recognized downdip stretching lineations in the Clampton Fault zone.

The Mount Dimer Shear is a poorly exposed, northwesterly trending structure approximately 150 km long. Interpretation of aeromagnetic images suggests that, like the Koolyanobbing Shear, it has both sinistral and dextral kinematic indicators (Fig. 3). For example, the southern end of the Mount Hunt Range appears to have been displaced sinistrally by the shear zone, whereas greenstone units to the south of the Mount Dimer Shear have a dextral shear sense (Figs 1 and 3).

The Evanston Shear is a north-easterly trending ductile shear zone, approximately 100 km long and 2–6 km wide (Fig. 2). Most shear fabrics are penetrative and defined by upper greenschist- to lower amphibolite-facies minerals in sheared mafic rocks. S–C fabrics and en echelon quartz veins in the deformed Rainy Rocks Monzogranite and adjacent amphibolites indicate dextral transcurrent movement, with plunges of lineations subhorizontal to the northeast and southwest.

Synthesis

The interpreted structural evolution of the Marda–Diemals area is summarized in Table 1.

The earliest inferred event (D_e) may have involved the development of extensional growth faults at the margins of the developing greenstone basins. These growth faults may have been reactivated during later events.

Structures ascribed to D_1 reflect a north–south compressive regime. Ductile transcurrent movement along the Koolyanobbing Shear is consistent with north–south compression, which suggests that this structure could have been either initiated or reactivated during D_1. If that was the case, dextral displacement at the northwestern termination of the Koolyanobbing Shear may also have caused tectonic downwarping that facilitated the deposition of the Diemals Formation and extrusion of the Marda Complex. Isoclinal folds in BIF boulders from the Diemals Formation indicate at least one folding deformation event prior to deposition. Thus the Diemals Formation was deposited after D_1 folding. The intrusion of the Pigeon Rocks Monzogranite at 2729 ± 4 Ma and the eruption of the Marda Complex at 2735 ± 2 Ma give a minimum age for D_1.

East–west compression dominated during early D_2 upright folding. However, reorientation of folds into northeast and southeast trends in the eastern part of the Marda–Diemals greenstones may be due to westward-directed compression during late D_2. This would also account for the intense buckling of greenstones observed on the eastern side of the Pigeon Rocks Monzogranite.

Late D_2 differential compression probably reactivated the major shear zones. Westward-directed compression would result in sinistral displacement along the Koolyanobbing and Mount Dimer Shears, and dextral displacement along the Evanston Shear. Pre- to syn-kinematic intrusion of the Rainy Rocks Monzogranite took place at 2678 ± 14 Ma.

In the final stage of this tectonic cycle, east-northeasterly–west-southwesterly compression produced brittle conjugate north-northeasterly and east-southeasterly faults prior to cratonization and the development of crustal-scale, easterly trending fractures.

Table 1. Structural evolution of the Marda–Diemals greenstones

Age (Ma)	*Label*	*Strain regime*	*Event*	*Structure*
>3023 ± 10	D_e	E–W extension	Basin-forming event; deposition of lower greenstones	N- and NNW-trending growth faults
	Early D_1	N–S compression	–	E-trending folds and thrust faults; dextral movement on NNW-trending shear zones
c. 2730	Late D_1	N–S compression	Intrusion of Pigeon Rocks Monzogranite; deposition of Diemals Formation; extrusion of Marda Complex	–
	Dextral movement on NNW-trending shear zones	–	–	–
2678 ± 14	Early D_2	E–W compression	Intrusion of Rainy Rocks Monzogranite	N–S folds
	Late D_2	E to W compression	–	Reorientation of N-trending folds; sinistral movement on NNW-trending shear zones; dextral movement on NE-trending shear zone
		ENE–WSW compression	–	Brittle NNE and SSE faults
		E–W ?compression	Dolerite dyke emplacement	Craton-scale E–W faulting

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Neoproterozoic glacigene successions, western Officer Basin, Western Australia

by K. Grey[1], S. N. Apak, C. Eyles, N. Eyles, M. K. Stevens, and G. M. Carlsen

Abstract

Neoproterozoic glacigene deposits in the Officer Basin are present within the Lupton and Boondawari Formations, but to date, their age and correlation have been uncertain. The Lupton Formation type section has been revised and is thinner than previously described. New evidence from Empress 1 and 1A drillcore, including the identification of a 'cap dolomite', isotope chemostratigraphy, and stromatolite biostratigraphy, indicates a Marinoan age (approximately 600 Ma) for the Lupton Formation and that it correlates with the Boondawari Formation. As a consequence of these new results, glacigene strata of the Officer Basin can now be correlated with similar units elsewhere in Australia.

KEYWORDS: Neoproterozoic, stratigraphy, glacial sediments, diamictite, Officer Basin, Lupton Formation, Boondawari Formation.

Introduction

Neoproterozoic glacigene successions in Australia are regarded as significant marker horizons for chronostratigraphic correlation (Preiss et al., 1978). Two main glacial intervals were recognized in the Neoproterozoic of the Centralian Superbasin and Adelaide Rift Complex: the Sturtian glaciation and the Marinoan glaciation, with ages estimated at 700–690 Ma and 605–595 Ma respectively (Walter et al., in press).

Despite numerous descriptions of Neoproterozoic glacigene successions in the Officer Basin (Fig. 1), the age and correlation of these widely scattered units remains uncertain. Four western Officer Basin formations were originally ascribed a glacial origin (Jackson and van de Graaff, 1981; Williams, 1992): the Lefroy, Lupton, Turkey Hill, and Boondawari Formations. Of these, only the Boondawari and Lupton Formations (Fig. 2) are demonstrably Neoproterozoic glacigene deposits.

The type section of the Lupton Formation (Lowry et al., 1972; Jackson and van de Graaff, 1981; Cockbain and Hocking, 1989) at Lupton Hills (latitude 26°31'S, longitude 128°01'E; Fig. 1) was remeasured in 1998 (COP 98/3, Fig. 3). A synclinal axis was recognized in outcrop, reducing the measured thickness of the unit from 240 to 69 m. Here, the Lupton Formation contains coarse-grained diamictite with rare striated pebbles, confirming a glacigene origin. The Neoproterozoic Lupton Formation was probably folded during the Petermann Ranges Orogeny.

Because of poor outcrop, the Boondawari Formation (Williams and Tyler, 1991; Williams, 1992; Walter et al., 1995) is divided between three type areas. The stratigraphically lowest part is diamictite (latitude 23°31'32"S, longitude 121°29'57"E); the second area consists of a diamictite with overlying coarse-grained sandstone (latitude 24°17'57"S, longitude 122°16'19"E); and the third area comprises a lutite and carbonate succession (latitude 23°34'56"S, longitude 121°38'25"E).

Diamond corehole GSWA Empress 1 and 1A (Fig. 1) penetrated 197 m of glacigene diamictite and an overlying 30 m-thick sandstone, separated by an approximately 50 cm-thick dolomitic horizon. The diamictite was initially assigned to the '?Lupton Formation' and the upper 30 m to an 'unnamed unit' (Stevens and Apak, 1999). The uncertainty about its correlation arose because the core interval is commonly finer grained than the type section. However, based on lithostratigraphic and facies comparisons, the diamictite is here correlated with the Lupton Formation (Fig. 2). From biostratigraphy and isotope chemostratigraphy, the overlying dolomitic horizon is correlated with the Marinoan 'cap dolomite' found elsewhere in the Centralian Superbasin and Adelaide Rift Complex.

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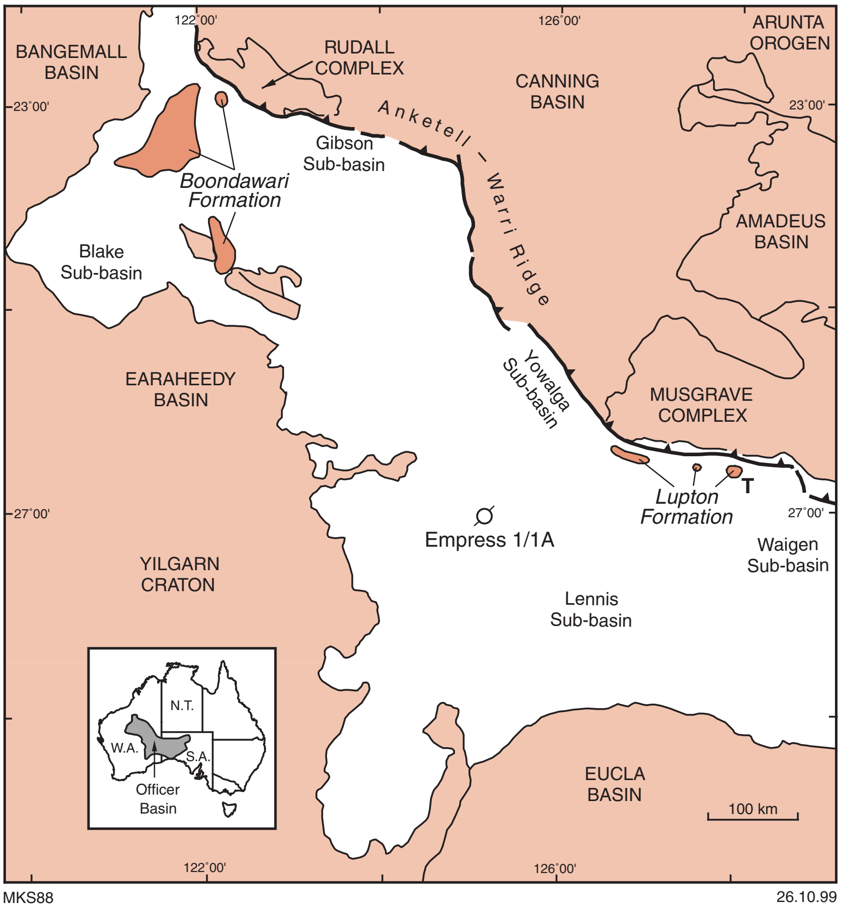

Figure 1. Location of outcrops of Neoproterozoic glacigene rocks and Empress 1 and 1A in the western Officer Basin. T = type section of the Lupton Formation and measured section COP 98/3 (see Figure 3)

Description of glacigene units of the Officer Basin

The Lupton Formation outcrops at Lupton Hills, near Ainslie Gorge (latitude 26°14'S, longitude 126°38'E), and elsewhere along the southern edge of the Musgrave Complex (Fig. 1). At Lupton Hills, the remeasured type section consists of a lower unit of massive, very poorly sorted pebble to boulder conglomerate, and overlying interbedded conglomerate, sandstone, and siltstone (Fig. 3). Outcrops elsewhere consist mostly of fine-grained diamictite with scattered large boulders, and interbeds of fine-grained, well-bedded sandstone and coarse-grained cross-bedded sandstone. A glacigene origin is indicated by rare faceted and striated clasts.

Empress 1 and 1A was drilled about 170 km southwest of the nearest outcrop of the Lupton Formation (Fig. 1) and, based on lithostratigraphic similarity, the interval from 317.1 – 486.0 m (Fig. 3) is here assigned to the Lupton Formation. Clasts in the diamictite are compact to platy or elongate, subangular to subrounded, and sometimes faceted, and there are rare striations, indicating a glacial origin. The Lupton Formation grades upwards into an unnamed sandstone-dominated unit (286 – 317.1 m) that is fine to medium grained with minor coarse to very coarse grained bands.

Six facies types were identified in the Lupton Formation in Empress 1 and 1A (Fig. 3). Massive and stratified diamictite dominates the succession (Dmm and Dms, Fig. 3), with an approximate cumulative thickness of 90 m, and is associated with mudstone and sandstone facies (Fl, Fm, Sm, Sh, Fig 3). Massive diamictite (Dmm) is structureless and consists of clasts scattered in a muddy, medium-grained sandstone matrix. Stratified diamictite (Dms) shows crudely developed bedding defined by poorly organized concentrations of clasts or changes in matrix texture (or both). Associated fine-grained laminated and graded sandstones and mudstones are interpreted as the deposits of dilute, low concentration turbidity currents; isolated clasts found within these facies were probably ice-rafted. Sandstone facies are massive (Sm) or horizontally laminated (Sh) and often contain deformation structures that typically result from downslope subaqueous slumping. Sandstone characteristics are also consistent with a depositional origin by sediment gravity flows such as turbidites. The close association of diamictites with muddy and sandy turbidites suggests a subaqueous origin for diamictite facies, either by slumping and sediment gravity flows (debris flows) or by ice-rafting and 'rain-out' of suspended fines. A glacio-marine setting is provisionally suggested.

The uppermost Lupton Formation (317.1 – 318.7 m) consists of interlaminated and interbedded, fine- to coarse-grained sandstone, mudstone, and thin dolomite bands (Fig. 4). It contains patches of rounded jaspilitic grains, and resembles the bed of 'dark red-brown cherty dolomite about 1 m thick' that forms the Marinoan cap dolomite at the top of the Pioneer Sandstone in the Amadeus Basin (Walter et. al., 1979; Fig. 2). Additionally, thin bands of laminated, micritic, light-grey dolomite contain incipient stromatolite columns (Fig. 4), here assigned to ?*Elleria minuta* Walter and Krylov *in* Walter et al. 1979, a form previously recorded from the Pioneer Sandstone cap dolomite (Walter et al., 1979).

Correlation of the dolomite in Empress 1A with the Marinoan cap dolomite is supported by isotope chemostratigraphy (Walter and Hill, 1999). Analyses of $\delta^{13}C_{carbonate}$ samples from the dolomitic bands show similar values to those recorded from (1) the cap dolomite immediately above the Boondawari Formation diamictite; (2) carbonate in the glacigenic Boord Formation, a lateral equivalent of the Pioneer Sandstone in the western Amadeus

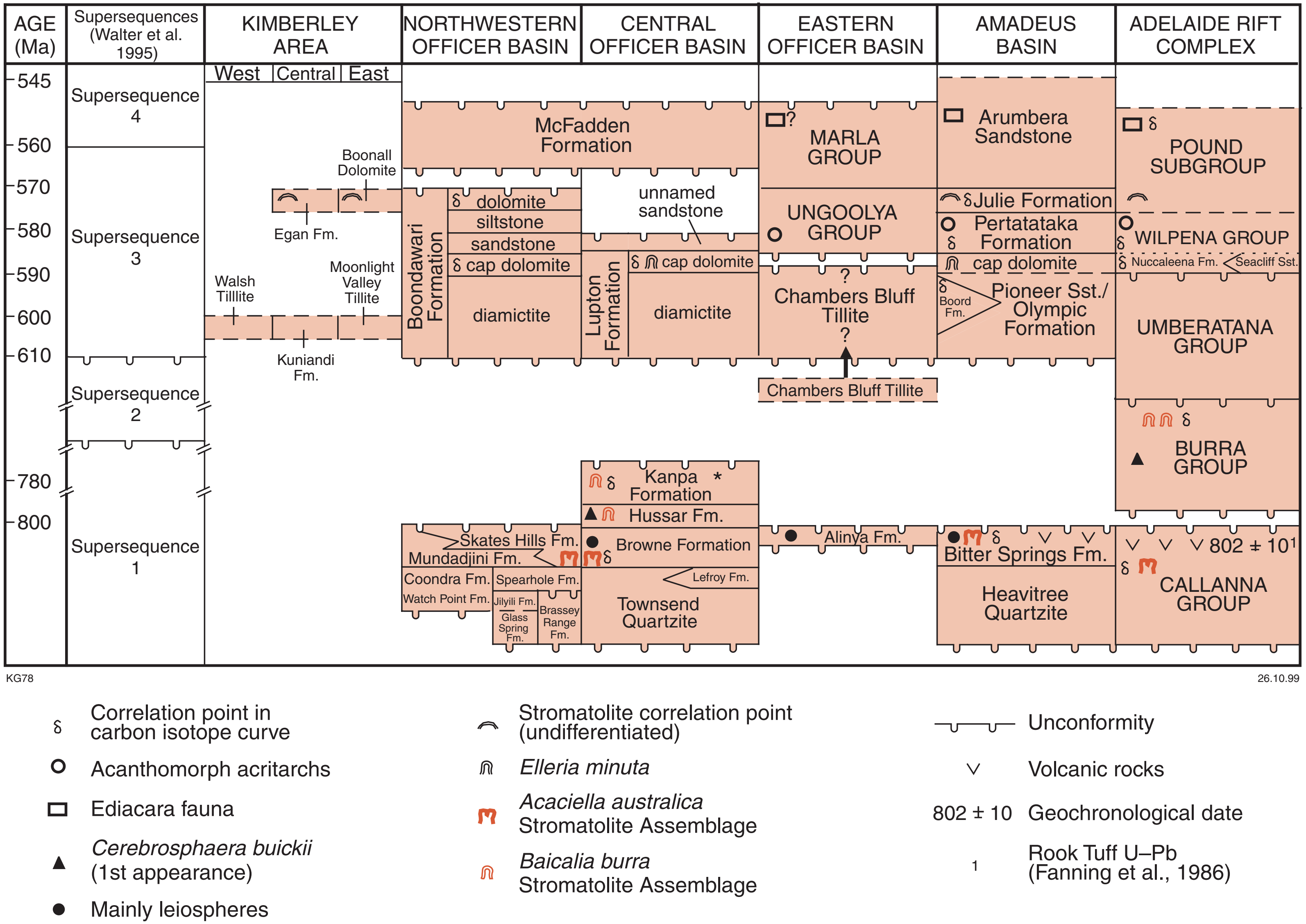

*Figure 2. Neoproterozoic glacigene stratigraphy (Supersequence 3) of the western Officer Basin, and stratigraphic correlation with selected units from other areas of the Centralian Superbasin and Adelaide Rift Complex. Type of data used for correlation of units is indicated. * See revision to stratigraphy in Apak and Moors (in prep.)*

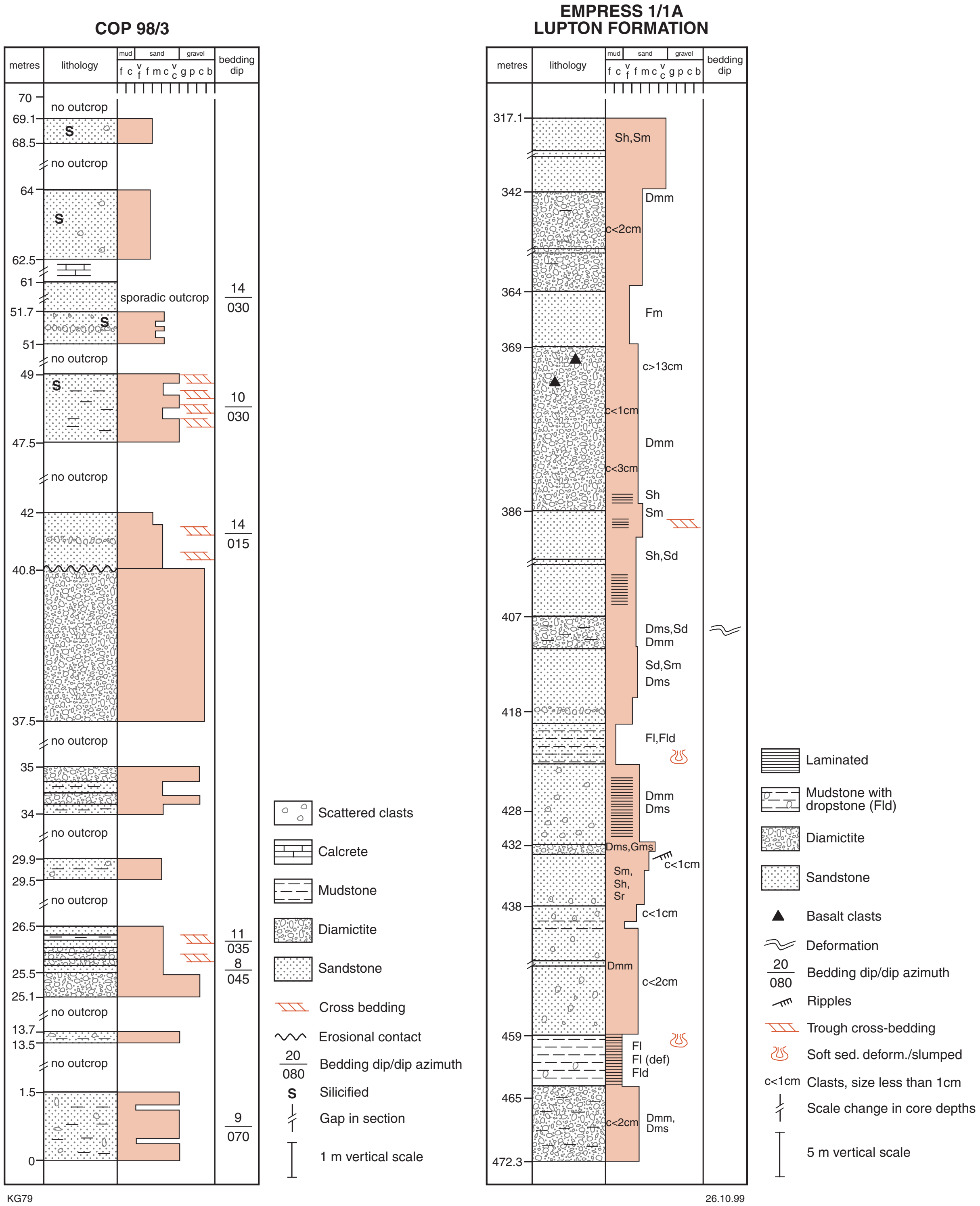

Figure 3. Lithostratigraphic columns for the type section of the Lupton Formation at Lupton Hills (COP 98/3), and the Lupton Formation in Empress 1 and 1A, western Officer Basin. D = diamictite facies; Dmm = matrix supported, massive; Dms = matrix supported, stratified; G = conglomerate facies; gms = stratified; S = sandstone facies; Sm = massive; Sd = deformed; Sh = horizontally laminated; Sr = rippled; F = fine-grained (mudstone) facies; Fm = massive; Fl = laminated; Fl(def) = laminated and deformed; Fld = laminated with dropstone

