ANNUAL REVIEW

GOVERNMENT OF WESTERN AUSTRALIA

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 1996-97

GEOLOGICAL SURVEY · WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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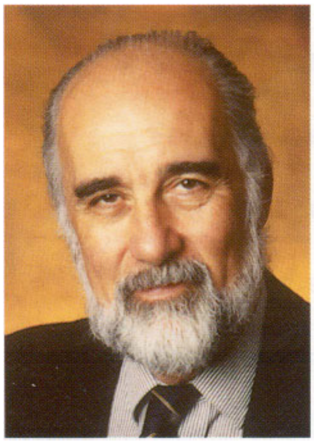
Cover:
***Argutastrea* sp., a rugose coral from the Upper Devonian Gneudna Formation. The specimen was recovered from 632 m in GSWA Barrabiddy 1A, drilled on the Wandagee Ridge, Southern Carnarvon Basin.**

Frontispiece:
Spectacular exposure of the Lower Palaeozoic Tumblagooda Sandstone overlain by Lower Cretaceous Birdrong Sandstone (in weathered upper slopes) with a capping of Pleistocene Tamala Limestone. Shell House, south of Kalbarri.

Foreword



The Geological Survey of Western Australia's Annual Review is now well established as a means of early communication to customers the directions and results of the Survey's activities.

This Review for 1996–97, our fourth, follows the familiar pattern of feature articles and technical papers, as well as a formal reconciliation of products and services delivered in 1996–97 against the original program for the past financial year. I am confident the latter will highlight the Survey's effectiveness and ability to finish and deliver projects on budget and schedule.

Our readers' comments clearly indicate that previews of significant preliminary results have stimulated exploration interest in some of our project areas; often followed by industry geologists making direct contact with our geoscientists and in some cases securing tenure over the areas in question.

I believe these exchanges are vital for the GSWA to formulate a program that is relevant and effective in enhancing the prospectivity of our State and in supporting the exploration industry in the generation of new and exciting exploration concepts and strategies.

The Review also recognizes the very creditable effort by the GSWA's professional and support staff in 1996–97, a year in which achievement of our objectives and performance milestones seemed, for some unclear reason, harder than usual.

Thank you.

P Guj
DIRECTOR

Contents

Geological Survey of Western Australia

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

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

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, based on the acquisition and analysis of field data. 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.

Feature articles

The year in review

by Pietro Guj

Strategic considerations

Fiscal 1996–97 brought home the sudden realisation to Western Australians that we are now competing globally for international exploration investment. Not that the Geological Survey of Western Australia (GSWA) was not already aware of this. Nonetheless, we had probably failed to appreciate the full impact of the opening up by developing and transitional economies of their vast territories until now inaccessible to western exploration, and of aggressive introduction of attractive regulatory and fiscal exploration incentives. This has combined with current land-access uncertainty in Australia in bringing about an escalating redirection of venture capital abroad. The magnitude of this trend makes, in my view, the need for Western Australia to remain internationally attractive as an investment destination one of the main Government challenges for the foreseeable future.

There is no doubt that the main incentive to explore in any country is a perception of prospectivity and that companies will tolerate a degree of regulatory and land-access-related complexity if they believe there are new orebodies to be discovered. Even accepting that WA can claim a high level of prospectivity, there is no room for complacency as many explorers are lured to take advantage of opportunities for early discoveries that are bound to occur in essentially unexplored countries, irrespective of their absolute level of prospectivity.

It would be very short sighted to shrug off these issues just on the basis that investment in exploration in Western Australia has continued to increase both in absolute terms and against a shrinking Australia-wide total. Some would, in my view erroneously, maintain that this is evidence that the land-access blues relating to the uncertainty surrounding the administration of the Native Title Act (NTA) have had no significant effect and seem to conveniently ignore the fact that over the last two years industry investment risk surveys indicate Australia has slipped from Rank 1 as the preferred exploration destination to Rank 6. Some also seem slow to accept evidence of increasing overseas diversification on the part of Australian exploration companies, large and small alike, and that neither the capital nor most of their consequential profits are likely, under the current Australian taxation regime, to return to Australia. I guess we will never know what level of investment we would have experienced had Australia managed its land-access issues better. We must ask ourselves what can be done to counteract current trends.

Luckily, the GSWA has managed, with the support of industry representative bodies, to reinforce in the policy makers' minds the critical importance of geoscience and the relevance of the GSWA's role in enhancing and promoting the prospectivity of Western Australia. This has translated over recent years into increasing financial support for the Survey.

Another aspect of concern is the current over-reliance of the Western Australian economy on gold mining and on off-shore petroleum, both in terms of exploration and development investment, and as a proportion of WA's total value of mineral production. Presumably this focus is at the expense of the search for other metallic commodities (e.g. base metals, platinoids, etc.) and petroleum in on-shore basins, in spite of the fact that a very good case could be made for their significant prospectivity in Western Australia. The GSWA is attempting to redress this strategic issue by balancing the resources directed to greenfields and frontier basins (44% of its budget), as opposed to those devoted to the support of the exploration industry in active areas (19% of its budget) as shown in Table 1.

Changes at the top, but no changes in direction

The year saw some significant changes at the Ministerial and Departmental level, although it was essentially a fairly stable one as far as the GSWA is concerned.

Firstly, there was a change in the Ministry, with Mr Norman Moore, MLA succeeding Mr Kevin Minson, MLC. The introductory interview with our

Table 1. 1996–97 regional geoscience mapping and information project contributions to strategic objectives

Strategic objectives				*(all figures as $000)*
ENHANCEMENT AND PROMOTION OF STATE PROSPECTIVITY *Gathering of new data and use of information* 7 065 63%	Minerals 4 690 42%	Established and producing areas 1 682 15%	Precious metals	677
			Base metals	530
			Ferro-alloys	390
			Non-metallics	85
		Green fields 3 008 27%	Precious metals	901
			Base metals	1 686
			Ferro-alloys	362
			Non-metallics	59
	Petroleum and coal 2 375 21%	Producing areas	4%	441
		Frontier areas	17%	1 934
		PROSPECTIVITY ENHANCEMENT	**subtotal**	**7 065**
INDUSTRY AND COMMUNITY INFORMATION SERVICES *Management and provision of data and information* 4 080 37%	Exploration and resource information for exploration concept formulation and strategy 1 920 17%	Minerals		1 206
		Petroleum		714
	Legislation and titles advice 298 3%	Minerals		248
		Petroleum		50
	Information for State development, landuse planning and R&D 1 862 17%	State development		503
		Land access		488
		Research, development and education		871
		INFORMATION SERVICES	**subtotal**	4 080
		TOTAL 1996–97 BUDGET		**11 145**

new Minister provided an excellent opportunity to discuss the main issues currently affecting the exploration industry, and by reflection the GSWA, and to lay solid foundations for possible future exploration incentive initiatives, which may bring significant results in the context of the 1997–98 budget.

Secondly, the Director General of the Department of Minerals and Energy, Mr Ken Perry, resigned his position to lead a resources finance company. For the GSWA, his departure came at the point where the majority of the significant structural (e.g. stratification) and corporate changes (e.g. introduction of the Performance Enhancement Program (PEP), of Workplace Agreements etc.) had already been bedded down and commenced to bear fruit. From a personal point of view I will miss the frank style of communication and rapport which we had been capable of establishing, and our clear agreement concerning strategic directions and future performance for the GSWA.

Financial and Human Resources applied to improved productivity

The GSWA finished the year on budget having spent, by the end of June 1997, a total of just over $11.1 million. This financial outcome includes adjustments for devolution of some functions previously budgeted for corporately, and for the redirection of around $0.5 million to cover some of the Departmental costs involved in administering the impact of the NTA on the processing of mining tenements, for which no specific allocation had been made in the State 1996–97 budget. After considerable discussion, this redirection of funds was achieved by the suspension of the popular Regolith Geochemical Mapping program. This was considered preferable to spreading the reduction in funding across the board, thus impacting, to a lesser or greater degree, on the effectiveness of all GSWA programs. It also meant that the impact of the reduced level of funding would be clearly evident and a matter of policy choice rather than hidden in a generally reduced level of GSWA performance. Restoration of some of these funds to the GSWA towards the end of the financial year and savings from other GSWA projects allowed, as discussed later in this article, the reactivation of geochemical mapping.

In spite of these budgetary pressures the GSWA managed to achieve a real efficiency/productivity improvement of 3% during the year as measured by our Total Productivity Index (TPI).

In theory, 1996–97 was supposed to be a year of consolidation; of reaping the benefits of the significant organizational changes introduced in previous years. As it was not a year of significant growth for the GSWA, things should have been easy. Yet for some unclear reason, achieving our productivity improvement milestone seemed heavy going. One reason may have been that in 1996–97 the GSWA had to digest significant increases in salaries that resulted from the introduction in 1995–96 of individual Work Place Agreements (WPA) and of the Performance Enhancement Program (PEP) for which only minor funding support had been received from Treasury. In effect, inflationary pressure on the GSWA's cost composition was much higher than average CPI increases and the 3% real target probably translated to savings of the order of 6 to 7% in nominal terms.

During the year, the GSWA employed on average 143 people. Of these 91 were geoscientists and other professionals, with the remaining 52 being technical, field and clerical support staff. Most new appointments were made on a contract basis and as a consequence the proportion of the GSWA's workforce employed on contract rose to just under 40% with the remainder being permanent public servants.

Around 80% of all GSWA staff, irrespective of whether contract or permanent employees, accepted the second round of individual Work Place Agreements with the remainder employed under the collective Enterprise Bargaining Agreement.