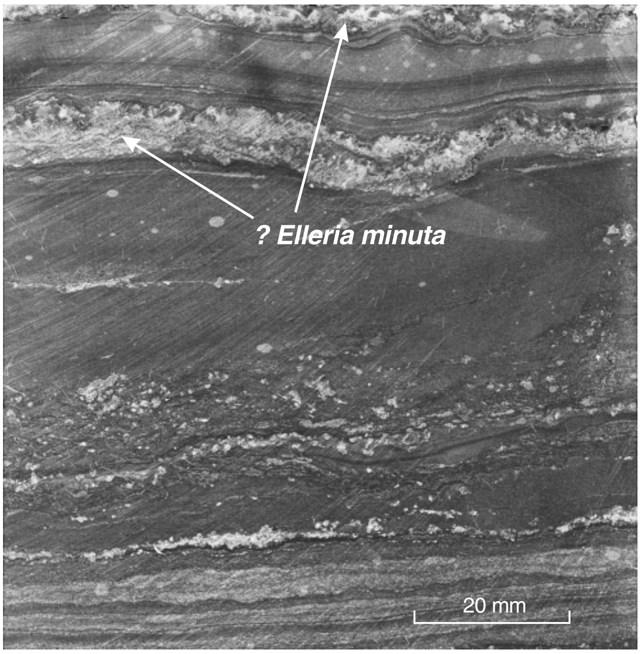

*Figure 4. Photograph of cap dolomite in Empress 1 and 1A (317.62 – 317.79 m) showing incipient stromatolite columns of ?***Elleria minuta** *(arrowed)*

Basin; (3) the cap dolomite above the glacigene Pioneer Sandstone, central Amadeus Basin; and (4) in the Nuccaleena Formation, Adelaide Rift Complex (Preiss, 1987; Walter et al., 1994, 1995; Calver, 1995; Calver and Lindsay, 1998; Fig. 2).

The unnamed sandstone unit above the diamictite and caprock of the Lupton Formation in Empress 1 and 1A is a probable lateral equivalent of the Seacliff Sandstone of the Adelaide Rift Complex (Preiss, W. V., 1998, pers. comm.; Fig. 2). It was probably deposited on an open marine shelf. The lower part consists of a fining-upwards succession, including mudstone, that indicates a post-glacial transgression resulting from a rise in sea level.

In the northwestern Officer (formerly Savory) Basin (Perincek, 1998; Bagas et al., 1995, 1999), the glacigenic Boondawari Formation (Figs 1 and 2) outcrops near Boondawari Creek. It is poorly exposed, and has a total maximum thickness of about 800 m (Williams, 1992; Walter et al., 1994). Lithologies include diamictite, and a thin (~15 cm thick), red, micritic dolomite with depleted carbon isotope values similar to those recorded for cap dolomite elsewhere in the Centralian Superbasin and Adelaide Rift Complex (Walter et al., 1994). It is overlain by 30–40 m of red siltstone with sandstone interbeds, which resembles siltstone in the same relative stratigraphic position in the Pertatataka Formation of the Amadeus Basin and the Brachina Formation of the Adelaide Rift Complex. From lithostratigraphic, biostratigraphic, and isotope chemostratigraphic evidence, the Boondawari Formation appears equivalent to the entire Marinoan succession elsewhere in Australia.

Although different stromatolite taxa occur in the upper Boondawari Formation and the Julie Formation of the Amadeus Basin, they lie at the same relative stratigraphic position above the diamictite, and have similar carbon isotope values. A sample from the upper Boondawari carbonate shows marked enrichment in ^{13}C ($\delta^{13}C_{PDB}$ values ranging from +6.8 to +8.0‰) and compares with values obtained from the Julie Formation and other end-Marinoan carbonates in Australia (Walter et al., 1994; Calver 1995).

Discussion

At present there is no stratigraphic record of Sturtian age glaciation recognized in Western Australia (Fig. 2). Either deposition did not extend this far west, or, more probably, any deposits were subsequently eroded. In contrast, evidence for the presence of Marinoan glacigene rocks in the western Officer Basin is now convincing, and correlations can be made with successions in central and South Australia. The Boondawari and Lupton Formations, and the overlying unnamed unit in Empress 1 and 1A, are equivalent to the diamictite, cap dolomite, and overlying sandstone in other parts of the Centralian Superbasin and Adelaide Rift Complex (Fig. 2).

It must be emphasized that correlation between the western and eastern Officer Basin remains problematic. The Chambers Bluff Tillite (Fig. 2) of the eastern Officer Basin, presently regarded as Sturtian, could be Marinoan. A pink dolomite near the top of the formation (Morton, 1977) may be a cap-dolomite equivalent. Biostratigraphically significant acritarch assemblages in the overlying Ungoolya Group indicate correlation with the Pertatataka Formation above the cap dolomite in the Amadeus Basin (Grey, 1998). Kimberley glacigene successions (Fig. 2) are now all considered to be Marinoan in age, based on lithostratigraphy and stromatolite biostratigraphy (Grey and Corkeron, 1998), and the Egan Formation appears to be a younger glaciation that is time equivalent to the Julie Formation of central Australia (Grey and Corkeron, 1998).

Petroleum potential

The major hiatus between Supersequence 1 and the Marinoan glaciation (Fig. 2) represents a break of at least 150 million years. Karstification at the top of the Kanpa Formation unconformity includes vuggy porosity in Empress 1 and 1A (Stevens and Apak, 1999). This may indicate reservoir development, and overlying diamictite and mudstone facies of the Lupton Formation could have seal potential for poor to good source rocks identified in the underlying Kanpa Formation (Ghori, 1998; Carlsen et al., 1999).

Conclusions

The type section of the Lupton Formation has been remeasured and revised following the recognition of folding. Glacigene rocks in Empress 1 and 1A are assigned to the Lupton Formation from comparison of the lithostratigraphy. A Marinoan age for both the Boondawari and Lupton Formations in Empress 1 and 1A is indicated by the presence of a cap dolomite, $\delta^{13}C_{carbonate}$ isotope chemostratigraphy, and is supported by limited biostratigraphic data. The Neoproterozoic glacigene successions of the western Officer Basin can now be confidently correlated with the Amadeus and Georgina Basins, the Adelaide Rift Complex, and the Kimberley region.

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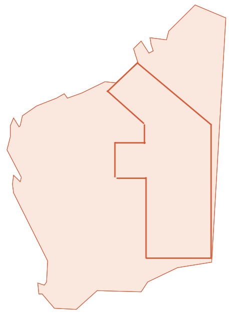
Program review

Program 3
Subprogram 3012
MINERAL AND PETROLEUM RESOURCE STUDIES

Interior Basins petroleum initiatives project

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



Highlights and activities 1998–99

The main activities during 1998–99 were the compilation of the Empress 1 and 1A well completion report and compilation of other Records in progress. These Records contain details of significant improvements in the understanding of potential Neoproterozoic petroleum systems of the Officer Basin (Fig. 1). Additional fieldwork in the Waigen Sub-basin of the Officer Basin has provided new data leading to future revisions of the COOPER 1:250 000 geological map. This improved understanding of the stratigraphy of this remote region of the Officer Basin has also contributed to the selection of a drilling locality for a scheduled 2000-m stratigraphic test, Vines 1, in the Waigen Sub-basin of the Officer Basin (Fig. 1). Site-clearance surveys, water wells, track improvements, and drilling pad preparations were completed prior to the end of the financial year, and the well was spudded on 4 July 1999.

Analysis of cores, cuttings, and logs from Vines 1 will provide new data for the reservoir, source-rock, and biostratigraphic interpretation of the Officer Basin. These data will be used, along with outcrop studies, for correlation to previous wells drilled in the basin, and to extend the depositional model for organic facies in the Officer Basin. This model will be applied to other sub-basins of the Officer Basin in the search for additional stratigraphic coring locations that would prove the source facies for hydrocarbon generation, migration, and entrapment.

Estimates of sedimentary thickness and structural data necessary to select a stratigraphic drilling location in the Waigen Sub-basin were interpreted using a detailed gravity survey carried out in 1997–98. No seismic data or stratigraphic tests currently exist for the Waigen Sub-basin. Detailed interpretation of the gravity data indicates that the Waigen Sub-basin in Western Australia is an extension of the Birksgate Sub-basin in South Australia, where a viable petroleum system has been defined around the Alinya Shale (source) and Pindyan Sandstone (reservoir). The Vines 1 stratigraphic test will be drilled to further define the stratigraphy of the Waigen Sub-basin and provide correlation to the Yowalga Sub-basin in Western Australia and the Birksgate Sub-basin in South Australia.

1998–99 publications and products

One Report and three Records were published during the year. They are:

- Report 68: 'Stratigraphy and petroleum exploration objectives of the Permo-Carboniferous on the Barbwire Terrace and adjacent areas of the northeast Canning Basin, Western Australia';
- Record 1998/3: 'Petroleum source-rock potential and thermal history of the Officer Basin, Western Australia';
- Record 1999/4: 'GSWA Empress 1 and 1A well completion report, Yowalga Sub-basin, Officer Basin, Western Australia'
- Record 1999/8: 'Waigen gravity survey—the contribution of semi-detailed gravity data to the stratigraphic and structural interpretation of the Waigen Sub-basin, Officer Basin'.

In addition, three papers were published in the proceedings of, and presented at, the West Australian Basins Symposium (held in Perth in August–September, 1998); and one paper was published in the Australian Petroleum Production

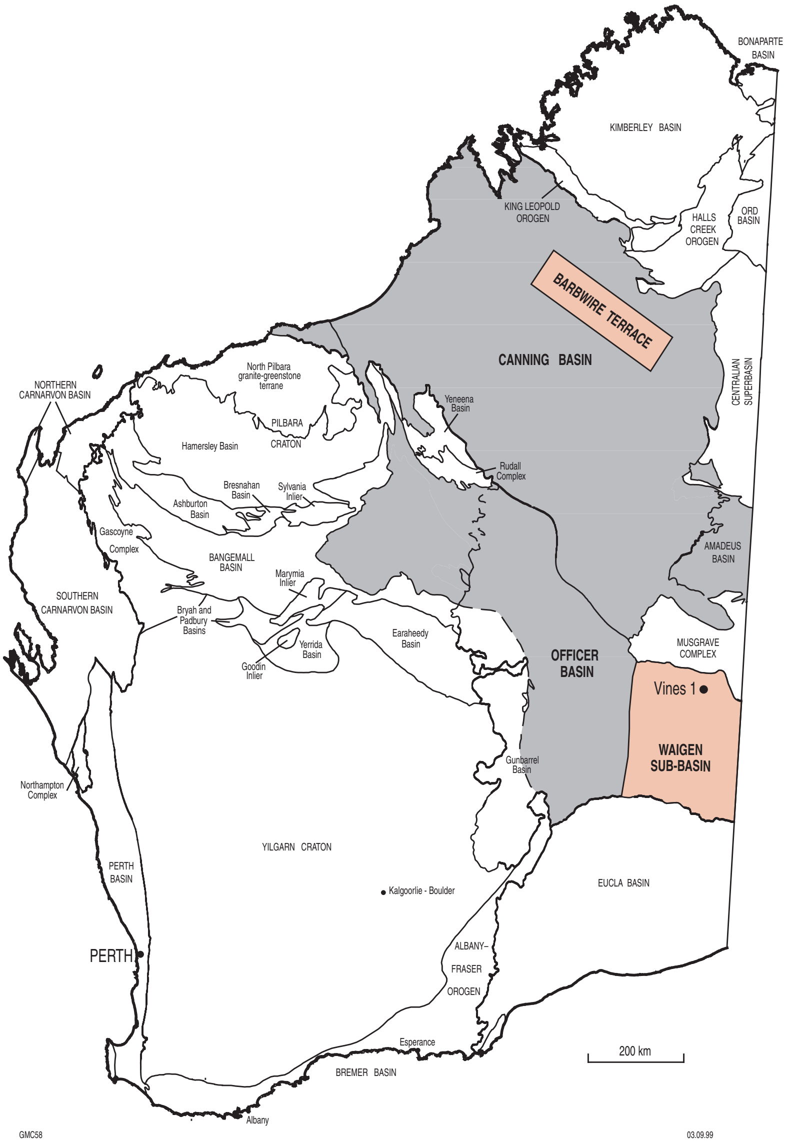


Figure 1. Location of the Interior Basins petroleum initiatives project

and Exploration Association (APPEA) Journal and presented at the APPEA Conference in Perth. These papers were respectively:

- 'The Lennard Shelf revisited';
- 'Reinterpretation of the Permo-Carboniferous succession, Canning Basin, Western Australia';
- 'Petroleum-generating potential and thermal history of the Neoproterozoic Officer Basin, Western Australia';
- 'Petroleum potential of the Neoproterozoic Western Officer Basin, Western Australia, based on a source-rock model from Empress 1A'.

Future work

Compilation of analytical data, core descriptions, and geophysical logs, together with preliminary interpretations will be included in the Vines 1 well completion report.

Following completion of fieldwork and stratigraphic coring in the Waigen Sub-basin, a series of reports on the exploration potential of the Yowalga, Gibson, Lennis, and Waigen Sub-basins will be prepared. In order to promote the work of the Geological Survey of Western Australia and, in particular, the results of the petroleum initiatives team, external publications and presentations at the next APPEA Conference and American Association of Petroleum Geologists (AAPG) Conference are in preparation.

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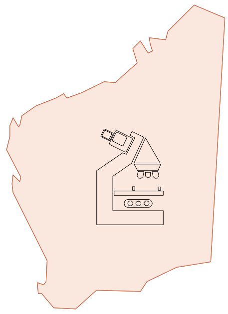
Biostratigraphy and palaeontological services



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

Highlights and activities 1998–99

Dr John Backhouse resigned in November 1998 to take up a part-time position at the University of Western Australia and to work as a consultant. During his 30 years at GSWA, John prepared more than 1000 internal reports and produced a substantial number of publications. His final contributions were to studies of the Permian and Carboniferous strata of the Canning Basin, an Australia-wide palynological correlation of the Permian, and palynological studies of Mesozoic to Devonian strata in the Carnarvon, Canning, and northern Perth Basins.

The highlight of the year was the organization of a field excursion in June 1999 to display new sites containing the most convincing fossil evidence yet discovered for early life to a group of leading world specialists in Archaean palaeobiology. A study of stromatolites in the Warrawoona Group of the eastern Pilbara region, carried out with Professor Hans Hofmann of Montreal University, points to a widespread development of complex morphology by 3.45 Ga. The excursion raised many issues, and it is hoped that future collaborative studies will add considerably to our knowledge of early life and the atmospheric and sedimentary environments in which it developed. A slab containing three-dimensionally preserved stromatolites was removed and will be displayed in the Western Australian Museum. Part of the excursion was filmed for the Quantum television program and screened in September 1999.

Other work completed this year contributed towards detailed correlation of Neoproterozoic successions in the western Officer Basin using stromatolites and palynology, and in placing the Officer Basin succession into context within the Centralian Superbasin. Detailed studies were carried out on Neoproterozoic successions in the GSWA Empress 1 and 1A drillcore. Kaye Cotter of Macquarie University completed a study of palynomorphs from other drillholes in the western Officer Basin. Integration of palynostratigraphy, stromatolite biostratigraphy, and isotope chemostratigraphy has substantially improved Australia-wide mid-Neoproterozoic correlations.

Progress continued in other areas of Precambrian biostratigraphy, and included studies of stromatolites and evaporites in the c. 2.3 Ga Bubble Well Formation, and possible microfossils associated with thermal spring deposits in the slightly younger Bartle Member of the Killara Formation, both from the Yerrida Basin.

Much of the section's output is either in publications or in the form of data used by other geologists in preparing their products. In 1998–99 the section contributed information to the Western Margin and Interior Basins petroleum initiatives projects, and, to a lesser extent, to the Glengarry, Earaheedy, Bangemall, Paterson, Pilbara, and King Leopold and Halls Creek Orogens projects, and the production of the new State geological map. Cataloguing and maintenance of the fossil collection is an ongoing task, and this year the type collection was reorganized and details entered in the fossil database, PALAEOBASE. The Phanerozoic non-type collection was reorganized, and the extensive palynological slide collection was catalogued and transferred to the statutory exploration information group (SEIG) relinquishment collection. An index to internal Palaeontological Reports written between 1962 and 1996 was compiled and was issued together with the scanned reports as a CD in 1999.

The section continues to answer a large number of queries on palaeontological and correlation matters, both internally and externally. Topics addressed included queries from the mining and petroleum industry on the age and regional correlation of various Proterozoic units; advice on the illegal export of fossils; information about stromatolites ranging in age from the Archaean to Recent, including assisting overseas researchers to set up projects at Shark Bay and to visit the Yalgorup Lakes area; advice to the Northern Territory Geological Survey on correlations between the Victoria River Basin and areas in Western Australia; Devonian palynology; and a variety of more general palaeontological queries and loan of fossil specimens.

Kath Grey was awarded her PhD for a thesis titled 'Ediacarian acritarchs of Australia', submitted to Macquarie University in August 1998.

1998–1999 publications and products

Altogether, 11 papers were published, seven are in press, and four are in advanced stages of preparation. Palaeontological publications included:

- Report 68: 'Stratigraphy and petroleum exploration objectives of the Permo-Carboniferous on the Barbwire Terrace and adjacent areas of the northeast Canning Basin, Western Australia';

- studies on the Permian strata of the Canning Basin (in The sedimentary basins of Western Australia 2);
- an Australian Permian palynological correlation (in Proceedings of the Royal Society of Victoria);
- a palynological study of western Officer Basin drillholes (in Alcheringa);
- a preliminary stratigraphic interpretation of the Empress 1 and 1A drillcore (in the GSWA Annual Review 1997–98);
- contributions to a paper on Officer Basin source-rock models (in APPEA Journal);
- appendices on Permian palynology and Neoproterozoic palynology and stromatolites in Record 1999/4 (Empress 1 and 1A well completion report);
- a proposed stromatolite correlation of the Neoproterozoic glacigenic Egan Formation in the Kimberley area with the late Marinoan of the Amadeus Basin and Adelaide Rift Complex (in Precambrian Research);
- a proposed correlation between the Ruby Plains Group of the eastern Kimberley region (formerly part of the Bungle Bungle Dolomite) and the c. 800 Ma old Bitter Springs Formation of the Amadeus Basin (in Australian Journal of Earth Sciences).