Considering the very buoyant market conditions for geoscientists, 1996–97 had a relatively low turnover in professional officers. This is a reason for some pride as it indicates that, in general, GSWA has a highly motivated, satisfied, and well-adjusted professional workforce. There were nonetheless

28 retirements and resignations among which were key players such as Drs Cees Swager and Wally Witt, who joined strategic think tanks in industry.

Among new appointments I wish to welcome Ms Margaret Ellis, who joined the GSWA to lead the new Exploration Information Section formed through the merger of the WAMEX and WAPEX sections. The new section is now housed with the Library in refurbished and, above all, more functional offices on the 5th floor of Mineral House, and should provide better and more efficient customer services with single-point access to all information services.

Another critical appointment in view of our future development was Mr Philip Burden who joined us from Oman to lead our Geographical Information System (GIS) Section.

Delivering products and services

The success of the GSWA in achieving both its planned achievements and productivity targets for 1996–97 was in part due to the continued guidance and support from the Geological Survey Liaison Committee (GSLC) and its technical sub-committees as well as to contributions and ideas from individual companies and professional members of the mineral and petroleum exploration industry. Total product released included an unprecedented 21 geological maps comprising 16 at a scale of 1:100 000 and five at other scales, three GIS regolith/geochemical packages, 25 bulletins, reports, records, and explanatory notes, two aeromagnetic/radiometric surveys, and two gravity survey data packages.

There is no doubt that the GSWA has become a very effective organization and developed a strong cultural ethos about finishing and delivering to customers high-quality geoscience products and services to their satisfaction. In this context it was pleasing to receive formal endorsement by the GSLC that our services in 1996–97 had been more than satisfactory in terms of their relevance, quality, and usefulness to industry.

Achievements for 1996–97 are broken down and described in terms of various GSWA programs and activities below.

Regional geoscience mapping

Data continued to flow from projects where fieldwork was completed last year (Lennard Shelf, King Leopold and Halls Creek Orogens, the former Glengarry Basin, Paterson Orogen, and the Northern Eastern Goldfields), with 14 of the total of 16 map sheets at 1:100 000 scale published being related to these projects. New 1:250 000 Kurnalpi and 1:100 000 Millrose map sheets were published in the Eastern Goldfields and several additional sheets were prepared for publication in 1997–98. A study of the Eastern Goldfields granitoids, with an accompanying regional geological map was also released during the year. It is intended that from now on, every product from this region should be compiled in a form that will allow easy integration into a comprehensive, seamless, GIS-based mapping database. This will be constructed and maintained by a strongly revitalized Kalgoorlie office geological team under the leadership of a 'Terrane Custodian'.

Revision of selected 1:250 000-scale map sheets continued, with two maps published in the Pilbara (ROY HILL) and Gascoyne (BYRO) regions. Progressive revision of key sheets will continue, as new geological interpretations are dictated by issues arising from the 1:100 000-scale mapping program and industry activities in the region.

The National Geoscience Mapping Accord (NGMA) continued to run at a fast pace: two map sheets at 1:100 000 scale were published from recent work on the Pilbara project, and a further two sheets are ready for imminent publication, with a large amount of field mapping undertaken in the Pilbara despite AGSO's field season having been progressively curtailed by budget cuts imposed on them by the Federal Government.

It is intended that, in view of cutbacks to AGSO's programs, the GSWA should strengthen its position in the Pilbara in an attempt not to excessively delay completion of this project.

Priorities set in consultation with industry have led to new projects in the Southern Gascoyne, Southern Cross, Earaheedy, and Bangemall regions.

Significant acquisitions of coloured aerial photography and airborne geophysical aeromagnetic/radiometric data were secured to support these programs and for future release to industry. Some surveys (e.g. Central Pilbara, East Pilbara, and Nabberu) were funded directly or jointly with AGSO under the NGMA and, because they hold copyright, data could be released to industry without delay. In addition GSWA and AGSO have purchased access to 100 000 line kilometres of multiclient data from the Diemals–Marda area north of Southern Cross. The contract provides for an option to gain joint copyright and to be able to release this survey to industry within three years. A similar deal was renegotiated for the Bangemall and Gascoyne multiclient survey acquired in 1995–96.

Mineral prospectivity

This program is designed to enhance the perceived prospectivity of the State and to encourage exploration in areas that are considered underexplored. It integrates, in a GIS environment, open-file statutory data within the existing geological framework.

Mineral occurrences data collection represents the main element of this new range of products that will be released from 1998 onward. Data collection has been completed for the Northern Eastern Goldfields, the Southwest Yilgarn, and the Bangemall projects, with spatial indices to exploration activity nearing completion.

The GSWA was commissioned to carry out the Southwest Yilgarn survey in cooperation with the Bureau of Resources Sciences (BRS) of the Commonwealth Department of Primary Industry and Energy (DPIE) for a qualitative assessment of the known and potential mineral, coal, and petroleum resources of the Southwest Forest Area. This represents a critical input to the Comprehensive Regional Assessment on which the Commonwealth–State Regional Forest Agreement (RFA) negotiations will be based. The objective is to determine economically rational conditions to balance forest resources development with the establishment of a system of reserves which should be cast with cognisance of other industrial and socio-economic considerations in this region.

Mineral occurrences data collection and spatial indices of exploration activity are currently also being assembled for the West Pilbara and the Kimberley regions.

Systematic documentation of 200 gold deposits in the Kurnalpi–Edjudina area has been completed in preparation for a special report, also to be published in 1998.

A database of industrial mineral occurrences is currently being assembled and a Bulletin on the kaolin resources of the State is in preparation.

Petroleum Exploration Initiative — onshore basin studies

In 1996–97, work on the onshore basins of WA concentrated on the Officer, Canning, and Carnarvon Basins. Records dealing with the hydrocarbon prospectivity of the Canning and Officer Basins and Savory Sub-basin, and seismic structure maps of the northern Perth Basin were prepared.

Five stratigraphic holes were drilled. The first four, totalling 3123 m, provided high-quality analytical data on the source and reservoir potential of the Silurian and Devonian stratigraphy of the Gascoyne Platform of the Carnarvon Basin. The latest, Empress 1, which it is proposed should reach a depth of 2000 m in the Yowalga Sub-basin to test the Neoproterozoic sequence near the western margin of the Officer Basin, is in progress at the time of writing.

With the recent awarding of a Special Prospecting Licence covering much of the Canning Basin, the work program initially proposed for this basin has now been deferred until the relevant data become available. This will allow re-assignment of resources to accelerate work in 1997–98, particularly in the Officer Basin. Activities will include acquisition of gravity data (in the

Waigen and Coolcalalaya Sub-basins), supervision and immediate release to industry of stratigraphic drilling to be carried out by industry in the Savory Sub-basin, and interpretation of reprocessed seismic data (in the Merlinleigh, Lennis, Yowalga, and Gibson Sub-basins).

Regolith geochemical mapping

In 1996–97 three 1:250 000-scale sheets from the Capricorn Orogen (Robinson Range, Mount Phillips, and Nabberu) were published and two 1:250 000 sheets (Mount Egerton and Glenburgh) were sampled using helicopters.

Reinstatement to this project late in the financial year of some of the funds previously redirected to the administration of the NTA not only enabled the project to recover some lost ground, but precipitated an accelerated and successful, helicopter-supported sampling program (humorously referred to as Operation Desert Storm). Much was learned from this start–stop experience and from the pressure to complete the sampling of two sheets at a scale of 1:250 000 against short and inflexible deadlines (or lose the funds to Treasury). Major improvements had to be introduced in our logistical planning, in awarding and managing external contracts, and above all in realising the critical importance of flexibility in the Survey's staff roles. In essence, this experience has piloted and set in place significant operational and organizational changes for the regolith geochemistry program to be carried out more effectively and efficiently in the future.

Mineral and petroleum exploration information

During the year just under 4000 mineral exploration reports were received, an increase of around 16%, bringing the total WAMEX database collection to some 56 000 volumes.

The petroleum exploration scene was also hectic, with a 26% increase in volume of entries registered in the WAPEX database.

Significant increases were also experienced in the proportion of material submitted in digital form to both databases. This has precipitated a review of the adequacy of current processes and of how the GSWA should position itself to be effective in handling and curating data in various new media for which it is currently under-equipped.

A new product in the form of the 'Schedule of wells' was extracted from the WAPEX database and well received by industry. So far, information on the Perth, Canning, Officer, Eucla, and Bremer Basins has been recovered and released during 1996–97.

Besides industry, internal requests for information linked to the accelerated mapping and petroleum initiatives programs also contributed to swell the workload of the exploration data management and library teams.

The increased level of activity was handled with essentially static resources through productivity gains derived from the merger of the two original mineral and petroleum exploration data sections, and through continuous improvement in their processes and customer service.

Promoting Western Australia's prospectivity

It would of course be pointless to produce high-quality geoscientific information if the results were not to be effectively disseminated to industry to assist existing explorers and ideally to attract new ones. In many respects this has been somewhat of a weakness on the part of the Survey. I am grateful to our past Director General, Mr Ken Perry, for having focused my attention on the inadequacy of our promotional activities, which, as he colourfully put it, until recently amounted to winking at a girl in the dark. Discussion with industry confirmed that the GSWA must do more to ensure that users are made immediately aware of the availability of new products and services, and that the GSWA must broaden the scope and range of media used to communicate with industry.

We have taken notice of these comments, and during 1996–97 expanded the number of scientific and industry forums in which we have made presentations and, above all, mounted displays of our products and activities.