Two talks were presented at the Geological Society of Australia Convention in Townsville, and one at the GSWA '99 open day. Contributions were made to promotional displays at these meetings, and at the West Australian Basins Symposium in Perth, the 1999 APPEA Conference in Perth, and the Rodinia Workshop.

Future work

A description of the Warrawoona Group stromatolites will be published in August 1999 in the Geological Society of America Bulletin. Other papers on various Proterozoic fossils will be published in the next year. Work continues on reports on the Empress 1 and 1A drillholes. Palynological and stromatolitic studies are anticipated on the Vines 1 drillcore, from the southeastern part of the western Officer Basin. A Neoproterozoic stromatolite monograph, a review of palynological preparation techniques, and a revision of Officer Basin stratigraphic names are due for completion in 1999–2000.

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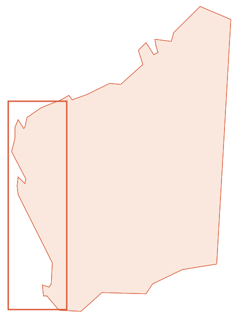
Western Margin petroleum initiatives project



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

Highlights and activities 1998–99

The main activities during the year were the preparation of reports and external papers on the Southern Carnarvon Basin and Peedamullah Shelf (Fig. 2). Studies of the Woodleigh impact structure continued, and included the drilling of two wells and a gravity survey. The most significant result during the year was that the drilling confirmed the Woodleigh structure as an impact feature. Shallow drilling in the Coolcalalaya Sub-basin indicated that Upper Carboniferous and Lower Permian strata with low organic yields are more widely distributed than previously thought. Consequently, the planned deeper stratigraphic tests in that area were not drilled.

The review of petroleum exploration wells in the central and southern Perth Basin completed in 1998 is to be published in 1999–2000. This study is centred on post-mortems of wells, but also rationalizes the stratigraphy of the southern areas with the studies to the north, and reviews play concepts and subcommercial petroleum discoveries.

A review of the Peedamullah Shelf and adjacent Onslow Terrace is nearing completion. The review focuses on well post-mortems, but also includes seismic mapping, a review of geochemical data, and geohistory modelling of the deeper wells. A paper is being prepared with AGSO on probable biogenic gas within the Peedamullah Shelf, for the Petroleum Exploration Society of Australia (PESA) Journal.

1998–99 publications and products

A number of significant publications were released during the year:

- Report 61: 'Structure and petroleum potential of the southern Merlinleigh Sub-basin, Carnarvon Basin, Western Australia';
- Report 69: 'Geology and petroleum potential of the Gascoyne Platform, Southern Carnarvon Basin, Western Australia';
- Report 72: 'Silurian–Devonian petroleum source-rock

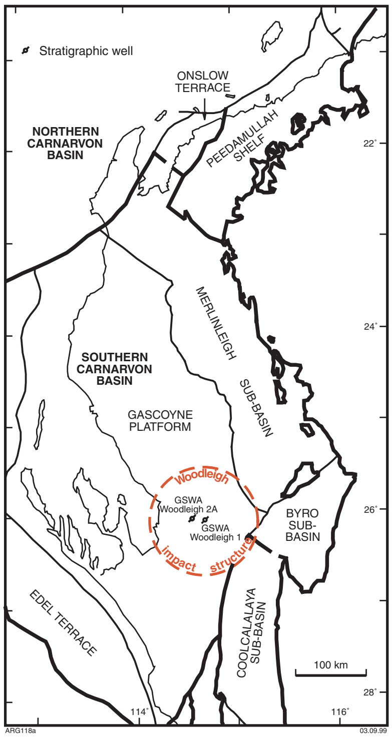


Figure 2. The northern part of the Western Margin petroleum initiatives project area, showing the location of the Woodleigh structure

potential and thermal history, Carnarvon Basin, Western Australia';

- Record 1998/6: 'GSWA Mooka 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia';
- Record 1999/3: 'GSWA Barrabiddy 1 and 1A well completion report, Wandagee Ridge, Southern Carnarvon Basin, Western Australia';
- Record 1999/5: 'Coburn 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia';
- Record 1999/7: 'Yaringa East 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia';
- Record 1999/9: 'Gravity data — Wyloo 1:250 000 sheet, Western Australia'.

Preliminary results on the Palaeozoic source rocks of the Carnarvon Basin, the structure of the Gascoyne Platform, and the petroleum geology of the Peedamullah Shelf were included in five papers prepared for the West Australian Basins Symposium. In addition, a paper on the geochemical results from GSWA Barrabiddy 1A was published in the PESA Journal. Papers on reservoir quality in the Merlinleigh Sub-basin, and Silurian dolomitization in the Gascoyne Platform have been submitted to the AAPG Journal and Journal of Sedimentary Research.

Promotional booths, containing displays of major products from the Western Margin and Interior Basins teams were prepared for the West Australian Basins Symposium, the 1999 APPEA Conference (held in Perth), the GSWA '99 open day, and the 1999 AAPG Conference (held in San Antonio, USA).

Future work

Due for completion in 1999–2000 are reports and papers on the petroleum geology of the Peedamullah Shelf, the Woodleigh structure, and the hydrocarbon potential of the Coolcalalaya Sub-basin. Work on a Bulletin on the evolution and petroleum potential of the Southern Carnarvon Basin, synthesizing previously published GSWA reports and some new regional interpretation of offshore data, is to commence in 1999–2000.

The only new data to be acquired during 1999–2000 will be analyses of existing core, mainly from Woodleigh 1 and 2A, and a small gravity survey in the northern Perth Basin.

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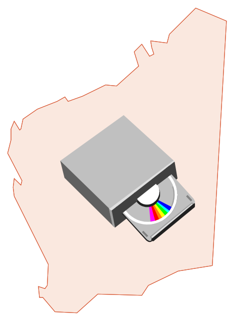
Resource assessment and geoscientific advice

Resource studies and MINEDEX database



Objectives: *To maintain a detailed inventory of the State's identified mineral resources, monitor mining and exploration activities, and provide advice on mineral resources, mineral exploration, and potential for mine development. All these functions are primarily supported through MINEDEX, the Department's mines and mineral deposits information database.*

Highlights and activities 1998–99

In 1998–99 ongoing data capture into DME's mines and mineral deposits information (MINEDEX) database formed a significant part of the function of this section, together with advice to a wide range of customers. Data capture commenced on locations of and production from historic mine sites. An updated non-confidential digital dataset from MINEDEX, including information on mineral resources and mine locations, commodities, ownership, and development status, was released to the public to accompany the previously released Record 1996/13. This supplements the new 'Western Australia Atlas of mineral deposits and petroleum fields', published in 1999, showing resource localities superimposed on the simplified 1998 State geological map. The Atlas is one of the most popular publications of the Geological Survey of Western Australia.

Position papers were prepared on the economic impact of nickel laterites on the nickel industry, and overview of exploration and development in Western Australia during 1997–98. A report on the geology and mineral resources of the Mid West region was prepared for the Department of Resources Development, the project manager for the joint Federal–State–industry project 'Mid West Regional Minerals Study' looking at possible development and infrastructure scenarios within the region for the next ten years.

Quarterly updates of mineral exploration activity in Western Australia were produced during the year. Mineral exploration (excluding petroleum) has been steadily declining (in trend terms) in Australia and Western Australia since the record highs in mid-1997, but with a sharper decline in early 1999. Exploration activity (generally) is now 25–30% lower than for one year previously. Gold exploration expenditure in Western Australia has now dropped about 50% over the last two years, dropping from a level of about $150 M per quarter in mid-1997 to only about $70 M per quarter in early 1999. Gold now accounts for only 66% of all exploration expenditure in Western Australia (other than petroleum). This is a sharp fall from the 76% of the total gold commanded in mid-1997. Gold exploration activity is now at levels last experienced in mid-1993.

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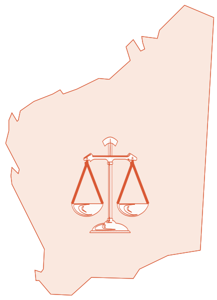
Geoscientific advice relating to exploration

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



Highlights and activities 1998–99

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

Exploration performance on 773 mineral tenements (Table 1) was reviewed during 1998–99 (956 in 1997–98) as part of the assessment of applications for exemption from expenditure conditions, applications for extension of term of exploration licences, applications for retention licences, applications for special prospecting licences, and applications for Ministerial consent to dealings in exploration licences during their first year of tenure.

Table 1. Tenement reviews

Geological advice provided	*Number of tenements*			
	1995–96	*1996–97*	*1997–98*	*1998–99*
Expenditure exemption	3 004	458	821	580
Extension of term of exploration licences	353	186	27	48
Dealings in first-year exploration licences	36	58	21	27
Iron ore authorization (Exploration Licences)	na	6	13	9
Iron-ore drop offs (Exploration Licences)	na	13	10	27
Retention licence applications	na	na	5	3
Special Prospecting Licence applications	na	na	11	14
Other	na	na	48	65
Total	**3 393**	**721**	**956**	**773**

NOTE: na = not available

The number of applications for exemption from expenditure has increased by about 10% to 5570 during 1998–99. However, referral of such applications to the Geological Survey for geological advice has dropped to only 14% of the total applications (from about 20% in 1997–98), which is mainly due to two factors. Firstly, applications under Section 102(2)(e) (i.e., that the tenement contains a deposit which is currently subeconomic) are now only referred to the Geological Survey if grounds under 102(2)(e) have not been previously verified. Secondly, geological advice is not sought for the current application unless there is a change in the resource estimate.

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

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Industrial minerals

Objectives: *To promote development of industrial minerals in Western Australia by the systematic documentation of industrial mineral occurrences and production of reports on industrial mineral commodities, and to provide advice concerning industrial mineral resources to industry, government, and the public.*

Highlights and activities 1998–99

An important objective of the Geological Survey of Western Australia is to provide advice to Government, industry, and the public on the geology, prospectivity, and distribution of industrial minerals in Western Australia. The main projects completed during 1998–99 included the publication of one commodity Bulletin, one Report, and one miscellaneous publication.

Commodity studies

One commodity Bulletin was published: Mineral Resources Bulletin 19 — 'Kaolin in Western Australia'. The Bulletin contains comprehensive summaries of all known deposits and occurrences in the State, past production, and aspects of mineralization, and chapters on the mode of occurrence, prices, and specifications for various end-uses. Although the historical production of kaolin in the State is low, there are large high-grade deposits that are yet to be mined. Although many residual kaolin deposits in the South West region contain kaolin of acceptable brightness for paper-grade applications, more detailed testing on rheology and particle-size distribution is required to fully evaluate many of these deposits.

Geological investigations for the project 'Speciality clays and common clays in Western Australia' were carried out during 1998–99 and a draft Mineral Resources Bulletin is in preparation.

A miscellaneous publication, entitled 'Armour-stone investigation north of King Bay, Burrup Peninsula, Western Australia', was released during 1998–99. The publication describes a program of geotechnical drilling and rock mechanics designed to locate a suitable source of armour-stone on the Burrup Peninsula. The project, carried out for the Department of Resources Development, was successfully completed with the identification of 2.3 Mt of armour-stone with a natural size of less than 0.3 m.

Joint Western Australia – Zhejiang Province (China) research project

This project was initiated in 1994 under a Memorandum of Understanding of a Government-initiated Sister-State Agreement with the Department of Geology and Mineral Resources (DGMRZ) of the Zhejiang Province in the Peoples Republic of China. Part of the agreement was for the provision of experts in industrial minerals from DGMRZ to assist in a research project in Western Australia relating to a number of undeveloped industrial mineral deposits that indicate potential for development. The project was finalized during 1998–99 with publication of Report 67: 'Six industrial mineral deposits of significance in Western Australia: bentonite, feldspar, kaolin, micaceous iron oxide, talc, and tourmaline'.

Industrial minerals database

An industrial minerals module of GSWA's Western Australian Mineral Occurrence (WAMIN) database was further developed during the year. Standardized information on industrial mineral occurrences within the Mid West and Gascoyne regions were captured during the year.

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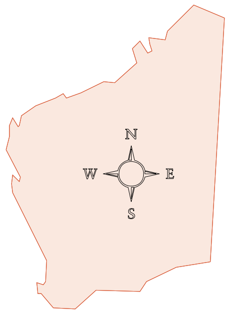
Regional mineralization mapping



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

Highlights and activities 1998–99

During the year, two data packages on the mineral occurrences and exploration potential of the Bangemall Basin and of southwest Western Australia were published. A data package on the west Pilbara region was compiled in draft form. Compilation of databases continued for three other areas: the east Kimberley, north Kimberley, and east Pilbara (Fig. 3).

In each data package there is a Report that synthesizes information on the mineral prospectivity of an area, accompanied by a 1:500 000 map showing mineral occurrences, mineralization styles, commodity groups, and geology. The CD-ROM in each package contains the following datasets available in Arc Explorer format: WAMIN (spatial index database of Western Australian mineral occurrences); EXACT (formerly SPINDEX, spatial index database of mineral exploration activities); MINEDEX (extract of DME's mines and mineral deposits information database); TENGRAPH (extract of DME's electronic tenement-graphics system); geology (solid and regolith); Landsat images; aeromagnetic data; radiometric data; gravity data; and topographic and cultural features.

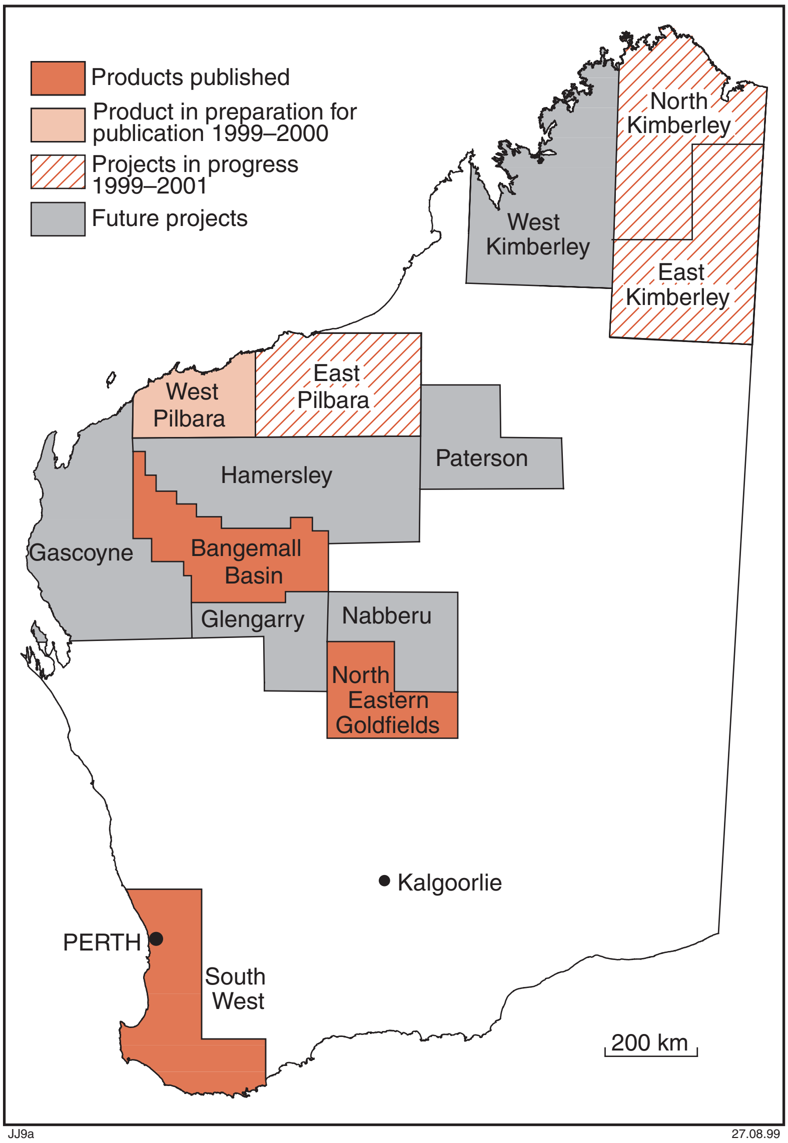


Figure 3. Progress of regional mineralization mapping projects

In 1998–99, the Report, 1:500 000 map, and CD-ROM data package for the west Pilbara area were compiled in draft form. For the east Pilbara area, which includes four 1:250 000 sheets (PORT HEDLAND, MARBLE BAR, YARRIE, and NULLAGINE), compilation and digitizing of spatial data commenced for mineral occurrences and mineral exploration activities from the Western Australian Mineral Exploration (WAMEX) open-file statutory reports, Departmental records, and other published sources. Field checking of mineral occurrences also commenced.

In the east Kimberley and north Kimberley areas, compilation and digitizing of spatial data continued for mineral occurrences and mineral exploration activities. The east Kimberley area includes six 1:250 000 sheets: Lissadell, Dixon Range, Gordon Downs, Mount Ramsay, Mount Bannerman, and Billiluna. The north Kimberley area includes seven 1:250 000 sheets: Londonderry, Drysdale, Ashton, Mount Elizabeth, Lansdowne, Medusa Banks, and Cambridge Gulf.

1998–99 publications and products

Three Reports, including two mineralization mapping reports, were released at the beginning of the year:

- Report 64: 'Mineral occurrences and exploration potential of the Bangemall Basin';
- Report 65: 'Mineral occurrences and exploration potential of southwest Western Australia';
- Report 66: 'Mineralization of the Halls Creek Orogen, east Kimberley region, Western Australia'.

Future work

The report and map on the west Pilbara area (Report 70) are to be published in 1999–2000. Compilation and digitizing of spatial data will continue for mineral occurrences and mineral exploration activities for the east Kimberley, north Kimberley, and east Pilbara areas. It is planned to complete work and compile a report on the east Kimberley region by the end of 1999–2000.

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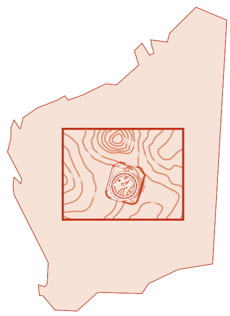
Urban and development areas geological mapping

Objective: *To undertake detailed geological mapping in areas of the State that are likely to see significant development, and where landuse planning would benefit from the availability of digital and hard-copy geoscience datasets. Also to provide high-quality and timely information and advice to Government, industry, and the public on mineral occurrences and resources, solid and regolith geology, and geohazards, both onshore and in shallow near-shore areas.*



Highlights and activities 1998–99

The project commenced in 1998 with field mapping on the Geraldton, Howatharra, Cowaramup, Karridale, and Leeuwin 1:50 000 map sheets (Fig. 4). Close ties were developed with the local shires and several Government departments, and with other potential map users ranging from viticulturists in the South West region to industrial developers in Geraldton. The mapping of land systems and resources follows on from earlier work done by GSWA in the coastal belt (urban and environmental maps).

A mapping methodology was developed involving the systematic collection of surface and near-surface material properties, and landform properties and patterns. Data were compiled in the developing Western Australian field observation (WAROX) database, which continued to be tested in both the field and office. Map compilation in the field using high-resolution orthophotographs has resulted in significant improvements to spatial integrity as well as a shorter compilation period. The land-systems based mapping methodologies adopted by AGSO for Kalgoorlie and by Agriculture WA for the agricultural belt have been combined and adopted to produce a unified mapping system for the new 1:50 000 series urban and development areas geological maps.

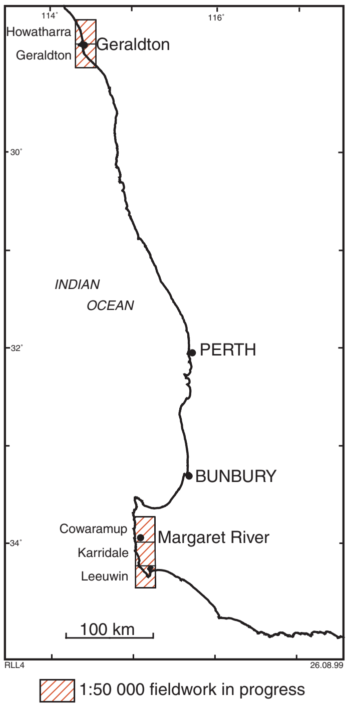


Figure 4. Progress of urban and development areas geological mapping

Future work

The compilation and design of the first Geraldton and Cowaramup

1:50 000 map sheets, combined with the development of complementary digital datasets and a Report, will occupy the early part of 1999–2000. Accession of textual attribute data to the corporate database is complete, and will be complemented by the addition of image data, completing the capture of all field observations in digital form.