We attended no fewer than 12 such events and ran a number of courses and seminars in our own right, including some on volcanism, granitoids, and coastal processes. We have also been more active in terms of press releases and short articles that are now routinely prepared when a new product is released to the public.

We also introduced quarterly information pamphlets called Fieldnotes and are exploring ways of effectively using the Internet as yet another medium to promote our products and, most importantly, our State's prospectivity.

What about the future?

Western Australia, given its dependence on the mineral and petroleum industry, will confront significant medium-term challenges both in the global and in the domestic arenas.

Challenges will arise from increasing international competition for exploration and development investment as well as from competition arising from increasing domestic emphasis on alternative and even conflicting landuses.

The way these issues will be addressed has the capacity to significantly influence the future quality of life and well-being of the Western Australian community. It is therefore paramount that in formulating future policy decision-makers should base their deliberations not only on political values but also on high-quality factual geoscientific information.

I have no doubt that there is, and will continue to be, an important role for the GSWA to play in optimizing the benefits of our rich resource endowment to the community. I am also comforted by the fact that our political masters have clearly indicated, by a number of recent decisions, that they fully appreciate the importance of this role.

For our part, the GSWA executive has come to the conclusion that the best way for us to satisfy future needs is to focus our activities primarily on efficient field collection and prompt release of factual geoscientific information of a regional nature. I believe we have, in consultation with industry, clearly identified our niche, thus avoiding potentially wasteful overlap of effort between the roles of Government and of private enterprise. We have also pulled back from a range of research activities of a specific or detailed nature unless they had a critical and direct bearing on the understanding of regional geological frameworks. These are by their nature the niche of university and other research organizations.

Another principle that we will strenuously defend will be the maintenance of our traditional character and our need to generate, retain and, if necessary, acquire copyright of broad regional datasets that should be as promptly and freely available to the public as possible.

In this respect we are moving against a strong trend in which public organizations are being forced to shape their activities and set their pricing policy to generate revenue at their level in the economy, rather than through stimulation of tenement acquisition, resources discovery and development and, finally, royalties with all their related multipliers. The Survey hopes to be allowed to continue to price its products at the cost of reproduction rather than that of the information. We feel that more maps in the hands of more explorers will ultimately add better value than fewer more expensive maps.

A major challenge will be to maintain a modern, up-to-date inventory of maps, which on average should not be more than 20 years old, in a State with 163 sheets at 1:250 000 scale and some 980 at 1:100 000 scale. Obviously we will never be sufficiently resourced to achieve this through conventional mapping strategies. As a consequence we envisage that, over time, gradual progression of our 1:100 000 mapping program of key areas will trigger two strategies.

In areas of more mature map coverage, the Survey will commence the construction of comprehensive, seamless, digital maps and databases covering entire superterranes. These databases will exhaustively collect all geoscientific information relevant to the local regional framework irrespective of source. Thus, while the basis will be the Survey's own work, a large component will be provided by extracting information generated by industry and contained in the mineral (WAMEX) and petroleum (WAPEX) exploration databases as well as information published by academia and research organizations.

Each of these databases will be the responsibility of a senior geoscientist called the *Terrane Custodian*, who will continually liaise with industry and other researchers in his terrane in an endeavour to capture, at source, any emerging unresolved issues likely to significantly affect current regional interpretations. This will generate a number of specific regional mapping projects, both big and small, which will be prioritized and carried out in house or contracted out, leading to periodical revisions of the GIS map base with continuing releases to industry.

GSWA intends to pilot this concept with the first Terrane Custodian to be established in the Eastern Yilgarn and based in our Kalgoorlie office. Others will be established as the mapping coverage progressively matures over various terranes.

Conventional geological mapping will continue elsewhere, with the difference that, in general, there will be a tendency for concentrating rather than dispersing our efforts. This will accelerate the completion time of projects, with simultaneous or closely spaced release of a range of related products that will facilitate more robust terrane-wide interpretations and be more effective in attracting the exploration industry's attention to specific regions of the State. This approach, whether in the geological, geochemical and regolith, or geophysical areas, will also allow transfer of the relevant completed datasets to the local Terrane Custodian who will ensure their ongoing maintenance.

The use of bigger teams means that better, more experienced leadership and management can be provided, and also ensures that younger, energetic but inexperienced, geoscientists can be integrated in project teams without visible loss of product quality.

The impact of digital technology on data management has created major opportunities and challenges for the GSWA because it houses such large volumes of currently under-utilized geoscientific data, particularly in the WAMEX and WAPEX files. We must ensure that in future, data management systems in the GSWA should be able not only to integrate very large datasets from a wide range of sources, but also facilitate their availability to clients. The Survey has started a process of review that will explore options and hopefully result in a clear strategy for managing data, ideally based on a robust, staggered, but highly integrated work plan.

We recognize that this is not a trivial challenge as the costs are high, particularly when the impact of curating our voluminous seismic data collection is considered. The cost of failure is also potentially high. Ultimately, however, we cannot skirt around the fact that, in the emerging information era, our clients should be able to obtain the data they need, in the form they need, with minimal retrieval inconvenience and cost.

Geological Survey policy for all its products and services is not to compromise on quality. We define quality in two ways. Where a specific customer group and its needs can be identified, quality will be defined as 'fitness for purpose'. This could be the case for some of our exploration data and library services.

In the case of geological maps, the field of potential users is broader, and their needs vary from general to very specific and detailed. 'Fitness for purpose' is no longer a valid definition and quality acquires, in my mind, an absolute value.

This is, of course, easier said then done and involves the setting of very specific policies and standards concerning our map production process. It also entails stringent quality assurance and control mechanisms including exhaustive editorial and cartographic procedures.

How will we manage? The answer is by becoming more effective and productive. We will achieve this through:

- closer and more meaningful liaison with the mineral and petroleum exploration industry at all levels;
- development not only of superior regional geological mapping skills but also of leadership and of painstaking dedication to sound and systematic project and contract management and continuous process-improvement strategies; and
- attraction, development, and retention of highly and appropriately skilled professional and support personnel, and through human resources policies that align the individual interests and expectations with our corporate objectives, and engender a sense of purpose, loyalty, urgency and accountability in the GSWA team.

People accuse me of being an optimist, perhaps I am; but I do believe enthusiasm is a very powerful ingredient in personal and corporate success. I am glad to see a lot of it around in the Geological Survey of Western Australia.

Mineral exploration and development in Western Australia in 1996–97

by D. J. Flint and P. B. Abeysinghe

The geological setting of Western Australia has provided a rich endowment of mineral wealth covering a variety of mineral types and mineralization styles. In 1996–97, the value of mineral production amounted to $11.4 billion, with a further $5.0 billion from petroleum. Western Australia continues to be a very significant producer of gold, iron ore, bauxite–alumina, nickel, diamond, heavy-mineral sand products, salt, tantalite, and spodumene (lithium) in a world market context.

The minerals boom continues to dominate current and planned economic development in Western Australia. Mineral discoveries are critical to the continuance of project developments, although a number of evaluations and developments currently taking place are on deposits first identified over 30 years ago. Although the limelight is focused on value-adding by downstream processing of our minerals, particularly in the iron ore industry, such operations rely on the availability of suitable minerals in the ground and their improved economic viability of extraction. Advances in process technology, gas-price deregulation in Western Australia and, very significantly for Eastern Goldfields gold and nickel producers, wider gas distribution with the opening of the Goldfields Gas Transmission Line, are having a significant impact on project economics and are changing in some respects the focus of exploration effort. Mineralization that perhaps was not contemplated as having significant development potential a few years ago is now attracting major exploration effort.

Exploration overview

Western Australia's prospectivity is acknowledged by the level of exploration effort throughout the State, attracting a high level of exploration expenditure, which surged to new records. In 1996–97, mineral exploration expenditure (excluding petroleum) in the State was $690.1 million, an increase of $170.6 million or 33% on the previous year. This extends a significant period of growth in exploration expenditure in Western Australia, with seven successive years of growth (Fig. 1).

The surge in exploration activity in Western Australia helped push the Australian total of annual exploration expenditure (excluding petroleum) past the $1000 million mark for the first time ever — reaching $1156.8 million (original figures) for 1996–97. Western Australia now attracts 59.7% (54.1% previously) of all Australian exploration expenditure, the highest proportion for at least ten years (Fig. 1).

Another measure of total exploration activity in Western Australia is drilling statistics, which show a 20% increase in total metres drilled over the 1996–97 year. The following data (Table 1), extracted from the Department's WAMEX database, relate to mineral exploration reports received by the Department during the period, but may refer to work carried out up to one year earlier.