Once the product is established the team will prepare the HOWATHARRA, KARRIDALE, and LEEUWIN 1:50 000 sheets for publication. High priority will be given to fieldwork in Kalgoorlie.

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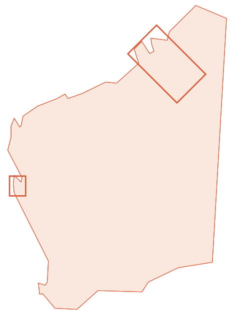
Subprogram 3103 REGIONAL GEOSCIENCE MAPPING

Lennard Shelf and Shark Bay project



Objectives: *To prepare comprehensive accounts and maps of the Devonian reef complexes of the northern Canning Basin and their associated terrigenous clastic deposits and of the geology and mineral resources of the Shark Bay World Heritage Area.*

Highlights and activities 1998–99

Mapping and section-measuring in the Devonian outcrop belt of the Lennard Shelf, with associated biostratigraphic, sedimentological, and subsurface studies, has been in progress since the project commenced in 1992. The objective is to increase geological understanding of the Devonian reefal succession and associated terrigenous conglomerates. The Devonian rocks are regarded as highly prospective for both zinc–lead mineralization and petroleum. The reef complexes form one of the classic features of world geology, and the results of the project will be of widespread interest to geoscientists and the public.

The last of the new series of seven geological maps of the outcrop belt was printed in June 1999 (Fig. 5). This regional map, at a scale of 1:250 000, covers the whole of the outcrop belt. This series of maps, which are to form plates in the forthcoming Bulletin, will be released separately in the second half of 1999.

The manuscript of a Report on the subsurface geology of the reef complexes was completed, and the preparation of the manuscript of a Bulletin on the surface geology is in progress. Papers on new concepts of the geology of the reef complexes were presented at the Australian Geological Convention in July 1998, the GSWA open day in March 1999, the Annual Meeting of the WA Branch of the Geological Society of Australia in April 1999, and the 1999 AAPG annual convention of the American Association of Petroleum Geologists (in San Antonio, Texas) in April 1999.

The Geological Survey has been involved in geological studies of the Shark Bay area since the early 1970s.

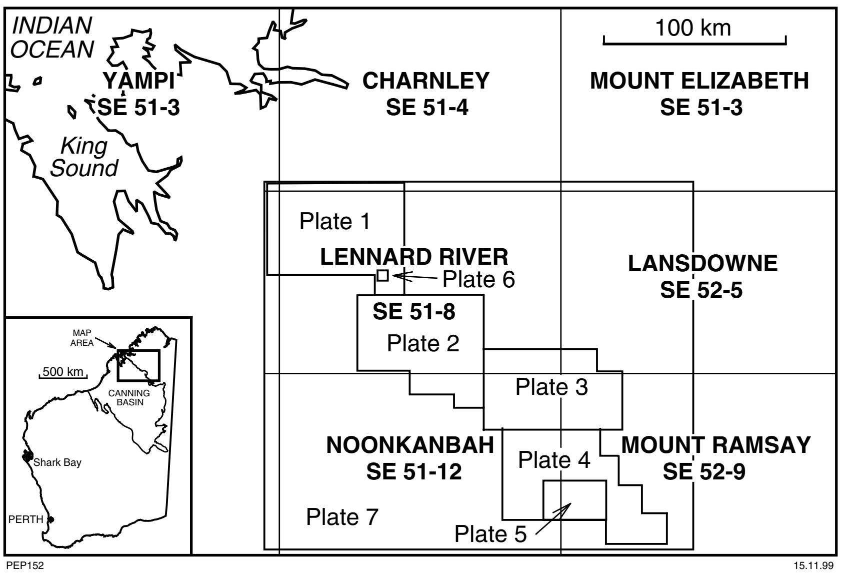


Figure 5. Location of Lennard Shelf and Shark Bay project

The present project has concentrated on the modern stromatolites of Hamelin Pool and the sedimentology and geological history of the Hamelin Coquina, a unit that has long been subject to small-scale mining operations, which are still continuing. There was no further work on this part of the project during the year.

Future work

Future work will concentrate on preparation of the Bulletin on the Devonian reef complexes of the Lennard Shelf.

Further work on the Shark Bay project will be deferred pending completion of the Lennard Shelf project.

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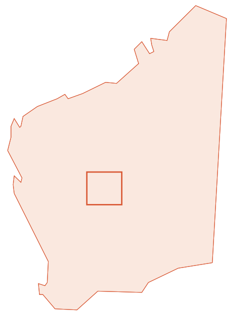
Glengarry project (Bryah, Padbury, and Yerrida Basins)



Objective: *To increase geoscientific knowledge of Early Proterozoic basins in the Glengarry region, on the northern boundary of the Yilgarn Craton, through the collection, synthesis, and dissemination of geological information. This is to be achieved through the production of geological maps and supporting publications that integrate field and laboratory studies, including mapping, petrology, geochemistry, geochronology, remote sensing, and metallogeny.*

Highlights and activities 1998–99

The Marymia 1:100 000 map sheet and Explanatory Notes were published in 1998–99. Geoscientific papers on Marymia were published in the 1997–98 GSWA Annual Review and an external journal. The Merewether 1:100 000 map sheet was compiled and it is being prepared for publication. Explanatory Notes for Merewether are being compiled. The eastern part of the Yerrida Basin is within the Merrie 1:100 000 map sheet, which was mapped as part of the Earaheedy Basin project. Merrie was published this year, thus completing the systematic field mapping of the entire Yerrida Basin (Fig. 6).

Two Reports (Report 59 for Bryah and Padbury Basins; Report 60 for the Yerrida Basin) have been compiled and await publication. These Reports conclude the Glengarry mapping program that began in 1994.

An interpretive 1:250 000-scale geological map of the Yerrida Basin (Plate 1) together with cross-sections on a separate plate (Plate 2) were published. These products are to accompany Report 60.

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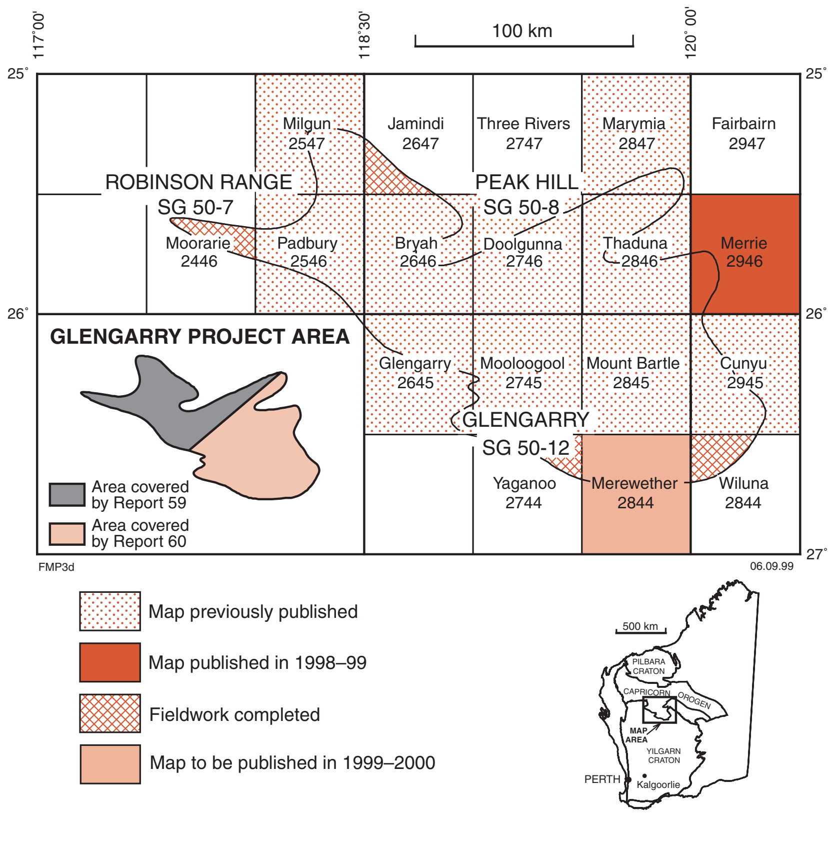
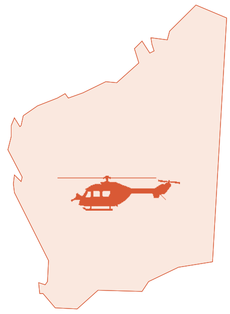


Figure 6. Progress of geological mapping in the Glengarry project area

Regional regolith and geochemical mapping

Objectives: *To ascertain the distribution and composition of surface material (regolith) over parts of Western Australia, and to provide these data as maps and digital datafiles as regional-scale, baseline information for the mineral exploration industry.*



Highlights and activities 1998–99

Maps and Explanatory Notes were published for the Collier and Wyloo 1:250 000 maps in 1998–99, and gravity was measured at each geochemical sample site on Wyloo (Fig. 7). Regolith sampling and gravity capture was carried out on six contiguous 1:100 000 map sheets over part of the Albany–Fraser Orogen (in conjunction with AGSO), and on the Ajana, Stanley, and Kingston 1:250 000 map sheets (Fig. 7), the latter also in conjunction with AGSO. Regolith samples from the six Fraser Range region 1:100 000 maps (Coonana, Zanthus, Yardilla, Symons Hill, Fraser Range, and Harms) and the Ajana 1:250 000 map sheet were analysed.

The GSWA regolith classification scheme was revised and applied to the Fraser Range region, Ajana, Kingston, and Stanley map sheets, with the scheme well suited to distinguishing different sand-dominated units on Ajana. Unlike other areas tackled during the program, the dense and extensive vegetation cover on parts of Ajana and the Fraser Range region created problems in the use of satellite imagery for determining the type and extent of different regolith units.

The regional regolith geochemical and gravity mapping program was a finalist in the 1998 Premier's Award in the area of Process Improvement. Presentations dealing with parts of the regional regolith geochemical program were made at the GSWA '99 open day in March 1999, and at the 19th International Geochemical Exploration Symposium held in Vancouver in April 1999.

Future work

During 1999–2000, GSWA will release maps and Explanatory Notes for the Fraser Range region, and the Ajana, Kingston, and Stanley map sheets. Aspects of current work will also be presented at Regolith '99, the national conference on regolith to be held in Adelaide, South Australia, in November 1999.

Regolith sampling was carried out on the Winning Pool – Minilya 1:250 000 sheets in July 1999.

Detailed gravity data have already been captured over parts of the Winning Pool map sheet; therefore, gravity data will only be measured over the eastern parts of this area. Maps and Explanatory Notes from this area are to be published by July 2000.

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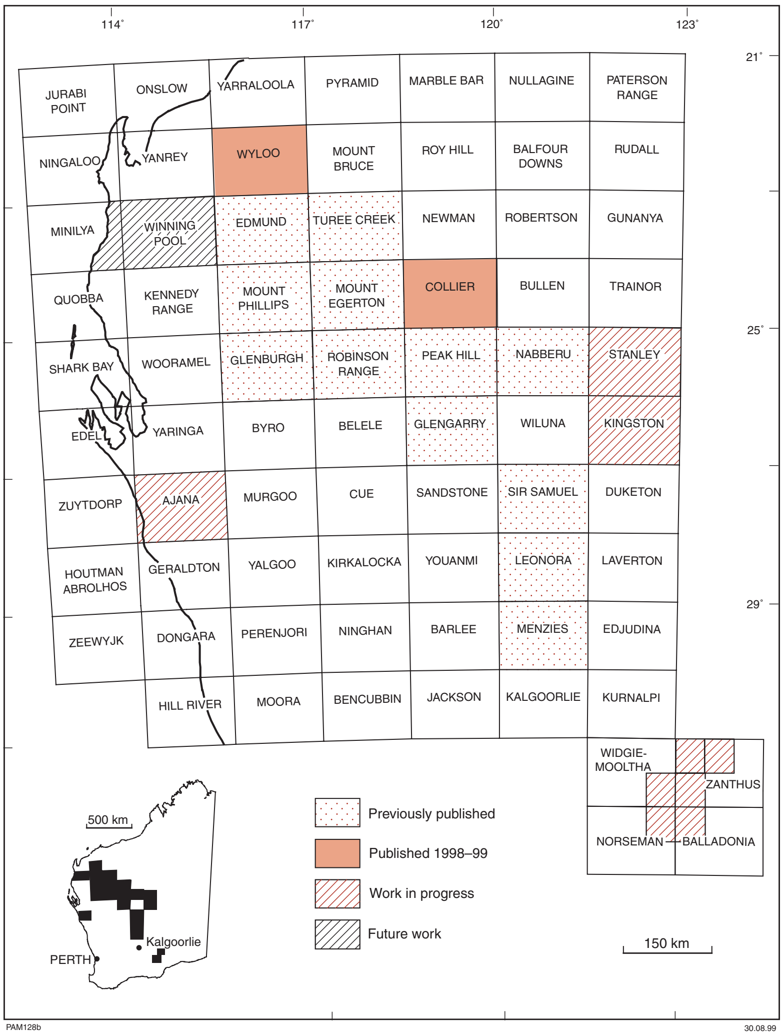
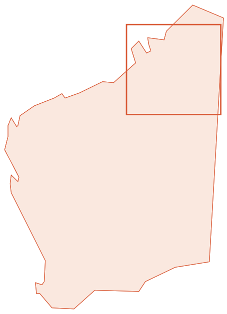


Figure 7. Summary of progress of the regional regolith and geochemical mapping program

King Leopold and Halls Creek Orogens mapping



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

Highlights and activities 1998–99

During 1998–99, compilation of a 1:500 000 geological map of the Halls Creek Orogen was completed, together with manuscripts for the Bow 1:100 000 and Lissadell 1:250 000 Explanatory Notes. Manuscripts for three papers that describe aspects of the geology and geochronology of the King Leopold and Halls Creek Orogens were submitted to Precambrian Research and the Australian Journal of Earth Sciences. Two papers for submission to the Journal of the Geological Society of London are in preparation. This is an NGMA project with AGSO.

1998–99 publications and products

During 1998–99, a second edition of the Dixon Range 1:250 000 geological map sheet was released, as well as Explanatory Notes for the Angelo, Dockrell, and Bow 1:100 000 map sheets (Fig. 8). AGSO published the Ruby Plains 1:100 000 geological map and Explanatory Notes.

Future work

During 1999–2000 the Explanatory Notes for the Lissadell 1:250 000 map sheet will be published. A 1:500 000-scale geological map of the Halls Creek Orogen will also be released. Manuscripts will be prepared for the Dixon, McIntosh, and Turkey Creek 1:100 000 sheet Explanatory Notes. Work will begin on a Bulletin on the geology of the King Leopold and Halls Creek Orogens. AGSO will release the Halls Creek 1:100 000 and Gordon Downs 1:250 000 geological maps and Explanatory Notes. AGSO will also release a Bulletin on the layered mafic–ultramafic intrusions of the Halls Creek Orogen.

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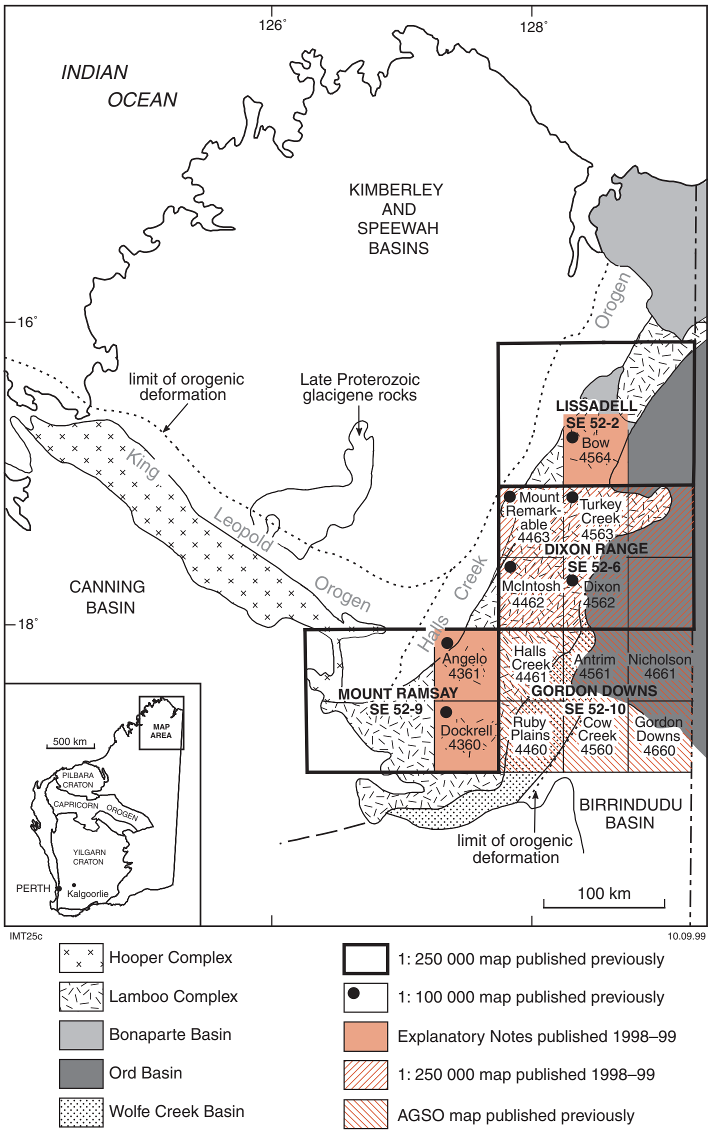
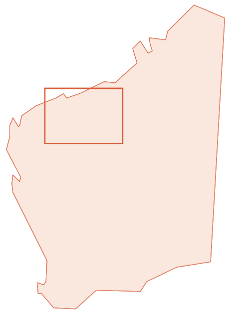


Figure 8. Progress of geological mapping across the King Leopold and Halls Creek Orogens

Pilbara Craton project



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

Highlights and activities 1998–99

In 1998–99 geological mapping was completed on the TAMBOURAH, SATIRIST, and WODGINA 1:100 000 maps, and commenced on the MOUNT EDGAR, WALLARINGA, SPLIT ROCK, and NULLAGINE 1:100 000 maps (Fig. 9). This is an NGMA project with AGSO, who contributed to the mapping on WODGINA, WALLARINGA, and MARBLE BAR. Results of the project were the subject of public presentations at the GSWA '99 open day in March. Field excursions for members of the public were conducted on the MUCCAN and NORTH SHAW 1:100 000 sheets, and special excursions covered Archaean stromatolite sites and tectonic evolution (both attended by invited international authorities in these fields). The ABC filmed part of the Archaean stromatolite excursion.