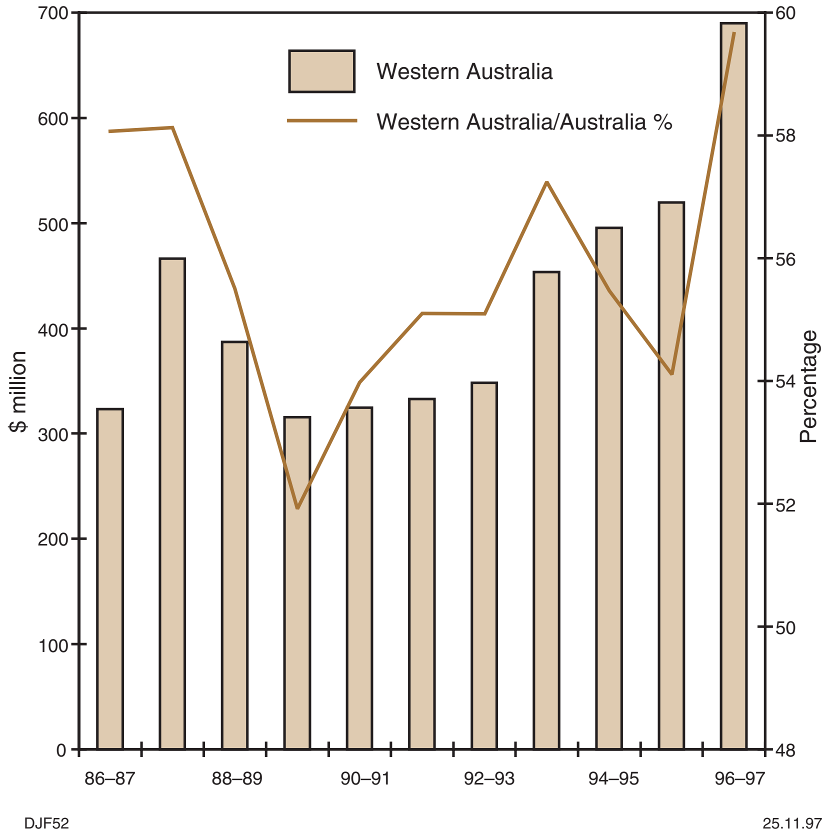


Figure 1. Mineral exploration expenditure (excluding petroleum) in Western Australia (dollars of the day, original figures) and Western Australia's percentage of the Australian total

In 1996–97, petroleum exploration in the State also set new records, with exploration expenditure of $444.1 million, an increase of $125 million or 39% on the previous year. This extends a significant period of increasing petroleum exploration in Western Australia, which now attracts 50.9% (44.0% previously) of all Australian petroleum exploration expenditure. This falls below the record proportion reached in 1990–91 of 54%.

The mineral prospectivity of Western Australia is being upgraded through grassroots exploration and reinterpretation of regional geology. With the recent mini boom in nickel exploration, at least three new Kambalda-style occurrences have been found, i.e. Goodyear (35 km southeast of Kalgoorlie), Lake Goongarrie or Lakeside prospect (15 km north of Scotia mine) and Cosmos (south of Mount Keith). Discovery of polymetallic massive sulfide mineralization at Trilogy, 25 km southeast of Ravensthorpe, probably in the Neoproterozoic Mount Barren Group, is a reminder that more than just the Archaean rocks are prospective in this area. The evolving concepts of the diamond prospectivity of the Yilgarn Craton have led to very active diamond exploration of the craton, particularly in the Menzies–Leonora area where there were unconfirmed reports of a significant kimberlite find by Stockdale Prospecting Ltd near Lake Ballard. A reminder of the often neglected gold potential of the Pilbara Craton, the Granites–Tanami Complex and the Ashburton Basin were the discoveries at Indee, Kookaburra and Mount Olympus, respectively.

Despite the record expenditure, Native Title issues continue to cause frustration and delays to the planning of many exploration programmes. Also, some successful exploration has defined mineralization that cannot be developed in the short term because of delays in granting mining leases when there are objections by Native Title claimants.

Table 1. Exploration drilling (metres) in Western Australia

Period	*Diamond drilling (m)*	*% change*	*RC drilling (m)*	*% change*	*RAB drilling (m)*	*% change*	*Total (m)*
1994–95	788 477		3 943 158		3 232 992		7 964 627
1995–96	677 622	-14%	4 153 925	5%	3 800 550	17%	8 632 097
1996–97	992 784	47%	4 391 703	6%	4 969 432	30%	10 353 919

Gold exploration was still paramount, accounting for 76% (previously 71%) of the total exploration expenditure in the State, with base metals (including nickel) at 13% (previously 12%), diamonds at 5% and iron at 4% (Fig. 2). Exploration for heavy-mineral sands and for other minerals are both at 1% of the total spent in the State. There is an imbalance between the importance of gold in the exploration sector to gold's proportion of the value of mineral production (excluding petroleum) in the State. Although gold exploration expenditure represents 76% of the total spent for 1996–97, gold's proportion of the value of mineral production was only 30%. The situation highlights the dynamic nature of commodity markets, which are constantly changing, but also suggests that the situation (high levels of exploration expenditure) may be driven by companies and their shareholders who perceive short-term money making opportunities. Once that perception changes, for whatever reason, a substantial fall in gold exploration expenditure is expected.

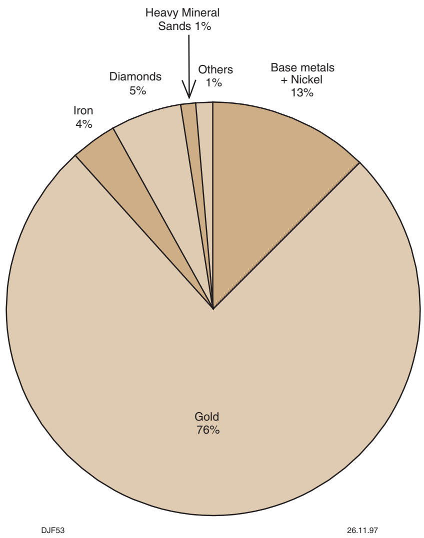


Figure 2. ***Mineral exploration expenditure (excluding petroleum) in Western Australia for 1996–97, by commodity (original figures)***

Western Australia attracts the major part of the Australian exploration dollar in iron ore (99%), gold (73%), diamond (65%), and heavy-mineral sands (51%). Western Australia attracts 41% of the Australian exploration dollar in base metals (Cu–Pb–Zn–Ni–Co); the percentage for Ni–Co is presumed to be higher but data sourced from the Australian Bureau of Statistics do not show Ni–Co separately.

The change in exploration expenditure in Western Australia for various mineral commodities over the year has been quite variable, with the major area of growth being gold (Fig. 3). Most of the State's $170.6 million increase in exploration expenditure was in this sector ($163.7 million increase). Such an increase overshadows the smaller, but significant, increases in exploration for iron ore, diamonds, heavy-mineral sands and other minerals. The only commodity group with less expenditure in 1996–97 than in 1995–96 was the undifferentiated Cu–Pb–Zn–Ni–Co group.

The changes in exploration expenditure in Western Australia by commodity over the year have been matched by the trends in the number of tenements being explored. The following data (Table 2), extracted from the Department's WAMEX database, relate to tenements for which mineral exploration reports were received by the Department during the relevant year. Note that tenements may be explored for more than one commodity. These figures also more clearly show the decline in base metals (Cu–Pb–Zn)

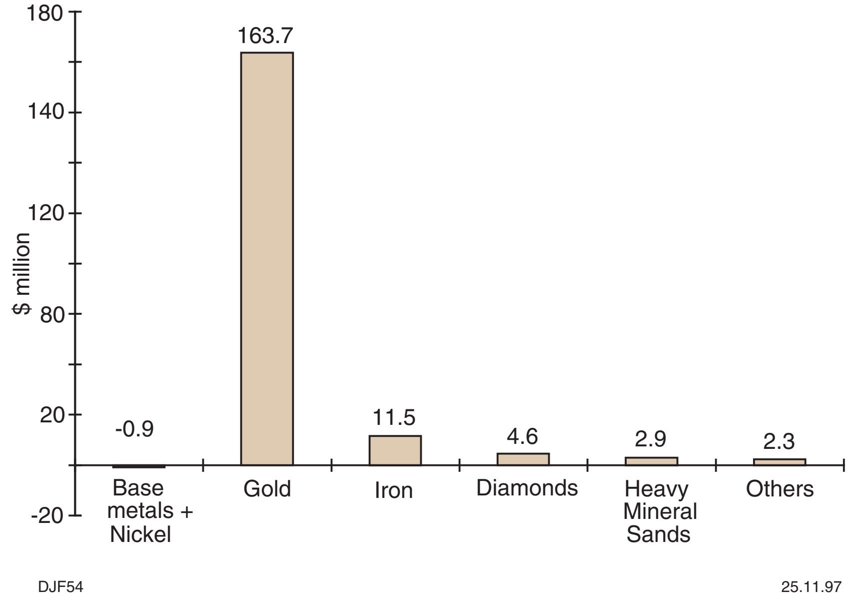


Figure 3. The change in mineral exploration expenditure (excluding petroleum) in Western Australia between 1995–96 and 1996–97, by commodity (dollars of the day, original figures)

exploration activity, whereas exploration activity for Ni–Co is increasing. Some care is needed in interpreting the data as, under the 1978 Mining Act, some exploration licences may be partially replaced by several smaller mining leases, hence the progressive increase in the number of tenements being explored may be partially caused by legislative provisions unrelated to actual trends in exploration.

Table 2. Number of tenements in Western Australia explored for selected commodities

Period	*Gold*	*Copper–lead–zinc*	*Nickel–cobalt*	*Diamonds*	*Uranium*	*Iron*
1994–95	10 307	821	612	737	70	191
1995–96	10 858	883	1 027	775	53	164
1996–97	11 140	691	1 680	761	45	206

Precious metals

Gold

In 1996–97, gold exploration expenditure in Western Australia increased by 44% over the previous year, rising from $368 million to reach a record of $531.7 million. Western Australia continues to lead the way in Australia, with 73% of all gold exploration expenditure in Australia during 1996–97. Gold is still the major sector of exploration expenditure in Western Australia, with 76% of the State's total (71% in 1995–96). Western Australia continues to be recognized by industry as the best place to explore for gold in Australia.

Gold production in Western Australia continues to increase, from 206 t (1995–96) to 230 t in 1996–97 — a new record. The rise in value of gold production to $3438 million was, however, a more modest 1%, caused by a lower average gold price and the appreciation of the Australian dollar. Approximately 15% of the gross value of gold production is returned as exploration funds — a level which is unlikely to be maintained.

In 1996, gold discoveries and upgrades of resource categories added about 313 t of contained in-ground gold resources to the measured and indicated inventory; from about 2696 t (1995) to 3009 t at the end of 1996. This translates, after allowing for production, to a discovery cost of around $26/ounce for 1996 compared with around $22/ounce in 1995. Exploration has surged during 1996, but the increase in resources found during 1996 was less than during the previous year. A large proportion of the resource increase is now in 'brownfields' areas around existing mines, and true 'greenfields' discoveries are most likely to be costing significantly more than the above figure. Nevertheless, numerous discoveries were made during 1996–97 and from diverse geological settings, including the Pilbara Craton, the Ashburton Basin, and the Granites–Tanami Complex along the Northern Territory border. These include Darlot Centenary (with an interim resource containing 2.1 million ounces), Quarters (which is 500 m from the Mount Pleasant gold processing facility and contains a 2.35 million ounce gold resource), Indee (east Pilbara), Mount Olympus/Zeus (30 km southeast of Paraburdoo, in the Ashburton Basin), Trident (Marymia Inlier), Three Rivers (Marymia Inlier), Woodley and Lennon lodes (near Bulletin, Wiluna), Federal (40 km north of Kalgoorlie), White Foil (23 km southwest of Kalgoorlie), Granny Venn (8 km north of Menzies), Rosemont (Duketon greenstone belt), Halfway Hill (Gindalbie), and Fairyland (Lawlers).

However, most of the exploration effort concentrated on extending known orebodies, identifying new lodes, and discovering satellite orebodies near existing mines.

Any euphoria associated with Western Australia's record levels of gold exploration expenditure and production in 1996–97, was completely overshadowed by gold's fall from grace as a result of the Reserve Bank of Australia's selling off some of its gold holdings, the poor price outlook for gold, the proposed introduction in Western Australia of a gold royalty, and the sharp falls in company profitability at the end of the 1996–97 year. Gold price weakness throughout the first half of 1997, caused partly by fears of and actual selling by central banks, reached a peak in early July 1997 when the Reserve Bank of Australia announced that it had sold off 167 t of gold, two-thirds of its gold holdings. This was combined with the Treasurer's reported comment that 'Gold no longer plays a significant role in the international financial system'. The gold price immediately fell to around $US322 per ounce, reaching 12-year lows, and has recovered only slightly since. Discussion continues on whether gold is a financial asset or just another commodity. Meanwhile, the threat of further sales from the huge official gold reserves of the various central banks around the world, estimated at about 36 000 t, continues to weaken gold prices.

The gold industry in mid-1997 was described as being in a state of 'meltdown'. Australia has the highest average production costs in the world, at $US358/ounce, which compares unfavourably with spot gold prices of around $US330/ounce in mid-1997. Current production from numerous mines is uneconomic, and at least 26 mines in Western Australia produced gold during the first half of 1997 at cash costs higher than prevailing spot gold prices. Many mines are surviving at the moment solely on the strength of various forward-selling and hedging programs; it has been estimated that for the top 20 producers, 59% of their 1996 profit was from forward sales and hedge activities (40% in 1995). The top 20 gold producers in Australia have about 41% of their reserves hedged (as at December 1996), corresponding to more than 700 t of gold. This should be compared with Australian annual production of about 250 t and worldwide annual mine production of 2300 t. Companies are reviewing their gold reserves, to assess those which are still recoverable economically. In many cases they are being adjusted downward. Several mines have already closed, including Palm Springs (Precious Metals of Australia Ltd), Golden Pig and Frasers (Sons of Gwalia Ltd), Badgebup (International Mineral Resources NL) and Bullabulling (Resolute Ltd), and Copperhead (Sons of Gwalia) is intended for closure. Operations at both Telfer (Newcrest Mining Ltd) and Reedy (Gold Mines of Australia Ltd) have been scaled back. In addition, develop-ments at several projects have been indefinitely deferred, including the planned plant expansion at St Ives (Western Mining Corporation) and Delta's development of Golden Feather (3 km east of Kanowna Belle). Western Mining Corporation Ltd (WMC) at

St Ives had planned a $157 million expansion and doubling of capacity to 5 Mt of ore per annum, to produce an extra 150 000 ounces of gold. Instead, the plant will be refurbished in a $30 million program that will maintain the present ore throughput rate of 3.2 Mt per annum.

The Eastern Goldfields continue to be the prime focus of exploration activity, with further discoveries in the Yandal greenstone belt in the northeast. In October 1996, Plutonic Resources Ltd announced the discovery of the Darlot Centenary mineralization, only 2 km east of its existing Darlot mine, 120 km north of Leonora. Centenary was discovered at a depth of 350 m on step-out drilling on a 320 x 320 m grid. This is regarded as a major discovery, with total identified resources (estimated in March 1997) of 8.4 Mt at 7.7 g/t Au, containing 2.1 million ounces of gold. One hole, MCD437, 40 m from the original discovery hole, returned a near-true thickness of 125 m at 3.3 g/t Au. One of the step-out holes intersected 59 m at 6.6 g/t Au. The discovery vindicates Plutonic's policy of deep diamond drilling in close proximity to known deposits.

Further exploration success continued underground at Bronzewing with delineation of the wide and persistent Herbison vein averaging 30 g/t Au. The total resources in all categories at Bronzewing, Jundee and Mount McClure increased substantially during the year and now totals about 12 million ounces. The Nimary mine, located 35 km northeast of Wiluna, in the Yandal greenstone belt, had the distinction of being probably the mine with the lowest cash operating cost in Australia for 1996 — at $205/ounce. Eagle Mining Corporation NL initially spent A$15.1 million on discovering the gold at Nimary, at an average discovery cost of $15/ounce.

Further east, the Duketon greenstone belt continues to attract significant exploration activity, but the highlight for the year was the official opening of Sunrise Dam mine on 6 August 1997 by the Premier, Richard Court. During the six months to June 1997, Acacia Resources Ltd produced from Sunrise Dam 41 341 ounces at a cash cost of $230 per ounce. Sunrise Dam, with development costs of $40 million, is expected to produce 130 000 ounces per year for at least six years, with cash costs of about $250/oz. A second highlight was the discovery by Johnson's Well Mining NL, in early 1997, of the Rosemont deposit located 90 km north of Laverton. Best results to 30 June 1997 include 29 m at 23 g/t Au from a depth of 109 m, 55 m at 6.3 g/t Au from a depth of 239 m, and 52 m at 4.9 g/t Au from a depth of 238 m. Mineralization is within a steeply dipping, fractured, sheared and altered quartz diorite, which has intruded ultramafic rocks. The ultramafic rocks are within a structural corridor, 50 km long, which also contains the Famous Blue mineralization. Gold, including visible gold, is associated with quartz veins, pervasive silicification and sulfides.

Drilling by Mount Kersey Mining NL at the Hayes New Find prospect, located 35 km north of Kanowna Belle, has intersected several areas of shallow oxide gold mineralization above primary gold mineralization in a vein stockwork containing quartz, sulfide and carbonate. Best results include 20 m at 3.3 g/t Au from a depth of 48 m (RC), and 8 m at 1.0 g/t Au from a depth of 28 m (RAB). The stockwork is at the contact of a porphyry with black shales and represents a significant new target.

Whereas a significant part of Eastern Goldfields exploration is at a relatively mature stage, new exploration projects have emerged in areas previously considered to be unprospective. At Quarters prospect, located 500 m from the Mount Pleasant gold processing facility, mineralization has been located beneath 35 m of cover and with a depleted supergene zone. The host Bent Tree Basalt has previously not been regarded as prospective. An extensive drilling program has increased the gold measured and indicated resources at Mount Pleasant to 1.6 million ounces of contained gold. Best results include 11 m at 23.7 g/t Au from 199 m (diamond drillhole) and 14 m at 69.4 g/t Au from 64 m (RC drillhole). Pre-stripping has commenced, with mining scheduled to begin in mid-1997.

In early 1997, Centaur Mining and Exploration Ltd announced what it considered was a major new gold discovery at the Federal prospect, 40 km north of Kalgoorlie. Drilling results included 28 m at 9.1 g/t Au from a depth of 76 m, 20 m at 7.6 g/t Au from a depth of 104 m, and 16 m at 13.3 g/t Au from a depth of 24 m. At the end of June 1997, total measured and indicated resources were estimated at 27.13 Mt at 2.7 g/t Au, containing 2.35 million ounces of gold. Unusually, mineralization is hosted by granitoid.

The potential of the White Foil prospect, 23 km southwest of Kalgoorlie, was substantially upgraded during 1996–97 by drilling by Mineral Commodities NL and Mines and Resources Australia Pty Ltd. The best drilling result for the year from White Foil, known previously as Kopai and drilled as early as 1993, was a spectacular 227 m at 2.55 g/t Au from 76 m. The initial estimate of inferred resources is 10.83 Mt at 2.51 g/t Au, using a 1 g/t Au cut-off, for 870 000 ounces of contained gold.

Discovery by Money Mining NL of Granny Venn, located 8 km northeast of Menzies, is regarded as another of the region’s significant gold discoveries for 1996. Some of the better intercepts from RC drilling include 15 m at 5.97 g/t Au from 30 m and 14 m at 4.27 g/t Au from 31 m.