Geological and geochronological data obtained from the mapping have shown that several previously published regional geological interpretations are either untenable

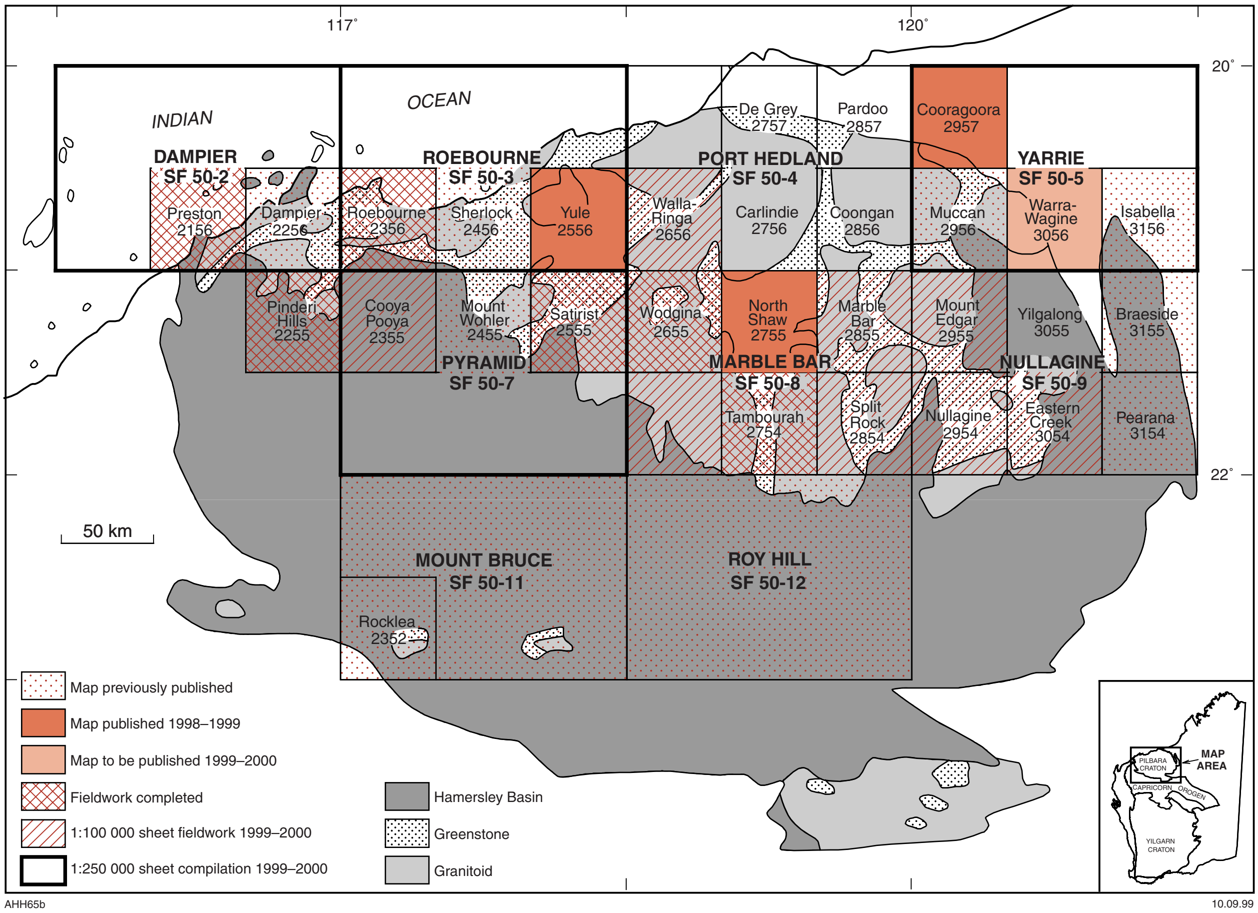


Figure 9. Progress of regional mapping in the Pilbara Craton

or require major revision to accommodate new constraints. In particular, the dome and syncline pattern in the granite–greenstone terrane of the east Pilbara can be demonstrated to be a product of diapirism, and not extensional tectonics as recently suggested by some workers. Similarly, our new mapping near Marble Bar has confirmed an earlier GSWA interpretation that the greenstone succession is at least 13 km thick, and not tectonically duplicated as was recently suggested. Isotope geochronology by U–Pb zircon dating using GSWA's sensitive high-resolution ion microprobe (SHRIMP) facility has supported this GSWA interpretation.

A major conclusion from the new mapping is that the north Pilbara granite–greenstone terrane can be divided into western and eastern terranes separated by the Mallina Basin. It is not, as was recently suggested, an amalgamation of six separate tectono-stratigraphic domains. This important revision was explained in oral and poster presentations at GSWA '99.

Field components of AGSO's 1998–99 program were seriously impacted by AGSO's funding cuts, and this has delayed the NGMA mapping program in the Pilbara region. Additional federal budget cuts in 1999–2000 will prevent AGSO undertaking further mapping, with the result that the project will now not be completed until 2002.

1998–99 publications and products

Maps published during the year were the YULE, COORAGOORA, and NORTH SHAW 1:100 000 sheets. Explanatory Notes for the PEARANA, MUCCAN, MOUNT WOHLER, and YULE 1:100 000 maps were also published, as well as several papers in external publications. AGSO and GSWA published a range of maps and images based on aeromagnetic, radiometric and Landsat data. Map compilation was completed for the ROEBOURNE, PINDERI HILLS and SATIRIST 1:100 000 sheets and for the ROEBOURNE 1:250 000 sheet. Members of the team also made important contributions to completion of the 1:2 500 000 State geological map (1998), and to the 1:500 000-scale west Pilbara mineralization and geology map (for Report 70), which will be published in the 1999–2000 year.

Future work

The 1999-2000 year will see the publication of the WARRAWAGINE 1:100 000 sheet, the completion of geological mapping for the MOUNT EDGAR, WALLARINGA, WHITE SPRINGS, and COOYA POOYA 1:100 000 sheets, and additional mapping on the SPLIT ROCK, NULLAGINE, MARBLE BAR, and EASTERN CREEK 1:100 000 sheets. Three 1:250 000 sheets, PYRAMID, DAMPIER, and YARRIE, will be compiled from data obtained during the 1:100 000 mapping program, supplemented by additional geological reconnaissance over areas not being remapped. The PRESTON 1:100 000 sheet will be compiled from mapping undertaken in 1997. Contributions will be made to a special issue of Economic Geology devoted entirely to the geology and mineralization of pre-2800 Ma Archaean terrains in Western Australia. SHRIMP geochronology will continue to support the mapping program.

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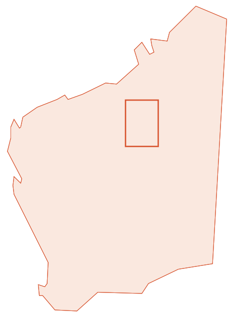
Paterson Orogen project

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



Highlights and activities 1998–99

The main activity during 1998–99 was the completion of Explanatory Notes and geological map sheets at various scales, and the commencement of new mapping on the PATERSON 1:100 000 sheet (Fig. 10).

The PATERSON 1:100 000 sheet and Explanatory Notes for the THROSSELL and BLANCHE–CRONIN 1:100 000 sheets were compiled. Writing of the PATERSON Explanatory Notes is at an advanced stage.

1998–99 publications and products

During 1998–99, Report 71 — 'Geological evolution of the Palaeoproterozoic Talbot Terrane and adjacent Meso- and Neoproterozoic successions, Paterson Orogen, Western Australia' was published. The BLANCHE–CRONIN 1:100 000 map sheet and second edition RUDALL 1:250 000 map sheet were also published.

Future work

The expected products for 1999–2000 are publication of the PATERSON 1:100 000 sheet; Explanatory Notes

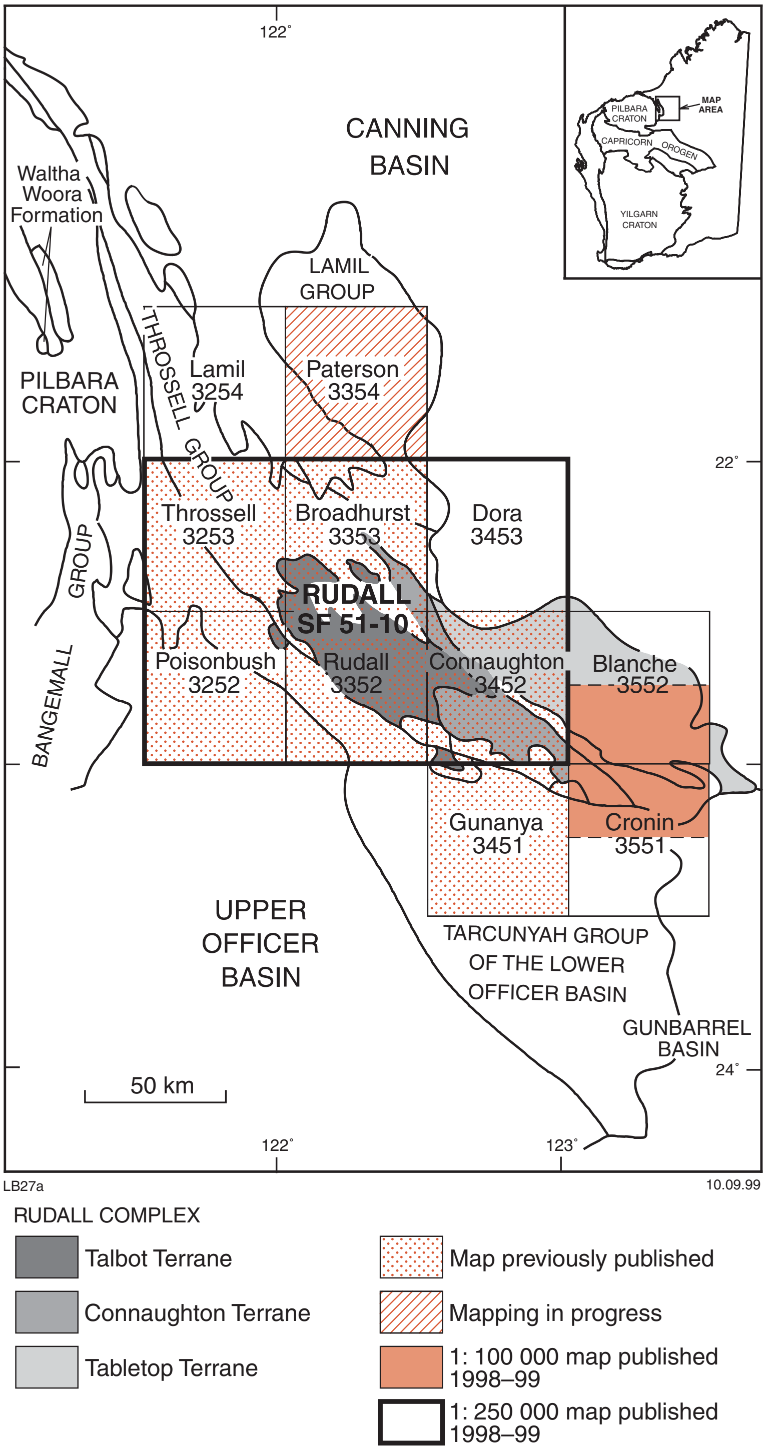


Figure 10. Location of the mapping program in the Paterson Orogen

for the RUDALL 1:250 000 sheet, and the THROSSELL, POISONBUSH, BLANCHE–CRONIN, and PATERSON 1:100 000 sheets; and geoscientific papers in the Annual Review and external journals.

This work will mark the successful completion of the Paterson Orogen project, which by 1999–2000 would have produced one 1:250 000 map sheet, eight 1:100 000 map sheets, nine Explanatory Notes, one Report, and various geoscientific papers.

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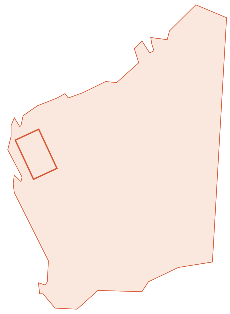
Southern Gascoyne Complex project



> ***Objectives:*** *To increase geological knowledge of the southern Gascoyne Complex by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps and supporting publications, which integrate field and laboratory studies, including mapping, petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*

Highlights and activities 1998–99

During the 1998 field season, remapping continued on the GLENBURGH and GOULD 1:100 000 map sheets and was extended onto the northern part of the ERONG 1:100 000 sheet (Fig. 11). Remapping on GLENBURGH was completed at the start of the 1999 field season.

Remapping of the northern part of the YALBRA 1:100 000 sheet also commenced during the 1999 field season and was carried out in conjunction with Honours students from the Tectonics Special Research Centre, based at the Curtin University of Technology and the University of Western Australia.

Compilation of most of the GLENBURGH sheet was completed during 1998–99. Compilation of the GOULD sheet commenced for inclusion as part of a second edition ROBINSON RANGE 1:250 000 geological map sheet.

Sampling for whole-rock geochemical analysis and geochronology was carried out during the 1998 field season. New SHRIMP U–Pb isotopic ages have been obtained from zircons separated from four samples, with zircons from a further ten samples still to be analysed. One sample, a foliated porphyritic granodiorite from the northern part of GLENBURGH, has an igneous crystallization age of c. 2544 Ma. Foliated and unfoliated granitic rocks in the same area, one of which intruded the Archaean rocks, range in age from c. 1810 to 1795 Ma. This first Archaean age from the Gascoyne Complex is distinctly different from known ages of Archaean granitic rocks from the Yilgarn Craton (older than c. 2600 Ma), and the Pilbara Craton (older than c. 2770 Ma). It is consistent with the northwestern edge of the Yilgarn Craton being marked by the Errabiddy Fault, and with the Gascoyne Complex representing a separate terrane, or collection of terranes, between the Pilbara and Yilgarn Cratons. Granitic rocks dated at c. 2000 to 1975 Ma are present in the southern part of the GLENBURGH sheet.

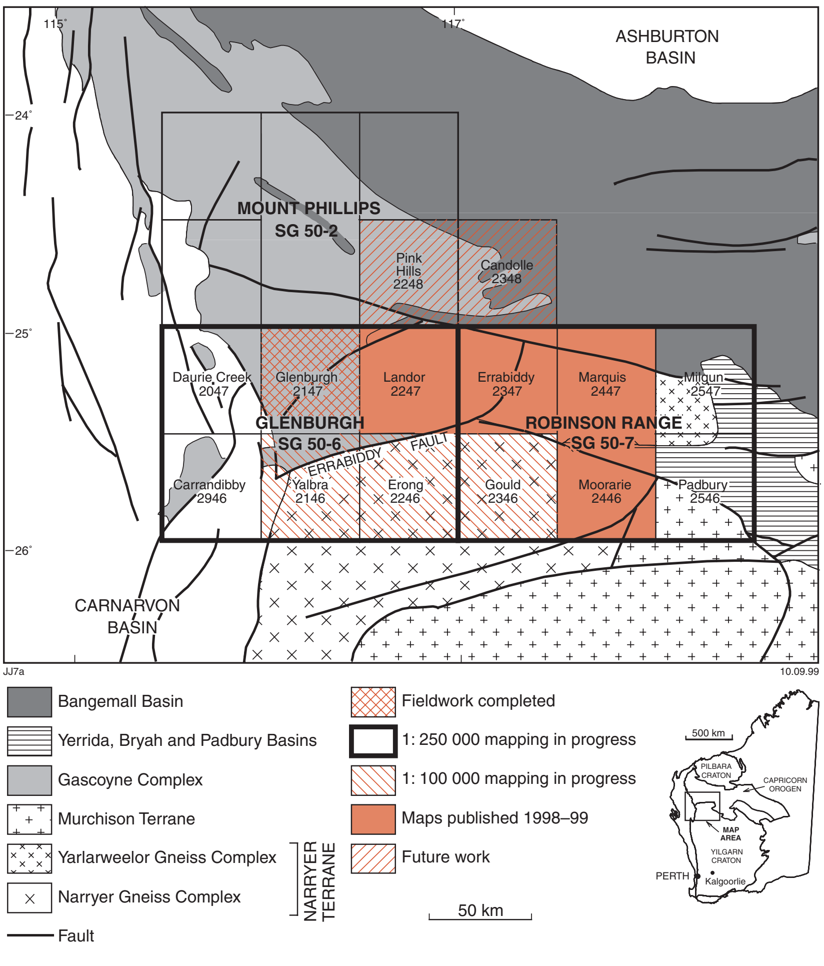


Figure 11. Progress of geological mapping for the Southern Gascoyne Complex project

1998–99 publications and products

During 1998–99 geological maps and Explanatory Notes for the MARQUIS and MOORARIE 1:100 000 sheets were released, together with preliminary editions of the ERRABIDDY and LANDOR 1:100 000 sheets. A paper on 'Syntectonic granite in the southern margin of the Palaeoproterozoic Capricorn Orogen, Western Australia' by S. A. Occhipinti, S. Sheppard, D. R. Nelson, J. S. Myers, and I. M. Tyler appeared in the Australian Journal of Earth Sciences. S. A. Occhipinti presented a paper at the Specialist Group on Tectonics and Structural Geology of the Geological Society of Australia conference at Halls Gap on 'The Palaeoproterozoic tectonic evolution of the southern margin of the Capricorn Orogen, Western Australia'. This talk was also presented at the GSWA '99 open day, and an extended abstract by I. M. Tyler, S. A. Occhipinti, and S. Sheppard was published in Record 1999/6 — 'New geological data for WA explorers'.

Future work

During 1999–2000, fieldwork on the GLENBURGH 1:250 000 geological map sheet will be completed, and fieldwork on the PINK HILLS and CANDOLLE 1:100 000 sheets will commence. Compilation of the GLENBURGH and the ROBINSON RANGE 1:250 000 geological map sheets will be completed. Explanatory Notes for the ERRABIDDY, LANDOR, and GLENBURGH 1:100 000 sheets will be written.

Further geochemical and geochrono-logical sampling will document the extent of the various terranes that appear to be present within the Southern Gascoyne Complex.

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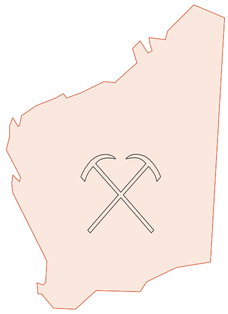
Central Yilgarn (Southern Cross) project



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

The central part of the Yilgarn Craton contains at least two volcano-sedimentary successions. The c. 3.0 Ga succession contains mafic–ultramafic volcanic and intrusive rocks; banded iron-formation, chert, and clastic sedimentary rocks; and subordinate felsic volcanic rocks. The c. 2.7 Ga succession contains calc-alkaline volcanic rocks and associated clastic sedimentary rocks. There have been several episodes of granitoid intrusion, and all greenstones have been deformed and metamorphosed. Metamorphic grade ranges from very low grade (prehnite–pumpellyite facies) up to relatively high grade (upper amphibolite facies). There are major gold deposits in the Southern Cross area, and substantial nickel deposits further south. The Windimurra Complex in the northwest hosts a world-class vanadium deposit.

Stratigraphy in the central Yilgarn is not well defined — the structural evolution remains controversial, and ages of the greenstone successions and deformation events are poorly constrained. The current mapping program will address these issues, and provide a wealth of new data, including geochronology, whole-rock geochemistry, geophysical interpretation, and regolith studies, which will further the under-standing of the metallogeny of the region, and assist in the develop-ment of new exploration models.

Highlights and activities 1998–99

The new central Yilgarn 1:100 000-scale field mapping program began in the Marda–Diemals area, the geographic centre of the Yilgarn Craton, in late 1997. The first of a new series of 1:100 000 map sheets, JOHNSTON RANGE, has been compiled, and will be published in 1999–2000. Field mapping on three more sheets, JACKSON, BUNGALBIN, and LAKE GILES, has been completed, and these sheets will also be prepared for publication in 1999–2000 (Fig. 12). Explanatory Notes for all these sheets will be released in subsequent years.

Further results of the mapping program to date include: a brief paper summarizing ideas about the structural evolution of the Marda–Diemals area (this volume); analysis of 48 whole-rock geochemistry samples; and three new SHRIMP U–Pb isotopic ages. A further 11 geochronology samples have been collected, and the forthcoming data should assist in the understanding of the structural evolution of the central Yilgarn greenstones, and elucidate the history of movement on the Ida Fault.