The Yilgarn Extension project, located south and southeast of Norseman, is another target area to have emerged in the last two years. Here, Pan Australian Resources has postulated a complex geological setting with significant potential for gold and base metals in an area of ill-defined greenstones on the edge of the Yilgarn Craton. This is still at a very early grassroots exploration stage. A discovery by Tectonic Resources NL in mid-1997 of massive sulfide mineralization (Cu, Au, Pb, Zn and Ag) at Trilogy prospect, southeast of Ravensthorpe, but apparently in Kybulup Schist, part of the Neoproterozoic Mount Barren Group overlying the Yilgarn Craton, increases the mineral potential of that region.

In the Southern Cross Province, the potential of the Tampia Hill deposit, located 135 km southwest of Southern Cross, was advanced following settlement of protracted court action, reaching a compensation agreement with the private landowners, and subsequent further drilling by Nexus Minerals NL. RC drilling produced results including 27 m at 4.29 g/t Au from 45 m and 12 m at 25.30 g/t Au from 21 m, with mineralization in a zone of stacked, sheeted quartz veins. The successful drilling during mid-1997, following resolution of land access problems, is a reminder that the potential of the southwest Yilgarn is not yet being fully realised.

Any assessment of the gold potential in the southwest Yilgarn is dominated by the Saddleback Greenstone Belt, hosting the Boddington and Hedges mines. The Boddington partners have decided to proceed with a full feasibility study, after completing an 18 month prefeasibility study, on the Extended Basement Operation (previously referred to as Wandoo). Resources (all categories) at the Extended Basement Operation total 311 Mt at 0.87 g/t Au and 0.10% Cu, containing 8.7 million ounces of gold. The total, based on a cut-off grade of 0.36 g/t Au, includes 51 Mt in the measured category, 165 Mt indicated and 95 Mt inferred. The resources, beneath the existing oxide open pits, were calculated from 807 diamond drillholes and 535 percussion holes, totalling more than 200 km of drilling and costing $18 million. The prefeasibility study indicated capital costs of $260 million, including a processing plant with a capacity of 11 Mt of ore per annum. Metallurgical recoveries of 86% for gold and 75–80% for copper are expected. Initial production of 300 000 ounces of gold per annum is planned, with cash operating costs estimated at $350/ounce (after copper credits at $US1.00 per pound). A final decision on whether to proceed is expected by the end of 1997, with a view to commissioning the plant in mid-1999.

In the Murchison Province the Dalgaranga mine was commissioned by Equigold NL and Western Reefs Ltd in October 1996, with the first gold pour on 22 November 1996. The planned throughput was 1 Mtpa of ore to produce about 55 000 ounces of gold over a mine life of 4.5 years. Reconciliation at the end of 1996–97 indicates that only 80% of reserve model ounces were recovered, apparently because of the spotty nature and distribution of gold in the weathered zone. Elsewhere in the Murchison Province the planned development of the Cuddingwarra deposit near Cue, a joint venture between St Barbara Mines Ltd and Normandy Mining Ltd, has not proceeded because of contractual uncertainty between the joint venture partners. At the other Cuddingwarra deposit northwest of Cue, Hillcrest Resources NL has outlined a small resource estimated at 368 000 t at 2.55 g/t Au, for about 30 000 ounces of contained gold.

The Marymia Inlier continues to be a successful exploration area, with discovery of the Three Rivers and Trident prospects, as well as expansion of known resources at existing operations. Good drilling results from the Three Rivers gold prospect held by Troy Resources NL, located about 20 km east of Peak Hill, were released in early 1997. Results include 9 m at 24.1 g/t Au from 60 m, as well as broad lower grade intersections, e.g., 20 m at 2.35 g/t Au — both from the Hawkeye Prospect. Exploration activities intensified in mid-1997; drilling is indicating multiple lodes, with high-grade shoots and broad alteration envelopes.

Marymia mine had been scheduled to close in November 1996, with mill feed to be exhausted by June 1997, but Resolute Ltd and Titan Resources NL discovered mineralization at the Trident prospect. This discovery is significant not only because of its high grades but also because it is a blind deposit, with the mineralized greenstones concealed below a large mass of unmineralized granitoid thrust over greenstones. The greenstone rocks were detected by airborne and surface magnetic surveys. Drilling of magnetic anomalies in 1996 intersected zones of high-grade gold between 100 and 120 m below the surface; some of the better drill intercepts include 21 m at 25.4 g/t Au from a depth of 182 m, 16 m at 29.8 g/t Au from a depth of 194 m, and 24 m at 14.5 g/t Au from 164 m. A substantial resource is expected to be established at this prospect.

The potential of the Marymia Inlier, which was fully realised only eight years ago, can be gauged by comparing current production rates with known resources. Contained gold in resources of all classifications at mines and prospects within the Marymia Inlier is estimated at about 229 tonnes (as at early 1997), whereas production in 1996 totalled a little over 10 tonnes.

Exploration activity by Newcrest in the Telfer region, Paterson Orogen, slowed during 1996–97 because attention was focused on restoring profitability to the Telfer mine.

An area of active grassroots exploration in the past 12 months was the Granites–Tanami Complex, where successful discoveries in the Northern Territory are being repeated in similar settings on the Western Australian side of the border. Several thick intersections of moderate-grade mineralization at shallow depth are being made below a masking blanket of sand. Glengarry Resources NL and Tanami Gold NL have spent at least $3 million since 1995 exploring 22 exploration licences, covering 2740 km^2 straddling the WA–NT border. Eighteen of the exploration licences are in WA. An inferred resource of 1.7 Mt at 2.1 g/t Au, for 115 000 ounces of contained gold, has been defined at Kookaburra prospect. Other prospects have been established at Sandpiper, Balwina and Afghan. Three high-grade shoots have been identified at Sandpiper, with best intersections from RAB and RC drilling of 59 m at 5.49 g/t Au from 170 m, 15 m at 4.37 g/t Au from 120 m and 17 m at 7.7 g/t Au from 8 m.

Mount Olympus (or Dublin Hill) was one of the outstanding discoveries of 1996, with mineralization discovered 30 km southeast of Paraburdoo highlighting the gold potential in Palaeoproterozoic rocks of the Ashburton Basin. At Mount Olympus, an oxidized cap, containing some 170 000 ounces of gold in inferred and indicated resources, overlies sulfide mineralization. A number of broad, high-grade intersections, including 77 m at 5 g/t Au, have been obtained by RC drilling. Other intersections include 80 m at 5.1 g/t Au from surface and 59 m at 3.8 g/t Au from surface. Initial metallurgical tests indicate gold recoveries of 85–95%. The exploration program has accelerated in order to find more oxidized resources, e.g., the Zeus prospect, located 1 km from Mount Olympus, is being drilled. Mineralization is commonly associated with pyrite with or without sericite, and quartz veining may also be present. Preliminary metallurgical testing on the sulfide mineralization at Mount Olympus indicates a refractory problem. Drill results through the sulfide ore includes 22 m at 10.2 g/t Au from a depth of 203 m. Sipa Resources International NL is still assessing methods for the economic recovery of refractory gold at Mount Olympus.

At the Indee discovery, about 80 km southwest of Port Hedland, Resolute Resources Ltd has revealed a new area of potentially economic (albeit low-grade) gold mineralization in the north Pilbara. The occurrence is located 11 km east of Mallina homestead, where gold was first found in the Pilbara in 1888. In 1982 WMC carried out soil and rock analysis that revealed slightly anomalous gold values east of Mallina, but decided that the values were not sufficiently encouraging to warrant drilling, and the company surrendered its mining tenements. Recently, Resolute undertook further soil and rock analyses followed by shallow drilling. Initial drilling gave encouraging results with economic grades of gold between 5 and 20 m below the surface. Deeper diamond drilling is in progress and has confirmed two zones of gold mineralization in the Mallina Formation (Camel 1 and 2). At Indee, gold in veins is associated with the 60-km long Mallina Shear Zone, recognized by the Geological Survey in 1995–96, which has potential to host further gold deposits.

This discovery at Indee will attract further exploration to the Pilbara region, where there is still significant unrealised mineral potential. Already, Lynas Gold NL and Haoma Mining NL have been actively competing for tenements. Lynas Gold is expanding its exploration programme, whereas Haoma Mining is continuing research into its Elazac process for the economic extraction of gold.

Silver

Detailed appraisal of the Elizabeth Hill high-grade silver deposit, located 35 km south of Karratha in the Pilbara, continued with the sinking of an 85 m-deep shaft and a 20–40 m cross-cut. A 100 t parcel of ore was collected to enable a more accurate assessment of the grade of mineralization, the mining and engineering characteristics of the ore, crushing parameters, optimum grind size, structural controls to mineralization, and possible by-products such as palladium and rhodium. Elizabeth Hill has inferred resources containing 2.5 million ounces of silver.

The Nimbus silver deposit, northeast of Kalgoorlie, continues to show promise. It also has ore-grade zinc and lead intersections of up to 31.9% Zn and 7.4% Pb. Measured and indicated resources at Nimbus currently stand at 891 000 t at an average grade of 282 g/t Ag, for an estimated 251 t of contained silver.

Platinum

Interest in exploring for PGE is currently low, but was sufficient for Australian Platinum Mines NL (APM) to list on the ASX in September 1996 and raise $4.5 million. The main target for APM is a layered ultramafic complex at the Copper Hill platinum prospect in the Rudall River region (Paterson Orogen), which was previously explored by CRA Exploration, Power Reactor and Nuclear Fuel Corporation of Australia, and North Flinders Mines Ltd. Induced polarisation surveys have been conducted by APM and drilling is in progress.