Compilation of mapping in the Marda–Diemals area confirms that there are two greenstone successions. The lower, c. 3.0 Ga greenstone succession comprises a basal quartzite overlain by high-Mg basalt and ultramafic rocks, followed by tholeiitic basalt, and two major units of banded iron-formation and chert intercalated with mafic and ultramafic volcanic and intrusive rocks. Felsic intrusive and pyroclastic rocks outcrop locally, but their absolute position within the stratigraphy is not clear. There is no evidence of regional-scale structural repetition of this succession, but there are small- to meso-scale faults and folds

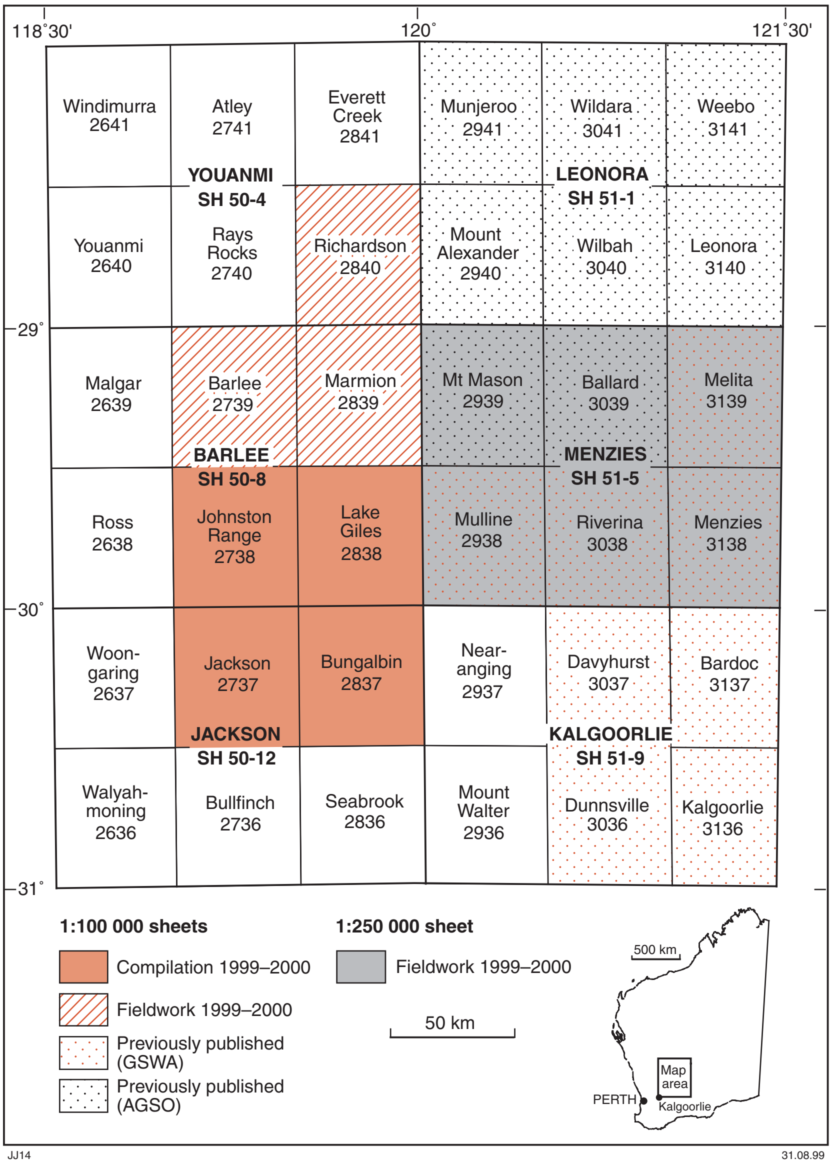


Figure 12. Progress of geological mapping for the central Yilgarn (Southern Cross) project

associated with the D_1 deformation event. The upper, c. 2.7 Ga greenstones contain clastic sedimentary rocks of the Diemals Formation, and acid to intermediate volcanic and volcaniclastic rocks of the calc-alkaline Marda Complex.

Future work

Fieldwork on the Barlee, Marmion, and Richardson 1:100 000 sheets will be completed in 1999–2000, and these sheets will be compiled with a view to release in the following year. The Johnston Range 1:100 000 Explanatory Notes, the first in a series, will be written. A new edition of the Menzies 1:250 000 sheet will also be prepared. This map will involve substantial revision of data presented on the existing 1:100 000 sheets in some areas. The reinterpretation will be based on newly acquired aeromagnetic data, Landsat TM imagery, and selected field traverses.

Explanatory Notes for the Riverina and Mulline 1:100 000 sheets will be published during 1999–2000. These sheets, mapped during an earlier phase of the regional program, include some of the best exposed sections of the Ida Fault, the crustal-scale feature that separates the dominantly c. 2.7 Ga greenstones of the east Yilgarn area from the older successions of the central Yilgarn area.

Other work in the coming year will include detailed structural studies in the Marda–Diemals area, a study of aspects of the volcanology of the Marda Complex, and further geochronological sampling of greenstones, granitoids, and gneisses.

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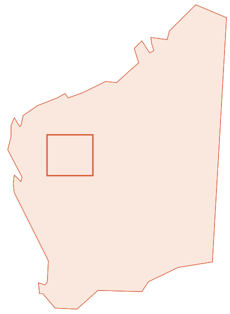
Bangemall Basin project

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



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

A revised stratigraphy for the Bangemall succession has been established, in which the Bangemall Group is elevated to supergroup status, and the component Edmund and Collier Subgroups are raised to group level. Two newly defined units, the Blue Billy and Muntharra Formations, are recorded within the Edmund Group. In addition, the boundaries between previously recognized formations within this group have been redefined in certain cases and localized lithological variations within these units have been described.

Highlights and activities 1998–99

Fieldwork in the northwestern part of the Bangemall Basin continued during 1998–99 and has resulted in the completion of detailed mapping on the Capricorn and Maroonah 1:100 000 map sheets (Fig. 13). As part of this work, the principal sandstone units were sampled for zircon provenance studies and additional material was collected from various dolerite sills for whole-rock geochemistry and geochronology. Representative stratigraphic sections through the Coodardoo, Backdoor, and Calyie Formations were also measured.

Office-based activities included the compilation of geological data for the Elliott Creek and Ullawarra 1:100 000 map sheets, compilation of data on the Bangemall Supergroup rocks on Capricorn, analysis of field data, and acquisition of digital topographic data.

Recent mapping of Bangemall Basin rocks on Elliott Creek, Ullawarra, Capricorn, and Maroonah has highlighted the fact that none of the existing published stratigraphic schemes adequately reflects the observed field relationships.

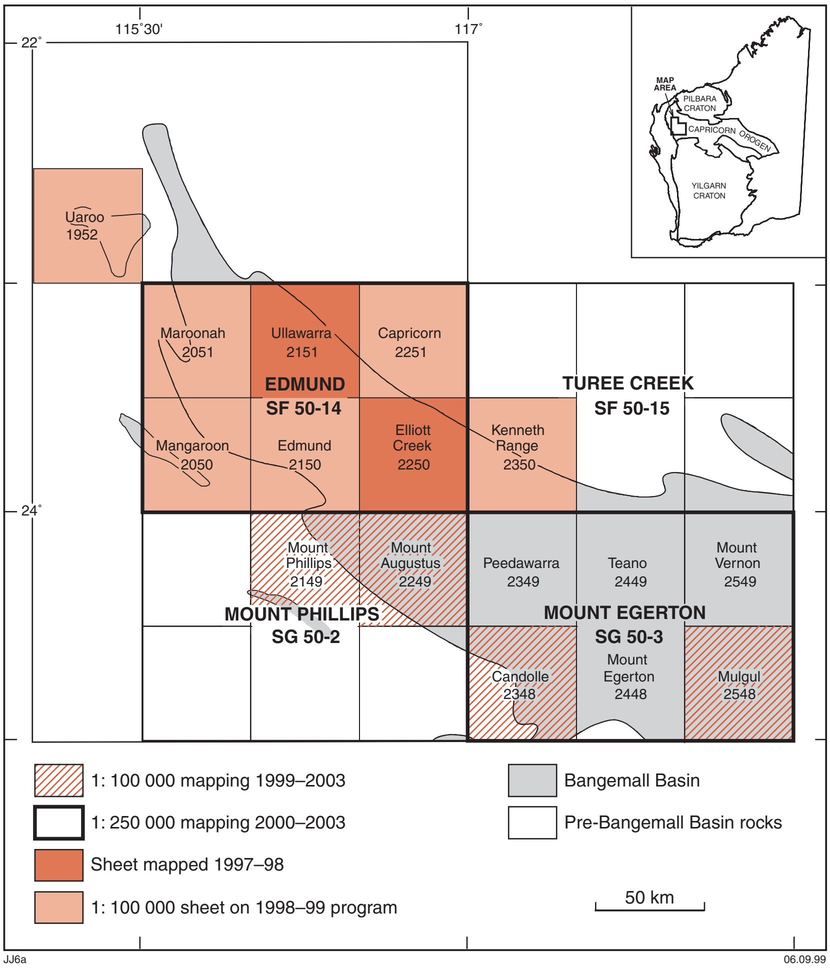


Figure 13. Progress of geological mapping for the Bangemall Basin project

1998–99 publications and products

The preliminary edition ELLIOTT CREEK 1:100 000 map sheet was published during 1998–99. A paper entitled 'The Mesoproterozoic Irregully Formation, Bangemall Basin: a preliminary interpretation of the type section' was published in the 1997–98 GSWA Annual Review.

Future work

Mapping of Bangemall Group rocks on the EDMUND and MANGAROON 1:100 000 sheets is to be completed during the 1999–2000 field season and work on the KENNETH RANGE 1:100 000 sheet will commence during this period. Principal objectives are to test and implement the revised stratigraphy in the southwestern and northeastern parts of the basin, to identify and sample suitable clastic horizons for U–Pb zircon geochronology and provenance studies, and to further examine the relationship between the Edmund and Collier Groups.

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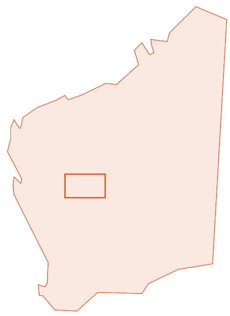
Earaheedy Basin project

Objective: *To increase geoscientific knowledge of Proterozoic basins on the northern boundary of the Yilgarn Craton, through the collection, synthesis and dissemination of geological information. This is to be achieved through the production of geological maps and supporting publications that integrate field and laboratory studies, including mapping, petrology, geochemistry, geochronology, remote sensing, and metallogeny.*



Highlights and activities 1998 –99

The Earaheedy Basin covers about 40 000 km^2 and developed as a depocentre after the Bryah, Yerrida, and Padbury Basins, but well before the Bangemall Basin. Thus constrained, the age of the basin is in the range 1700 to 1900 Ma. Dolomites in the Earaheedy Basin contain base metal mineralization, and there may be significant iron resources in granular iron formations. The project also includes a reassessment of the Troy Creek Schist (previously Troy Creek Beds, which host gold mineralization), parts of the adjacent Mesoproterozoic Bangemall Basin succession (Collier and Scorpion Groups), the Neoproterozoic Officer Basin (Sunbeam Group, ?Kahrban Group), and the Archaean granite–greenstone terrain to the south.

The Geological Survey's evaluation of the evolution and mineral potential of the Palaeoproterozoic Earaheedy Basin continued in 1998–99, working eastwards across the basin (Fig. 14). During the year, geological mapping and photoscale (1:25 000) compilation were completed for the RHODES and

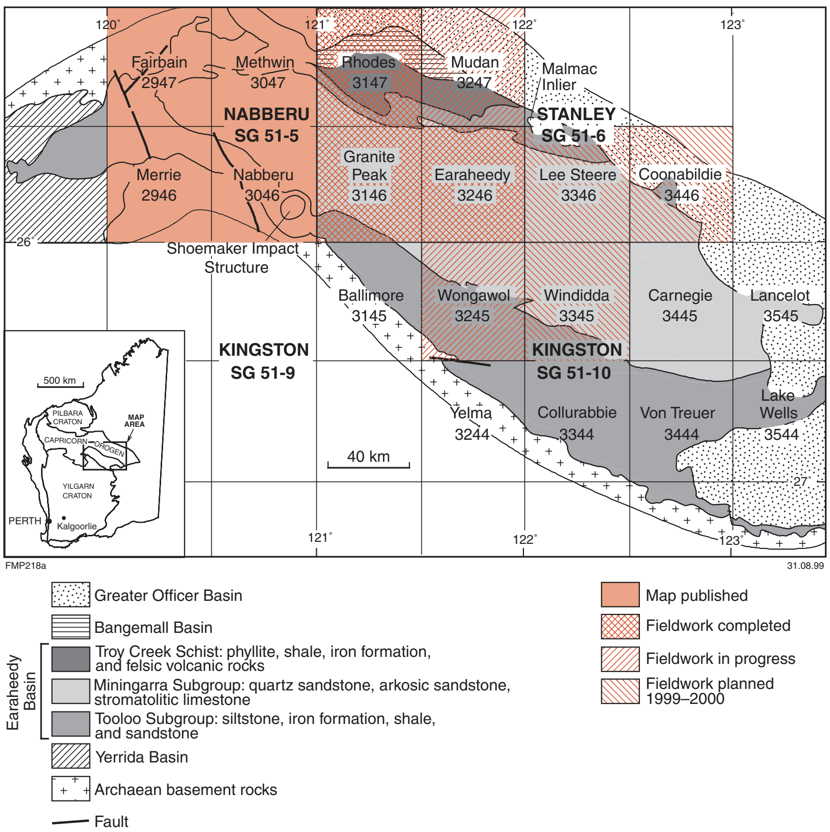


Figure 14. Progress of geological mapping for the Earaheedy Basin project

GRANITE PEAK 1:100 000 sheets, and continued for the EARAHEEDY sheet. Fieldwork commenced in the 1999 field season on the MUDAN and WONGAWOL 1:100 000 sheets.

Mapping to date has resulted in several apparently minor, but significant, changes to the lithostratigraphic framework of the Earaheedy Basin. The changes reflect the incremental increase in the understanding of the basin dynamics as mapping proceeds. The most important change is the recognition that the Troy Creek Schist, rather than predating the formation of the Earaheedy Basin, are actually dynamically metamorphosed Earaheedy Basin rocks. Many of the rocks mapped as Earaheedy Group along the basin's northern margin could justifiably be re-assigned to the Troy Creek Schist.

There have been two distinct phases of deformation along the northeastern margin of the Yilgarn Craton. Prior to deposition of the Earaheedy Group, the Yerrida Basin succession was deformed along the Goodin Fault as a result of collision with the Bryah Basin to the west. The Earaheedy Group itself was deformed in a separate, much later episode along its northern margin. This later episode was characterized by south-verging thrusting and penetrative deformation, and resulted in the development of the Troy Creek Schist.

Adjacent to the Earaheedy Basin, differences in the degree of deformation suggest that the Scorpion Group is part of the Bangemall Basin succession and may correlate with the Edmund Group, and that the Kahrban Group may be better correlated with the base of the Centralian Superbasin succession than with the Bangemall Basin. The Savory Group has been abandoned, after the recognition of major unconformities within the 'group', to be replaced largely by the Sunbeam and Disappointment Groups.

1998–99 publications and products

The first maps resulting from the recent mapping in the Earaheedy Basin (FAIRBAIRN, MERRIE, and NABBERU 1:100 000 map sheets) were published in 1999 (Fig. 14). These maps incorporate the changes in the understanding of basin dynamics made thus far.

Future work

Work planned for 1999–2000 includes publication of the METHWIN 1:100 000 sheet, completion of mapping and compilation on the MUDAN and WONGAWOL 1:100 000 sheets, and the start of mapping on the WINDIDDA, LEE STEERE, and COONABILDIE 1:100 000 sheets. With the mapping of the RHODES and GRANITE PEAK sheets complete, compilation of a second edition of the NABBERU 1:250 000 geological sheet can also begin. The mapping will further elucidate the sedimentology and structural history of the Earaheedy Basin, and assist in unravelling the Mesoproterozoic and Neoproterozoic history of areas adjacent to the basin. Presentations outlining the advances in knowledge of the region are planned for both national and international conferences, and should generate exploration interest in the basins.

The Shoemaker Impact Structure at the southern edge of the Earaheedy Basin is of interest both scientifically and for mineralization pathways, and work will continue on the structure through 1999–2000. This study involves investigations ranging from planetary geology to impact-related hydrothermal activity. Shatter cones and shocked quartz grains confirm that the structure is a meteorite impact crater, the oldest (about 1630 Ma) in Australia.

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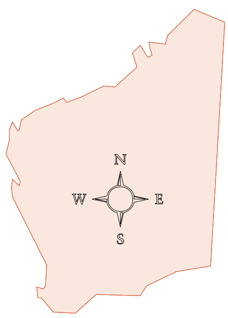
East Yilgarn terrane custodianship

Objectives: *To increase geoscientific knowledge of the East Yilgarn Terrane by the collection, synthesis, and dissemination of geological information, particularly through the production of systematic geological maps, GIS-based seamless geological databases, and supporting publications that integrate field and laboratory studies, including mapping, petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*



The area of the East Yilgarn terrane custodianship occupies the eastern two-thirds of the Yilgarn Craton and contains the economically significant Eastern Goldfields and Southern Cross provinces (Fig. 15). The Yilgarn Craton is characterized by extensive areas of granitoid and elongated belts of greenstone, and hosts numerous world-class gold and nickel deposits. The custodianship incorporates the Kalgoorlie regional office, the proposed Kalgoorlie drillcore storage facility, and the Eastern Goldfields and central Yilgarn (Southern Cross) field mapping projects.

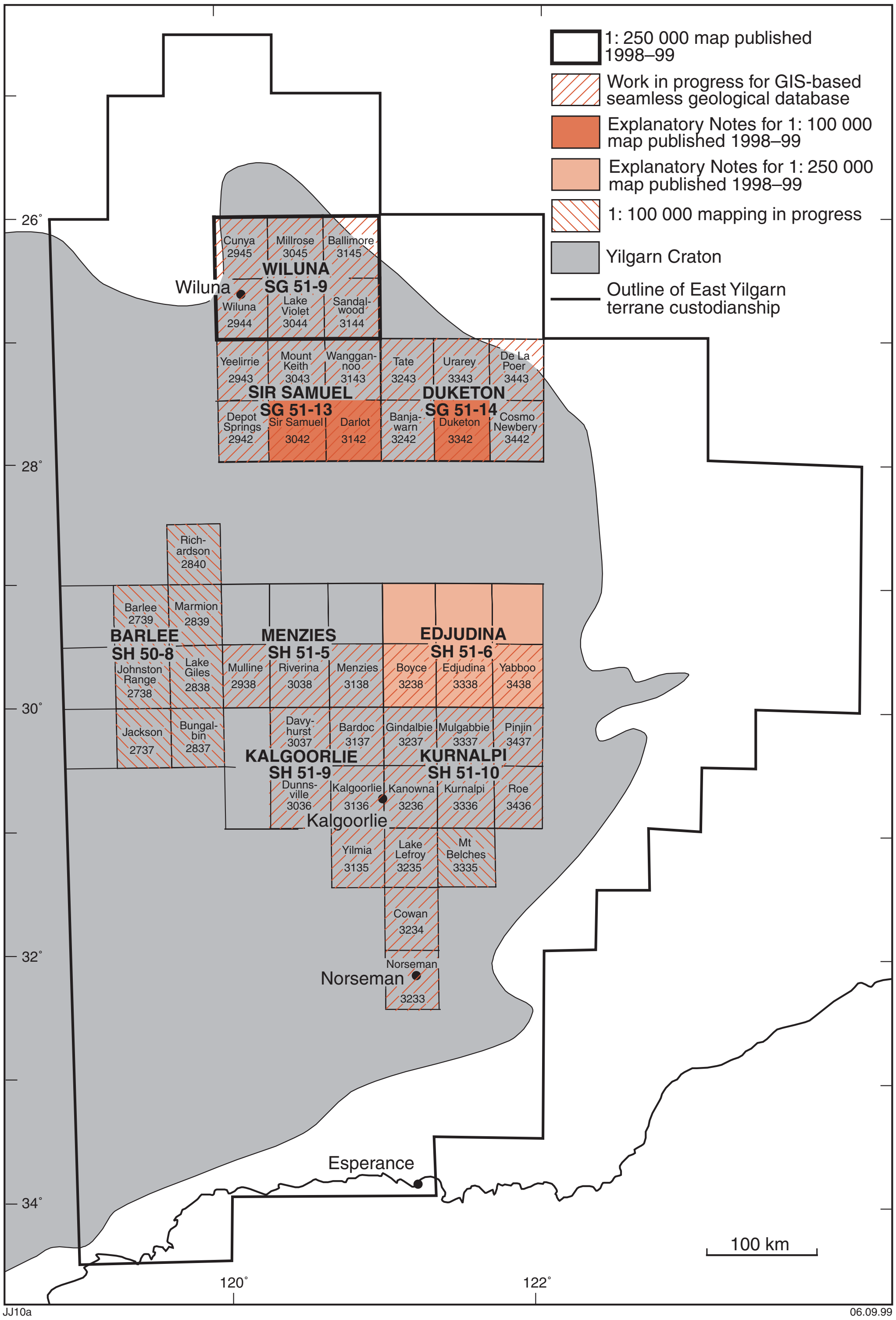


Figure 15. Progress of geological mapping in the east Yilgarn region and progress towards the GIS-based 'seamless' digital database

Highlights and activities 1998–99

The Kalgoorlie regional office has facilitated the role of the Geological Survey of Western Australia in disseminating geoscientific information to the mining industry and with the promotion of the mineral prospectivity of the region.

The Kalgoorlie regional office is open for public inquiries and for access to the WAMEX open-file database, GSWA publications, and past mining tenement plans. A new personal computer was acquired for public use, permitting access by clients in Kalgoorlie to the growing volume of GSWA's digital information. The Kalgoorlie regional office has continued to provide an operational base for some of the staff involved in the Southern Cross, Eastern Goldfields, and Earaheedy Basin regional mapping projects.

The staff in Kalgoorlie has evolved into a stable team, with expertise valued by the mining industry. The Kalgoorlie team has maintained good cooperative arrangements with the Western Australian School of Mines and has assisted with student excursions and student projects. The Kalgoorlie office has also been involved with activities associated with the local branch of the Australasian Institute of Mining and Metallurgy (AusIMM).

Compilation of the MENZIES 1:250 000 map sheet and the MOUNT BELCHES and WOOLGANGIE 1:100 000 map sheets are in progress (Fig. 15).

Aeromagnetic data for the KINGSTON, THROSSELL, and RASON 1:250 000 sheets have been obtained under the NGMA Eastern Goldfields project. As part of this project, AGSO carried out field mapping on the LEONORA 1:100 000 sheet; however, due to budget restrictions this mapping has not been completed.

In addition, the Kalgoorlie GSWA office has continued to provide logistical support in the Australian Mineral Industries Research Association Limited (AMIRA) Yilgarn granitoid study (AMIRA Project P482).

Landsat satellite imagery has also been acquired through the WA Department of Land Administration (DOLA) for the entire East Yilgarn terrane custodianship. This Landsat coverage is being used in the GIS-based seamless geoscientific database and the regional mapping programs.

In October 1998, a very successful combined GSWA and AGSO open day was held in Kalgoorlie. Attracting approximately 150 people, various posters were displayed illustrating the activities of both GSWA and AGSO. In addition, a talk was presented about the safety obligations of field geologists. It is envisaged that the next Kalgoorlie open day will be held in October 1999.

The first phase of the development of the GIS-based 'seamless' digital geoscience database for the East Yilgarn terrane custodianship is nearing completion. This initial phase covers an area from Menzies to Norseman and incorporates twenty 1:100 000 geological maps sheets: MULLINE, RIVERINA, MENZIES, BOYCE, EDJUDINA, YABBOO, DAVYHURST, BARDOC, GINDALBIE, MULGABBIE, PINJIN, DUNNSVILLE, KALGOORLIE, KANOWNA, KURNALPI, ROE, YILMIA, LAKE LEFROY, COWAN, and NORSEMAN.

1998–99 publications and products

Explanatory Notes for the EDJUDINA 1:250 000, and the DARLOT, DUKETON, and SIR SAMUEL 1:100 000 sheets were published.

Report 55 — 'Archaean felsic volcanism in parts of the Eastern Goldfields region, Western Australia' was published.

Explanatory Notes for the WILUNA, RIVERINA–MULLINE, and MILLROSE 1:100 000 sheets were compiled for publication in 1999–2000.

Future work

The WILUNA 1:250 000 sheet will be published in 1999–2000.

Compilation has started on the second phase of the GIS-based seamless digital geoscience database. This phase covers the northern Eastern Goldfields and includes the following eighteen 1:100 000 geological map sheets: CUNYU, MILLROSE, BALLIMORE, WILUNA, LAKE VIOLET, SANDALWOOD, YEELIRRIE, MOUNT KEITH, WANGGANNOO, TATE, URAREY, DE LA POER, DEPOT SPRINGS, SIR SAMUEL, DARLOT, BANJAWARN, DUKETON, and COSMO NEWBERY.

The third phase of the GIS-based seamless digital geoscience database will commence in 1999–2000 and covers the Leonora–Laverton region.

Geological mapping of the ERAYINIA 1:100 000 sheet has started and will be completed in 1999–2000.

The new Kalgoorlie drillcore storage facility will be built in the coming year. Located on the corner of Hunter and Broadwood Streets, this drillcore library will be a testament to the Geological Survey's commitment to assist the exploration industry in the Eastern Goldfields region. The facility will be able to permanently store valuable drillcore and will also incorporate a new Kalgoorlie operational base.

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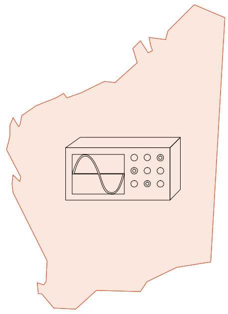
Subprogram 3104 SCIENTIFIC, TECHNICAL, AND FIELD SUPPORT

Geoscientific specialist support

Geochronology



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

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

Highlights and activities 1998–99

About 55 geochronology samples were dated by the sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon technique, with typical precision of ± 6 Ma. Samples were from the Gascoyne, Narryer, Pilbara, Southern Cross, Eastern Goldfields, Leeuwin, and Paterson regions for incorporation into GSWA geological maps and projects. In addition, two basalt samples from GSWA's Empress 1A stratigraphic drillhole in the Officer Sub-basin were dated by the K–Ar technique. GSWA Record 1999/2 documents all results from the geochronology work undertaken during calendar year 1998.

During the year, sample processing techniques were further streamlined and new laboratory procedures implemented. The existing zircon sample processing procedures were revised by simplifying the rock crushing process to gain improved efficiency and sample throughput. In response to requests from GSWA field geologists, new techniques were successfully developed for the isolation, preparation, mounting, and analysis on the SHRIMP of the uranium-rich rare earth mineral monazite ($ThPO_4$). This required the compilation of new data-processing software for the reduction of raw monazite data. Full details of these techniques were published in Record 1999/2.

Future work

Further sampling is planned for the Gascoyne, Paterson, Pilbara, Southern Cross, and Eastern Goldfields regions before the end of 1999–2000.

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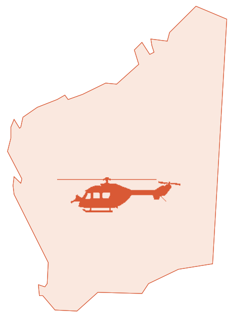
Geophysics



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

Regional airborne geophysics

During 1997–98 GSWA continued its program of regional airborne geophysical coverage, working with AGSO to complete new surveys over the RAWLINSON, WEBB, and WILSON 1:250 000 sheet areas, thus completing broad-scale regional aeromagnetic coverage of Western Australia. The release of data from these surveys in April and June 1999, when added to the release of NGMA–AGSO data over the KINGSTON, THROSSELL, and RASON 1:250 000 sheet areas in October 1998, resulted in an increase in public domain State coverage by approximately 300 000 line km of data.

Preparation for the continuation of this program of improved regional coverage in 1999–2000 saw the release of a request for tender for new airborne data over the STANLEY and YOUANMI 1:250 000 sheet areas. The new data, complementing existing private company data that have been acquired by GSWA and AGSO, will provide complete public domain coverage over these two sheets.

Airborne geophysical survey register and data repository

The implementation of the 1997 Airborne Geophysics Reporting Policy, designed to encourage greater availability of the very large quantities of detailed airborne survey data that are generated by private companies as part of their exploration activities, proved very successful. During 1998–99, more than 200 survey datasets containing approximately 1.2 million line km of data were received for inclusion in the Mineral Airborne Geophysics Information eXchange (MAGIX) data repository. Total data holdings in the repository are now in excess of 2 million line km.

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

Regional gravity surveys

The program to acquire regional gravity data in conjunction with the helicopter-assisted regional regolith and geochemical sampling program, which was successfully initiated in 1997–98, continued in four field excursions during 1998–99.

About 5000 gravity readings on an irregular 4 km grid were taken by geochemical sampling crews over the AJANA, KINGSTON, and STANLEY 1:250 000 sheet areas and over six 1:100 000 sheet areas in the Fraser Range area (Fig. 7). Two geochemical sampling crews in each of two helicopters used four La Coste and Romberg gravity meters (on loan from AGSO) to take gravity readings at geochemical sampling sites while the samples were being collected. A differential GPS receiver antenna mounted on the helicopter was used to provide height control to an accuracy of 50–80 cm.

Processed data from the WYLOO 1:250 000 sheet area (acquired in 1997–98) and from AJANA, KINGSTON, and Fraser Range were released through AGSO in June 1999. The STANLEY data will be released in early 1999–2000.

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Carlisle operations

Objectives:

- *To manage field support services, including transport and other equipment, and field assistants, and provide a safety backup for all GSWA field parties*
- *To ensure quality laboratory services for the preparation of samples for geochronology and other laboratory requirements*
- *To manage inventory services for all GSWA publications, including maps, Bulletins, and Reports*
- *To manage drillcore library facilities to service the needs of industry and GSWA*

The Carlisle operations team provides a wide range of support services to geoscientists, including vehicles, equipment, field assistants, and laboratory services. A drillcore store is also maintained as a service to industry and used as an archive for rock, fossil, and soil samples collected by the Geological Survey.

A high-frequency radio communications base is also maintained at the Carlisle depot and is the focal point for monitoring safe operations in the field.

Planning for the new drillcore library facilities to be built at Kalgoorlie and at Carlisle continued. Construction of the Kalgoorlie facility, which will include an operational base for the East Yilgarn terrane custodianship team, will commence in 1999–2000.

The Geological Survey's laboratory at Carlisle continues to maintain its focus on the preparation of samples for geochronological analysis by SHRIMP. A total of 85 samples were processed for SHRIMP analysis for the year. In addition to this work, 2586 thin sections, including 163 polished thin sections, were prepared. Other work carried out in the laboratory included heavy-mineral separations, crushing and pulverizing samples for geochemistry, specific gravity determinations, polishing rock faces, staining rock chips, and many other minor procedures. In future, most laboratory requirements, with the exception of the preparation of samples for geochronology, will be outsourced.

In response to increased demand for core library facilities, a fourth storage facility at Star Street, Carlisle, has been used.

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

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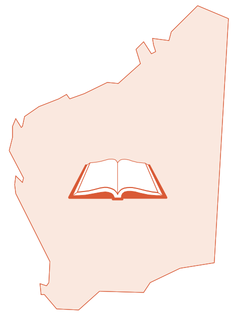
Subprogram 3105
GEOSCIENTIFIC EDITING AND PUBLISHING

Publications and promotion

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



Editing and publishing

During 1998–99, 28 geoscientific maps and 57 manuscripts were released (Appendix).

Two maps deserve special mention: the new 1998 edition of the State geological map (1:2 500 000); and a new edition of the 'Atlas of mineral deposits and petroleum fields'.

Other maps published included twelve 1:100 000-scale geological maps (of which three were 1:100 000-scale 'preliminary release plots'), two 1:250 000-scale geological series maps, and two sets of 1:250 000-scale regolith materials maps. A further ten plates (comprising maps, cross-sections and well correlations to accompany manuscripts either released or in preparation during the year) were also printed and released.

The 57 geoscientific manuscripts published for the year included two substantial Mineral Resource Bulletins, 11 Reports (of which two were accompanied by GIS datasets on CD), and 21 sets of explanatory notes to accompany series maps.

Promotional activities

During the year, advertisements and short articles publicising the release of GSWA published products were placed in a number of newspapers, industry magazines, and journals, including The West Australian, Kalgoorlie Miner, Register of Australian Mining, Western Australian Geologist, AusIMM Bulletin, Datum Post, Oil and Gas Gazette, and PESA Journal. Media releases were prepared (with assistance from the Corporate Communications Branch) for most published products released during the year.

A new edition GSWA Catalogue of Maps and Publications was released in March 1999 bringing together into one volume the separate catalogues of maps and publications previously in circulation.

Publication of FIELDNOTES (the GSWA quarterly newsletter first published in January 1996) continued during 1998–99. The mailing list has grown to almost 700 during the year.

The GSWA component of the Department's web site underwent considerable change during 1998–99. Existing web pages were upgraded or new pages published, covering:
- open-file data holdings and access to WAMEX and WAPIMS datasets;
- the MINEDEX database;
- the MAGIX register of airborne geophysical data;
- several GSWA publications were made freely available via the World Wide Web in PDF format (catalogues of GSWA maps and publications, FIELDNOTES, the GSWA Annual Work Program, and a Record documenting the MINEDEX database);
- a new 'Hot off the Press' feature was added giving details of new maps and books released on a monthly basis.

Displays of ongoing and completed geoscientific work by GSWA were presented at the following industry events:
- Fourteenth Australian Geological Convention: Geoscience 2000; for the new millenium (Townsville, July 1998);
- Ninth Australian Remote Sensing Conference (Sydney, July 1998);
- Australian Geoscience Information Association (AGIA) Seminar: Making Data Work For You III (Perth, July 1998);
- Australian Mineral Foundation: Information Session for Industry (Perth, August 1998);
- West Australian Basins Symposium (Perth, August–September 1998);
- GSWA Kalgoorlie Office open day (WMC Centre, Kalgoorlie, October 1998);
- Thirteenth Australian Association of Exploration Geophysicists Annual Conference — ASEG '98: 'Crossing the borders' (Hobart, November 1998);
- Australian Mineral Foundation: Porphyry and hydrothermal copper and gold deposits (Perth, December 1998);
- Prospectors and Developers Association of Canada (PDAC) Annual Conference (Toronto, March 1999);
- GSWA '99: New geological data for WA Explorers (Perth, March 1999);
- Bentley Microstation Forum 1999 (Perth, April 1999);
- Australian Petroleum Production and Exploration Association Annual Conference: APPEA '99 (Perth, April 1999);
- American Association of Petroleum Geologists Annual

Conference — AAPG '99 (San Antonio, April 1999);
- Chief Government Geologist's Conference (Perth, April 1999);
- Australian Prospectors and Leaseholders Association (APLA) Annual Conference (Perth, April 1999);
- GSWA–Industry forum on onshore petroleum exploration (Perth, April 1999);
- Argentina–Australia Mining Industry Mission (Buenos Aires, May 1999).

Of the above events, GSWA '99 was a highlight — industry feedback suggests that this event should become a regular item on our annual promotional calendar. Our push to promote the prospectivity of Western Australia overseas continued in 1998–99 with a significant presence at PDAC '99 in Toronto, a large geoscientific display at AAPG '99 in San Antonio, and a small but significant display at the Argentina–Australia Mining Industry Mission in Buenos Aires (with assistance from AusTrade).

Public enquiries

The rate of response to public enquiries in 1998–99 was steady through the year apart from surges coinciding with geoscience and mining units appearing in the school syllabus. Geoscientists in the Publications Section received and responded to enquiries requiring information and assistance for prospectors, tourists, and amateur fossickers, regarding urban geology for land owners, mining and its environmental implications, and educational geology for students and teachers.

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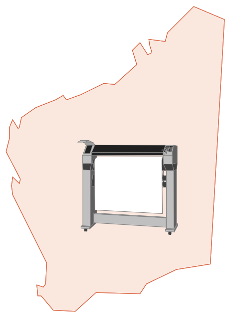
Geoscience data management

Objectives: *To deliver high-quality, spatially related geoscientific information in a timely manner to satisfy our clients needs by:*
- *disseminating geological information in the form of high quality maps;*
- *disseminating spatially related geoscientific information in the form of digital spatial information and products;*
- *designing, developing, and maintaining spatial databases for analysis and modelling;*
- *providing geoscientists with base maps for geological map compilation.*



1998–99 publications and products

Multi-coloured lithographic printing:

- Geological map of Western Australia, 1:2 500 000 (13th edition).
- Western Australia Atlas of mineral deposits and petroleum fields.
- Two 1:250 000 series geological maps.
- Nine 1:100 000 series geological maps.
- One plate to accompany Report 61: Merlinleigh Sub-basin.
- One plate to accompany Report 66: Mineralization of the Halls Creek Orogen.
- Two plates to accompany Report 60: Yerrida Basin.
- Two plates to accompany Report 57: Central and southern Perth Basin hydrocarbons.
- One plate to accompany Mineral Resources Bulletin 15: Lead, zinc and silver deposits of W.A.
- One plate to accompany Bulletin 145: Lennard Shelf regional geology.

Plotter output:

- Three 1:100 000 Preliminary Edition geological maps.
- Two regolith geochemistry packages covering the COLLIER and WYLOO 1:250 000 map sheets.

Databases:

- Implemented REGOCHEM (GSWA's regolith and geochemistry database) in an MS Access environment.
- Implemented WACHRON (GSWA's geochronology database) in an MS Access environment.
- Implementation of WAROX and WAMIN in Oracle, the GSWA corporate environment.
- Commenced development of WAREG (GSWA's regolith observation database) and WACHEM (GSWA's inorganic geochemistry database) in Oracle.

Digital data packages:

- Two regolith geochemistry packages covering the COLLIER and WYLOO 1:250 000 map sheets.
- Release of the mineral occurrences and exploration

potential data packages for the Bangemall Basin and southwest Western Australia (accompanying Reports 64 and 65).

Other activities completed:

- Translation of digital data in Microstation format into a format suitable for use in the GIS environment for 21 geological series maps.
- Revision of the Pilbara iron ore assessment map and dataset.
- Further amendments were made to the South West Regional Forest Agreement (RFA) project dataset.
- Demonstration material was prepared for presentation at various conferences.
- Continued implementation of web-enabling technology to disseminate geological data on the DME Intranet site.
- Responded to a high demand for base maps to support field activities.
- Handled 156 specific client requests for map and digital data products.

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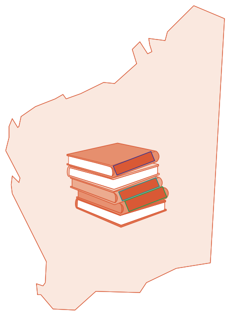
Subprogram 3106 GEOSCIENTIFIC AND EXPLORATION INFORMATION

Geoscience information library



Objective : *To respond effectively and efficiently to the geoscientific information needs of the Department, the minerals and petroleum industry, educational institutions, and the public.*

Highlights and activities for 1998–99

A project involving the capture of more than 2700 GSWA bibliographic records to an MS Access database was completed. The project aimed to capture bibliographic and indexing information on all GSWA publications and articles published since 1894. Each record was indexed with AESIS (Australia's National Geoscience, Mineral and Petroleum Reference database) subject terms, geological time, commodities, maps codes, and geological provinces. The database will form the basis of a comprehensive catalogue of GSWA publications that will also be linked to an index map of Western Australia allowing spatial searching of GSWA publications.

The automated Oracle Libraries database (OLIB) management software was upgraded and a Web version installed providing GSWA staff with direct access to the on-line Library catalogue via the GSWA Intranet. This substantially increases the accessibility of the Library collection to users, who can now search the Library catalogue by keyword, author, title or subject term direct from their desktop computer.

A substantial data-capture project has been undertaken over the past 12 months in order to transfer the remaining books recorded on the old Record Management System (RMS) to the OLIB database. This has included the capture of 837 books held in the Library, and a final 'clean up' of the RMS database in terms of book and journal issue loans is currently underway.

Library usage

During 1998–99, 5897 users visited the Library, a decrease of 21% on the previous year. This included 1065 users of the microfiche facilities to access open-file exploration data. Library staff dealt with 5880 enquiries, a decrease of 14% compared with the previous year.

Library collections and services

The Library took over full responsibility for ordering of aerial photography for GSWA staff, as well as accessioning and loans providing a centralized service.

Public access to TENGRAPH in the Library was enabled, including provision for A3-size colour prints.

A large collection of 1969–75 aerial photography covering the Eastern Goldfields region was obtained and forwarded to the East Yilgarn terrane custodianship to provide a base set of photography. A large set of photography was also received from the Mining Operations Division, mostly providing coverage over mine sites.