Major metals

Iron ore

There is a very high level of interest in iron ore, with numerous projects at the feasibility study stage and with considerable public promotion of developments connected with downstream processing (magnetite processing, direct-reduced ironmaking, hot briquetted iron and steelmaking). The reported level of iron-ore exploration in Western Australia for 1996–97, as indicated by ABS figures, rose sharply to $25.5 million for the year — an increase of $11.8 million or 86% from the previous year. This sharp increase reinforces the Survey's view that the ABS figures for iron-ore exploration have been significantly under-estimated for the previous two years. Iron ore exploration is currently at historic record levels, only exceeded by the $36 million spent in 1991–92.

With the gradual depletion of reserves of low-phosphorus Brockman ores in the Hamersley Basin, major producers are increasingly being forced to evaluate resources hosted by either the Marra Mamba Iron Formation or Robe River Pisolite. Targeted mineralization hosted by the Brockman Iron Formation now tends to be smaller satellite orebodies, such as Orebody 18 (total mineable reserves of 116 Mt of ore) that is undergoing detailed mine engineering studies. Apart from existing mines, high-grade iron ore resources (measured plus indicated) hosted by the Brockman Iron Formation total only 542 Mt in 11 undeveloped deposits. Detailed reserve definition and development appraisals are being conducted on some of the large undeveloped deposits hosted by the Marra Mamba Iron Formation (Mining Area C, West Angelas, Rhodes Ridge, Hope Downs and Silvergrass) and Robe Pisolite (Yandicoogina). The Marra Mamba Iron Formation contains a total of 5141 Mt of measured and indicated high-grade iron-ore resources in 59 undeveloped deposits, of which 22 contain more than 100 Mt. Measured and indicated resources of high-grade, low-alumina ore hosted by Robe Pisolite total 2640 Mt, but these are restricted to the Marillana Creek–Yandicoogina area (central eastern Hamersley Basin) and all are either being mined or undergoing mine feasibility studies. Ore from the Marra Mamba Iron Formation is yet to gain widespread market acceptance as direct shipping ore, yet this is seen as the long-term base of the Western Australian iron ore industry.

Continued interest is being shown in magnetite-rich deposits within primary banded iron-formation of the western Yilgarn (Tallering Peak, Koolanooka and Mount Gibson) capable of yielding, through beneficiation, a very high-grade product suitable for the direct-reduction process. The integrated An Feng Kingstream Mid-west project advanced during the year, and the State Agreement was signed in March 1997. At planned production levels, seven years of resources have been established at Tallering Peak. The large low-grade resources (25% cut-off grade) at Koolanooka were found by An Feng Kingstream Steel Ltd not to be amenable to upgrading by conventional beneficiation techniques without extensive grinding. Attention has now been redirected to the more distant deposits of the same style at Weld Range.

Other major developments during the year included BHP's hot briquetted iron project at Port Hedland where there have been higher than expected costs and technological problems. In October 1996, BHP commissioned operations at the expanded Yandi mine, where production capacity has increased by 10 Mtpa to 25 Mtpa of ore.

In order to attract further investment in iron-ore processing, a number of royalty concessions are now available from the State Government and were included in the Mid West State Agreement: 0.5% royalty concession for new iron ore projects involving pellet production within Western Australia; a 1.0% royalty concession for DRI production; and a 2.0% royalty concession for steel production.

Alumina and bauxite

Alcoa of Australia Ltd has placed on hold its proposed $960 million expansion of bauxite mining operations and alumina refinery at Wagerup, despite completing a full feasibility study and environmental review. The plan was to lift production at the Wagerup refinery to 3.3 Mtpa of alumina. Currently, Alcoa's total capacity of 6.4 Mt of alumina (Kwinana 1.7 Mt, Pinjarra 3 Mt, Wagerup 1.7 Mt) is 15% of the international market. Alcoa is apparently waiting for forecast improvements in the alumina price; development lead time is estimated to be 20 months. Alcoa already has 1 Mt of spare alumina refinery capacity.

Alcoa has announced that its Jarrahdale bauxite mine will close at the end of 1998, with operations moving to Huntly, east of Pinjarra. A two-year feasibility study had found it uneconomical to continue at Jarrahdale (where the State's first bauxite mining had commenced in 1963) because of an inflexible crushing system and long haulage distance for the ore. The changeover will coincide with an $88 million upgrade of facilities at Huntly, where production will expand to about 18 Mt of ore per year, with 7 Mt of ore going to Kwinana and 11 Mt of ore to Pinjarra.

Worsley Alumina will soon make a decision on the planned $800 million expansion of its refinery. A precondition for the expansion was a site agreement with unions, which was signed in mid-1997, designed to limit industrial conflict during construction. The agreement is similar to that implemented during construction of the Boyne Island aluminium smelter in Queensland. The expansion would increase Worsley's annual capacity from 1.7 Mt of alumina to 3.1 Mt. A go-ahead decision might enable construction to start in late 1998, with commissioning of the plant in about the year 2000.

Copper–lead–zinc

In 1996–97, the combined exploration effort on base metals and nickel–cobalt was $88.1 million, a decrease of $0.9 million or 1% on the previous year, but only marginally below the record figure of $89 million set that year. However, it is estimated that the nickel–cobalt search made up the major proportion of this total. Interest in sediment-hosted base-metal deposits in areas outside the traditional areas of the Yilgarn and Pilbara cratons has increased, with some major companies taking up ground in the Halls Creek Orogen, Lennard Shelf, Paterson Orogen and eastern Hamersley Basin.

Exploration for base-metals has concentrated in the Pilbara and Kimberley regions. Announcements of good drill intersections have come from volcanogenic massive sulfide-type (VMS) projects that have been explored for several years at Panorama in the Pilbara and at Koongie Park in the east Kimberley. Development activity by Western Metals Ltd is continuing at Pillara Range in the west Kimberley, which includes several Mississippi Valley-type deposits.

Cadjebut mine was due to close in December 1996, but salvage operations continued during the year and are now expected to be completed in December 1997. Cadjebut is being replaced by a new Pb–Zn mine at Kapok, and the first ore was mined in January 1997. Kapok contains a resource of 4.1 Mt at 9.1% Zn and 7.1% Pb, providing an anticipated mine life of 7–8 years. Full production capacity is planned at 500 000 tpa of ore.

A feasibility study by Western Metals of mining at Blendevale continued during 1996–97, with a final decision reached in mid-1997 to proceed with mine development. Ore reserves are 15 Mt at 7.5% Zn and 2.4% Pb, to yield an estimated 250 000 t of Pb–Zn concentrates per year (170 000 t of zinc and 65 000 t lead in concentrates), compared with the 120 000 t per year derived from Cadjebut. Construction has begun and the mine is expected to be commissioned about June 1998.

Exxon Coal and Mineral Australia Ltd, a subsidiary of Esso Australia, announced in February 1997 that it would sell off its Australian mineral investments, in order to concentrate solely on its energy business. Exxon owns 35% of the Golden Grove project, 225 km east of Geraldton, which contains the Scuddles Zn–Cu mine and the new Gossan Hill copper deposit. A feasibility study is underway at Gossan Hill. The exploration decline was completed in early 1997, and bulk samples extracted for beneficiation testing.

Murchison United NL and Straits Resources Ltd are close to making a commitment to mine the large, low-grade Maroochydore copper deposit, 70 km south of Telfer, which ranks as Australia's biggest undeveloped copper resource. Using a 0.2% Cu cut-off, the inferred resources are 167 Mt at 0.53% Cu and 0.021% Co, containing 885 000 t of Cu and 37 000 t of Co. Preliminary metallurgical work suggests that about 75% of the ore is amenable to conventional acid leaching and solvent extraction–electrowinning (SX–EW), supplemented by bacterial oxidation of partially oxidized ore. Feasibility studies suggest the possibility of producing 50 000–60 000 t of copper per year at a cost of $US0.55 per pound, with initial capital costs of $150–200 million. A bankable feasibility study is expected in late 1997, and may lead to the development of a heap-leach mine with a capacity of 8 Mtpa.

A feasibility study of the Whim Creek–Mons Cupri copper project, located 100 km east of Karratha, has confirmed the economic viability of the project. With projected annual production of about 10 000 t of copper cathode, cash costs of production were estimated at $US0.60–0.62 per pound, including royalties, with total costs estimated at $US0.70–0.74 per pound. However, some analysts have predicted a bleak outlook for copper prices, with some estimates for the copper price over the next 12–18 months to fall as low as $US0.79 per pound. Hence the immediate future for copper mining at Whim Creek is uncertain. The project was sold to Straits Resources Ltd in mid-1997.

Mount Isa Mines Exploration Pty Ltd is spending about $1.2 million per year on the Ryansville base-metals project, including the Glenview prospect, which is located about 50 km northwest of Cue, on the north flank of Weld Range. Mineralization is within a broad zone of alteration superimposed on felsic volcanics. Base metal mineralization is zoned, from lead–zinc-rich at the top, grading to copper-rich mineralization at the base.

Ferro-alloying metals

Nickel and cobalt

The surge in exploration and evaluation continued unabated during 1996–97 in an effort to upgrade mostly long-known occurrences to mine status. Early development of projects with low to medium operating costs is critical, because development of the huge Ni–Co–Cu deposit at Voiseys Bay on the Labrador coast of Canada threatens to dominate new market supplies from its commencement, now estimated at early next century. Although the demand for stainless steel and primary nickel had been expected to grow strongly, this has not eventuated and the LME nickel price has been in a broad downward pattern since a peak in early 1995.