Future work

A brochure introducing the services and collections available to the public will be printed.

A Library presence on the DME Intranet will be initiated. This will include access to the Library database, listings of new publications and maps received, information about services, and collections and links to other sites.

Library staff will further investigate and develop the use of the OLIB software in order to bring more services to users and increase information management efficiencies. Capture of selected serial holdings to OLIB will commence. There are approximately 2500 titles to capture, many of which are monographic serials. Initial data capture efforts will concentrate on GSWA and DME titles.

External user access to the OLIB database via the Internet is planned for 1999–2000.

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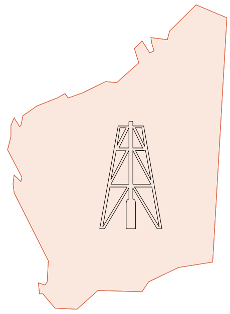
Statutory exploration information group



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

This subprogram covers all aspects of the submission, management and release of both mineral and exploration data through the WAMEX, WAPEX, and Western Australian Petroleum Information Management System (WAPIMS) databases.

Highlights for 1998–99

- During 1998–99, metadata and format standards for the reporting of exploration data in digital form were developed in consultation with industry groups. These standards were consolidated in ‘Requirements for the Submission of Mineral Exploration Data in Digital Format’, and form the core of standards accepted by the Chief Geologists Conference as the basis of national reporting requirements for the mineral exploration industry.
- The ‘Schedule of petroleum exploration wells — Carnarvon Basin: Lambert and Peedamullah Shelfs and Exmouth Sub-Basin’; and the ‘Schedule of petroleum exploration wells — Merlinleigh and Byro Sub-basins, and Gascoyne Platform’ were released. The current work program will be completed in 1999 with the release of the compilation for the Barrow Sub-basin.
- Mineral exploration reports are now being submitted in digital format, as .pdf files, and tabular data as ASCII tab-delimited files. Submission of digital data is voluntary and will not preclude submission of reports in hard copy format.
- Data from several sources are being linked in the WAPIMS database to produce a map-based browser to all petroleum exploration activities conducted in the State, including seismic lines, aeromagnetic and gravity polygons, and well locations
- Changes to the Western Australian Mining Act that clarify requirements in regard to technical reporting continue to lead to an improvement in quality of statutory reports from tenement holders.
- A web page has been developed that contains copies of all the relevant reporting guidelines for both minerals and petroleum reporting as well as details on how exploration data may be accessed from the Department.

Report submission

Mineral exploration

During the year, 3169 mineral exploration reports (4816 volumes) were received, representing industry activity on 11 779 tenements. This represents a decrease of 9% in the number of reports and a decrease of 5.7% in the number of tenements compared to 1997–98. The total number of volumes held is now 64 331. Gold is still the most commonly sought commodity with 74% of reports submitted relating to exploration programs for gold. Submission of data in digital form continues to increase, with about 17% of all reports submitted during the year containing some digital data.

Reporting standards (mineral exploration)

This year has been the third full year of required compliance with the ‘Guidelines for Mineral Exploration Reports on Mining Tenements’. These guidelines outline standards for format and content of hard-copy mineral exploration reports as required under the Mining Act. Increased quality-control checking by DME staff found that 23% of the reports submitted this year required some rectific-ation in regard to format or content.

The Department continued to be involved with two projects relevant to reporting. One is an inter-departmental working group that works towards the standardization of reporting across States and Territories. The other is an industry and government sponsored project (AMIRA P431) to develop an Australian standard data model for geoscientific data. The 'Requirements for the Submission of Mineral Exploration Data in Digital Format', which was developed in consultation with industry groups, have been adopted by the interdepartmental working group as the basis of national reporting requirements for the mineral exploration industry.

Petroleum exploration

During 1998–99, activities on the 206 active petroleum tenements in Western Australia generated 61 948 sets of data, a 12.4% increase over the previous year, to make a total of 633 404 registered sets of petroleum data held or administered by the Department. The datasets include reports, seismic sections, well logs, digital data, maps, cores and cuttings, and palaeontological data.

WAMEX, WAPEX, and WAPIMS database development

No significant enhancements of the WAPEX database were carried out during the year as most petroleum data are now being managed in the WAPIMS database. A project to develop a user-friendly, web-enabled, front-end to the WAMEX database commenced towards the end of the year.

Work on the prototype Paradox database (WAPIMS), for the management of petroleum data, has continued with digital downloads being made available to clients and the map browser front-end further refined. Petroleum data customers continue to support development of the WAPIMS database with a growing number of requests for downloads of data from the database. Departmental response time has decreased markedly as the increased functionality of the database has facilitated efficient fulfilment of these requests.

Data release

Mineral data

During the year, 1015 reports were released to open file bringing the total number of open-file mineral exploration reports to 26 221 volumes.

Petroleum data

During 1998–99, 357 edited reports, 767 unedited reports, 39 sets of well logs, and 19 sets of seismic sections were released. The downturn in exploration expenditure in the petroleum industry was most graphically reflected in the 28% decrease in requests for loans of seismic tapes, with 142 requests processed. The total number of tapes requested was 5466, a decrease of 71%. In addition, 69 requests to sample drillcore or cuttings and 26 requests for palaeontological data were satisfied.

Future work

- Implementation and refinement of the 'Requirements for the Submission of Mineral Exploration Data in Digital Format'.
- Scanning to .pdf files (rather than microfiching) of mineral exploration reports prior to release to open file.
- Deployment of a user-friendly, web-enabled, front-end to the WAMEX database will begin early in 1999–2000.
- Progressive capture of metadata for digital files submitted prior to the release of the 'Requirements for the Submission of Mineral Exploration Data in Digital Format'.
- Progressive acquisition in digital format of legacy tabular data previously submitted in hardcopy reports.

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Appendices

List of acronyms and abbreviations

AAPG	American Association of Petroleum Geologists
ABS	Australian Bureau of Statistics
AESIS	Australia’s National Geoscience, Mineral and Petroleum Reference database
AGIA	Australian Geoscience Information Association
AGSEAN	Australian Geologist Skills and Employment Advancement Network
AGSO	Australian Geological Survey Organisation
AMIRA	Australian Mineral Industries Research Association Limited
ANZMEC	Australian and New Zealand Minerals and Energy Council
ANU	Australian National University
APLA	Australian Prospectors and Leaseholders Association
APPEA	Australian Petroleum Production and Exploration Association Limited
ASEG	Australian Association of Exploration Geophysicists
ASX	Australian Stock Exchange
AusIMM	Australasian Institute of Mining and Metallurgy
BMR	Bureau of Mineral Resources
BRS	Bureau of Resource Sciences
DME	Department of Minerals and Energy
DOLA	Department of Land Administration
EXACT	Western Australian Mineral Exploration Activities database
GIS	Geographic Information System
GSLC	Geological Survey Liaison Committee
GSWA	Geological Survey of Western Australia
Landsat TM	Landsat Thematic Mapper
LME	London Metals Exchange
MAGIX	Mineral Airborne Geophysics Information eXchange
MERIWA	Minerals and Energy Research Institute of Western Australia
MINEDEX	DME's mines and mineral deposits information database
NGMA	National Geoscience Mapping Accord
PALAEOBASE	GSWA’s palaeontological database
PDAC	Prospectors and Developers Association of Canada
PESA	Petroleum Exploration Society of Australia
REGOCHEM	GSWA’s regolith and geochemistry database
RFA	Regional Forest Agreement
SHRIMP	Sensitive high-resolution ion microprobe
TENGRAPH	DME’s electronic tenement-graphics system
WACHEM	Western Australian Inorganic Geochemistry database
WACHRON	Western Australian Geochronology database
WAMEX*	Western Australian Mineral Exploration database
WAMIN	Western Australian Mineral Occurrence database
WAMPRI	Western Australian Minerals and Petroleum Research Institute
WAPEX*	Western Australian Petroleum Exploration database
WAPIMS	Western Australian Petroleum Information Management System database
WAREG	Western Australian Regolith Observation database
WAROX	Western Australian field observation database

NOTE: * WAMEX and WAPEX are registered Trade Marks

Planned achievements and publications released

Major planned achievements for 1998–99

The Geological Survey of Western Australia had an ambitious project-based program of work designed to promote Western Australia's exploration potential. The programmed Planned Achievements for 1998–99 were:

- release of 26 geological maps at various scales;
- publication of 54 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of two GIS-based regolith geochemistry data packages;
- publication of three GIS-based mineral occurrence and exploration potential packages;
- compilation in digital format of 83 topographic maps at 1:100 000 scale;
- continued and enhanced provision of geoscientific data and exploration information to industry and the public through our library services and the Western Australian mineral (WAMEX) and petroleum (WAPEX) exploration databases.

The publication milestones were exceeded for both maps and manuscripts released. Twenty-eight maps and fifty-seven manuscripts were published during the year. Two GIS-based regolith geochemistry packages were released as planned. Only two of the three planned mineral occurrence and exploration potential packages were released. The West Pilbara package was not completed. The delay resulted largely from the need to incorporate data from concurrent outcrop mapping in the area by the Pilbara regional mapping team. Digital topographic maps were produced for eighty-three 1:100 000 sheets in the Mid West – Gascoyne region. Statutory information services to industry via the WAMEX and WAPEX database systems continued. Development of an enhanced web-enabled interface commenced for WAMEX, and WAPEX was largely replaced by the more user-friendly Western Australian Petroelum Information System (WAPIMS) database.

Products released in 1998–99 allowed the Geological Survey to again (for the fourth successive year) exceed its target productivity improvement. A real productivity gain of 5.65% was achieved — 0.65% above target.

Maps, volumes, and datasets released in 1998–99

Output for the year is listed below:

Geological maps

1:100 000 Geological Series

BLANCHE–CRONIN (3552–3551)
COORAGOORA (2957)
FAIRBAIRN (2947)
MARQUIS (2447)
MERRIE (2946)
MOORARIE (2446)
NABBERU (3046)
NORTH SHAW (2755)
YULE (2556)

1:100 000 Geological Series preliminary release

Elliott Creek (2250)
Errabiddy (2347)
Landor (2247)

1:250 000 Geological Series

Dixon Range (SE 52-6) 2nd edition
Rudall (SF 51-10)

1:250 000 Regolith Geochemistry GIS packages

Collier (SG 50-4)
Wyloo (SF 50-10)

Geological maps at other scales

Geological map of Western Australia, 1:2 500 000, 13th edition

Western Australia Atlas of mineral deposits and petroleum fields 1999

Lead–zinc–silver — mines, deposits, prospects, and major occurrences of Western Australia
(Mineral Resources Bulletin 15, Plate 1, 1:5 000 000)

Lennard Shelf, Devonian reef complexes of the Canning Basin
(Bulletin 145, in prep., Plate 7, 1:250 000)

South–north log correlation: Sue 1 to Woodada 3
(Report 57, in prep., Plate 1)

Parmelia Group log correlation within the Vlaming Sub-basin: Challenger 1 to Minder Reef 1
(Report 57, in prep., Plate 2)

Interpreted geology of the Palaeoproterozoic Yerrida Basin
(Report 60, in prep., Plates 1 and 2, 1:250 000)

East–west geological sections, southern Merlinleigh Sub-basin, Carnarvon Basin, Western Australia, (Report 61, Plate 1, 1:250 000)

Mineralization and geology of the Bangemall Basin
(Report 64, Plate 1, 1:500 000)

Mineralization and geology of southwest Western Australia
(Report 65, Plate 1, 1:500 000)

Mineral localities, Halls Creek Orogen, Western Australia
(Report 66, Plate 1, 1:1 000 000)

Mineral Resources Bulletins

15 **Lead, zinc and silver deposits of Western Australia,** by K. M. Ferguson

19 **Kaolin in Western Australia,** by P. B. Abeysinghe and J. M. Fetherston

Reports

55 **Archaean felsic volcanism in parts of the Eastern Goldfields region, Western Australia,** by P. A. Morris

61 **Structure and petroleum potential of the southern Merlinleigh Sub-basin, Carnarvon Basin, Western Australia,** by R. P. Iasky, A. J. Mory, K. A. R. Ghori, and S. I. Shevchenko

62 **Lithostratigraphy and structure of the Palaeoproterozoic lower Padbury Group, Milgun 1:100 000 sheet, Western Australia,** by D. McB. Martin

64 **Mineral occurrences and exploration potential of the Bangemall Basin,** by R. W. Cooper, R. L. Langford, and F. Pirajno,

65 **Mineral occurrences and exploration potential of southwest Western Australia,** by L. Y. Hassan

66 **Mineralization of the Halls Creek Orogen, east Kimberley region, Western Australia,** by T. S. Sanders

67 **Six mineral deposits of significance in Western Australia: bentonite, feldspar, kaolin, micaceous iron oxide, talc and tourmaline,** by J. M. Fetherston, P. B. Abeysinghe, J. Shanqing, and W. Guowu

68 **Stratigraphy and petroleum exploration objectives of the Permo-Carboniferous succession on the Barbwire Terrace and adjacent areas, northeast Canning Basin, Western Australia,** by S. N. Apak and J. Backhouse

69 **Geology and petroleum potential of the Gascoyne Platform, Southern Carnarvon Basin, Western Australia,** by R. P. Iasky and A. J. Mory

71 **Geological evolution of the Palaeoproterozoic Talbot Terrane and adjacent Meso- and Neoproterozoic successions, Paterson Orogen, Western Australia,** by A. H. Hickman and L. Bagas,

72 **Silurian–Devonian petroleum source-rock potential and thermal history, Carnarvon Basin, Western Australia,** by K. A. R. Ghori

Records

1998/1 **Program 2 — Industry support, Geological Survey plan for 1998–99 and subsequent three years**

1998/3 **Petroleum source-rock potential and thermal history of the Officer Basin, Western Australia,** by K. A. R. Ghori

1998/6 **GSWA Mooka 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia,** by A. J. Mory and A. R. Yasin

1999/2 **Compilation of geochronology data, 1998,** by D. R. Nelson

1999/3 **GSWA Barrabiddy 1 and 1A well completion report, Wandagee Ridge, Southern Carnarvon Basin, Western Australia,** by A. J. Mory and A. R. Yasin

1999/4 **GSWA Empress 1 and 1A well completion report, Yowalga Sub-basin, Officer Basin, Western Australia,** by M. K. Stevens and S. N. Apak

1999/5 **Coburn 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia**, by A. R. Yasin and A. J. Mory

1999/6 **GSWA 99 extended abstracts — New geological data for WA explorers**

1999/7 **Yaringa East 1 well completion report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia,** by A. R. Yasin and A. J. Mory

1999/8 **Waigen gravity survey — the contribution of semi-detailed gravity data to the stratigraphic and structural interpretation of the Waigen Sub-basin, Officer Basin,** by K. A. Blundell

1999/9 **Gravity data — Wyloo 1:250 000 sheet, Western Australia,** by R. P. Iasky and S. Shevchenko

Explanatory Notes

1:100 000 Geological Series

Geology of the ANGELO 1:100 000 sheet, by T. J. Griffin, I. M. Tyler, K. Orth, and S. Sheppard

Geology of the BOW 1:100 000 sheet, by S. Sheppard, A. M. Thorne, and I. M. Tyler

Geology of the CONNAUGHTON 1:100 000 sheet, by L. Bagas and R. H. Smithies

Geology of the CUNYU 1:100 000 sheet, by N. G. Adamides, F. Pirajno, and T. R. Farrell

Geology of the DARLOT 1:100 000 sheet, by J. M. Westaway and S. Wyche

Geology of the DOCKRELL 1:100 000 sheet, by I. M. Tyler, T. J. Griffin, and S. Sheppard

Geology of the DUKETON 1:100 000 sheet, by R. L. Langford and T. R. Farrell

Geology of the MARQUIS 1:100 000 sheet, by S. Sheppard and C. P. Swager

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

Geology of the MOOLOOGOOL 1:100 000 sheet, by F. Pirajno, N. G. Adamides, and S. A. Occhipinti

Geology of the MOORARIE 1:100 000 sheet, by S. A. Occhipinti and J. S. Myers

Geology of the MOUNT WOHLER 1:100 000 sheet, by R. H. Smithies

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

Geology of the PEARANA 1:100 000 sheet, by I. R. Williams and A. F. Trendall

Geology of the RUDALL 1:100 000 sheet, by A. H. Hickman and L. Bagas

Geology of the SIR SAMUEL 1:100 000 sheet, by S. F. Liu, T. J. Griffin, S. Wyche, J. M. Westaway, and K. M. Ferguson

Geology of the THADUNA 1:100 000 sheet, by F. Pirajno and N. G. Adamides

Geology of the YULE 1:100 000 sheet, by R. H. Smithies

1:250 000 Geological Series

EDJUDINA, W.A. (2nd edition), by S. F. Chen

1:250 000 Regolith Geochemistry Series

Geochemical mapping of the COLLIER 1:250 000 sheet, by J. Coker and J. A. Faulkner

Geochemical mapping of the WYLOO 1:250 000 sheet, by K. J. Pye, A. J. Sanders, and J. A. Faulkner

Miscellaneous publications

GSWA Annual Review 1997–98

Armour-stone investigation north of King Bay, Burrup Peninsula, Western Australia, by S. J. Brice and P. B. Abeysinghe

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

Western Australia mineral and petroleum exploration and development 1997–98, by D. J. Flint, P. B. Abeysinghe, Gao Mai, D. B. Townsend, and R. H. Bruce

Schedule of petroleum exploration wells — Carnarvon Basin: Lambert and Peedamullah Shelfs, and Exmouth Sub-basin, by J. H. Haworth and L. M. Arden

Schedule of petroleum exploration wells — Merlinleigh and Byro Sub-basins, and Gascoyne Platform, by J. H. Haworth and L. M. Arden

Catalogue of geological maps and publications (March 1999)

Guide to preparing GSWA manuscripts (2nd edition)

GSWA Fieldnotes v. 10

GSWA Fieldnotes v. 11

GSWA Fieldnotes v. 12

GSWA Fieldnotes v. 13

Major planned achievements for 1999–2000

The GSWA will continue to pursue a project-based program of work and maintain a vigorous level of output to match funding received. Planned Achievements for 1999–2000 include:

- release of 32 geoscientific maps at various scales;
- publication of 52 geoscientific Bulletins, Reports, Explanatory Notes, Records, and other papers;
- publication of four GIS-based regolith geochemistry data packages;
- publication of two GIS-based mineral occurrence and exploration potential packages;
- publication of two urban and development area resources digital datasets;
- publication of 20 seamless 1:100 000 geological maps in the Eastern Goldfields (Menzies–Norseman);

- continued and enhanced provision of geoscientific data and exploration information to industry and the public through our library services and the mineral (WAMEX) and petroleum (WAPIMS) exploration databases.

External papers published by GSWA staff in 1998–99

APAK, S. N., and *BACKHOUSE, J.*, 1998, Reinterpretation of the Permo-Carboniferous succession, Canning Basin, Western Australia, *in* The sedimentary basins of Western Australia 2 *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia, West Australian Basins Symposium, Perth, W.A., 1998, Proceedings, p. 683–694.

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Note: GSWA authors are in italics

Geological Survey Liaison Committee

The Geological Survey Liaison Committee (GSLC) meets twice a year to review progress and advise on future work programs for the Geological Survey. The four Technical Subcommittees provide comment and advice in each of the special areas for consideration by the GSLC. Members of GSLC include representatives from the Association of Mining and Exploration Companies (Inc.), Chamber of Minerals and Energy Western Australia (Inc.), Australian Petroleum Production and Exploration Association Ltd, Australian Geological Survey Organisation, University of Western Australia, and Curtin University of Technology.

Committee members as at 30 June 1999

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Dr David Blight, Convenor
Dr Colin Branch
Mr John Begg
Dr Dennis Gee
Dr Mike Dentith
Dr Gordon Knox
Mr Steve Mann
Mr Peter Onley
Dr David Otterman
Dr Krishna Sappal
Dr Bryan Smith
Mr Terry Walker
Dr Neil Williams
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Dr Rick Rogerson

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Regional Geoscience Mapping and Mineral Resources Technical Subcommittee

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Dr Tim Griffin, Convenor
Dr John Myers
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Dr John Hronsky
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