The most notable impact of the nickel search and evaluation in Western Australia is the emergence of lateritic nickel deposits as the front runners for the next phase of development. This owes a lot to the application and adaptation of high-pressure acid-leach process technology (in conjunction with SX–EW) and cheaper power from the Goldfields Gas Transmission Line. Lateritic nickel projects are potentially very cost competitive in comparison to sulfide operations.

Of the lateritic nickel deposits, Bulong is the most advanced, with phase one of construction of the mine beginning in April 1997 and commissioning expected to commence in April 1998. Initial production rates are forecast at 9000 tpa of nickel cathode and 700 t per annum cobalt metal, rising over the three-year period to 22 200 tpa of nickel cathode. Drilling continues in an effort to increase high-grade reserves for processing in the early years of operation. Peak ore grades of 1.9% Ni are to be mined in the first year, and grades of about 1.5% Ni are to be mined during the first four years. Total identified resources are estimated at 140 Mt at 1.0% Ni and 0.1% Co. Mineable reserves are adequate for an initial 26 year mine life, but known resources, if eventually upgraded to reserves, could expand mine life to around 40 years.

Considerable effort is being expended by Anaconda Nickel Ltd on the Murrin Murrin – Central Bore deposits, east of Leonora, to realize a large-scale development. When operational, Murrin Murrin would be the biggest nickel mine in Australia and fifth largest in the world. So far, about $160 million has been spent on exploration and project development, with total capital costs estimated at about $900 million. Identified resources total 125 Mt at 1.02% Ni and 0.06% Co. Estimated operating costs are $US0.61 per pound. Anticipated production rates are about 43 000 t of nickel metal and about 3000 t of cobalt metal per annum, with commissioning in mid- to late 1998. Site civil works commenced in mid-1997. Anaconda's portion of the project financing has been secured, and the joint venture arrangement with Glencore International was formalized in July 1997.

The Cawse lateritic nickel project, located at Siberia, 55 km northwest of Kalgoorlie, is advancing more slowly and a commitment to develop has not yet been made. Drilling has defined measured plus indicated resources of 53 Mt at 0.8% Ni and 0.05% Co, with a further 140 Mt of inferred resources. The Department of Minerals and Energy has given the go-ahead for commencement of construction, and Centaur Mining and Exploration Ltd is evaluating tender bids on major items and components of the project. Late in 1996, Centaur announced several process design improvements to the project proposal, including switching the power station to gas turbines, upgrading the pressure leach circuit, and incorporating additional processing steps to minimize magnesium contamination and optimize recovery of nickel and cobalt. Pilot-scale test-work to enhance the screening up-grade, ammonia leaching, and SX–EW sections, continued during the year. When Cawse is in production, the expected production rate will be 8000–10 000 tpa of nickel and up to 2000 tpa of cobalt, at cash costs estimated at $US0.60–0.65 per pound of nickel, after cobalt credits.

In addition to developing these major lateritic deposits, significant regional exploration is continuing throughout the known nickel provinces and elsewhere, particularly Siberia (Ora Banda greenstone belt), Pinnacles (Mulgabbie district), Eucalyptus and Yundamindra (Edjudina greenstone belt), Laverton Downs (Margaret greenstone belt), Waite Kauri and Mertondale (Murrin Murrin greenstone belt), Weld Range (Murchison Province), and Ravensthorpe. Comet Resources has unveiled plans for a potential $200 million development of the Ravensthorpe lateritic nickel project at Bandalup, which contains resources totalling 90 Mt at 1.2% Ni.

Exploration for nickel sulfide deposits was not completely overshadowed by exploration for lateritic nickel deposits. Production commenced in June 1997 at the small, but spectacularly high-grade, Silver Swan deposit, discovered 45 km northeast of Kalgoorlie in 1995 and containing identified mineral resources of 440 000 t at 14% Ni. The mine is forecast to produce 12 000 tpa of nickel in concentrate over five years. Other deposits adjacent to Silver Swan, e.g. Cygnet and White Swan, are under examination. Cygnet has the potential to add another 6000 t per year of nickel in concentrates, and is accessible from the same decline used for Silver Swan. Current indications are that the large, low-grade disseminated mineralization at Black Swan is not economic to develop. Black Swan was discovered by Australian Anglo American Ltd in 1970 and contains resources of 3.5 Mt at 0.85% Ni and 0.04% Cu.

Forrestania Gold NL (now part of Lionore Mining International Ltd) announced in early 1997 its decision to proceed with a prefeasibility study on the Maggie Hays sulfide nickel deposit. Recent resource definition drilling has enabled the estimated fully diluted resources to be upgraded to 17 Mt at 1.2% Ni at 0.4% Ni cut-off, representing 200 000 t of contained nickel. The study is intended to better define expected production rates. The prefeasibility study is expected to be completed in late 1997 and will also evaluate mineralization at the nearby Emily Ann prospect. Gencor Ltd can earn up to 50% of the Lake Johnston JV, which contains Maggie Hays, by contributing its bacterial leaching technology and spending $5 million on exploration. At Emily Ann prospect, 3 km north of the Maggie Hays nickel prospect, a second drillhole, 120 m north of the discovery hole, intersected high-grade nickel sulfides — 1.08 m at 9% Ni from a depth of 213 m, and 5.8 m at 6.3% Ni from a depth of 231.7 m. Two mineralized zones, separated by non-mineralized felsic volcanics, are evident: one mineralized zone is hosted by ultramafic rocks and contains disseminated sulfides; whereas the second zone contains remobilized massive sulfides hosted by felsic volcanic rocks. The prospect is shaping up as a major nickel find.

Two large, low-grade deposits in the North Eastern Goldfields — at Yakabindie and Honeymoon Well — continued to attract attention, with both at the prefeasibility or feasibility stage. Possible development of Yakabindie, one of the world's largest nickel sulfide deposits with total resources of 293 Mt at 0.525% Ni and reserves of 184 Mt at 0.52% Ni, received a boost with news in mid-1997 that the Korean industrial company Daewoo Corporation had taken a 10% stake in the project by contributing 10% of the capital and operating costs of development, as well as contributing a further $9 million toward development of stage one. The first stage, costing $40 million, is expected to produce about 3000 t of nickel metal per annum. Stage two development would cost $340 million, with construction of the main treatment facility capable of producing 13 300 t of nickel metal and 350 t of cobalt metal per annum. The third stage would lift output to 32 000 t of nickel metal and 900 t of cobalt metal per year.

Honeymoon Well, near Wiluna, is currently subject to a prefeasibility study but the deposit has excessive overburden, and the JV partners are seeking to improve viability. In September 1997, Rio Tinto Ltd sold its 65% interest in the JV to its partner, Outokumpu Mining Australia Pty Ltd. Feasibility studies are expected to continue for up to two years. If developed, Honeymoon Well would be of a similar size to WMC's Mount Keith nickel mine.

Exploration at several new massive sulfide deposits attracted attention during 1996 and 1997, particularly at Goodyear (Titan Resources NL), St Patricks and St Andrews prospects at Lake Goongarrie (WMC and Dalrymple Resources NL), Cosmos (Jubilee Gold Mines NL) and RAV8 (Tectonic Resources NL).

Titan Resources NL discovered high-grade massive sulfides (Kambalda style) at the Goodyear (Hampton East Location 45) prospect, 35 km southeast of Kalgoorlie. The discovery intercept was announced in early 1996 and consisted of 3 m of massive sulfides averaging 4.9% Ni from a depth of 296 m. A follow-up deep diamond hole in 1997, 600 m south of the initial intercept, yielded a zone of massive sulfides 3.8 m thick from a depth of 544.8 m and averaging 7.32% Ni. The project area is within the Carnilya Anticline, and the geological setting is similar to WMC's Carnilya Hill and Blair nickel mines.

Another discovery of nickel sulfides during the year was that by WMC and Dalrymple at the St Patricks and St Andrews prospects (Lake Goongarrie), 15 km north of the old Scotia mine. Initial diamond drilling of coincident EM and magnetic anomalies within ultramafic rocks has identified promising mineralization well above the basal contact. Best results include 2 m at 2.19% Ni from 68 m and 3.35 m at 3.34% Ni from 64 m.

In mid-1997, Jubilee Gold Mines NL announced very high-grade nickel intercepts at the Cosmos prospect, south of Mount Keith and north of Leinster. Surface indications of mineralization include coincident geochemical and electromagnetic anomalies, and outcrop of gossan. The first diamond drillhole intersected 9.15 m of massive and disseminated sulfide mineralization in ultramafic rocks, including 3.02 m at 7.54% Ni from a depth of 129.53 m. The second drillhole included a spectacular intersection — 22.3 m at 9.29% Ni from a depth of 122.2 m.

Other sulfide nickel occurrences targeted during the year included the Cullens prospect (60 km northwest of Menzies). A sulfide resource of 350 000 t at 0.9% Ni had been previously estimated for Cullens. Recent RC drilling by Mount Kersey Mining NL to test the basal ultramafic contact yielded best results of 30 m at 0.67% Ni from a depth of 74 m, and 28 m at 0.5% Ni from a depth of 140 m. Drilling 900 m north of Cullens prospect has intersected nickel sulfide mineralization, including 14 m at 0.6% Ni from a depth of 78 m, but apparently from above the basal contact, suggesting the potential for massive high-grade nickel at the basal contact.

Other targets include Irwin Hills (90 km southeast of Laverton), Kurnalpi, RAV8 (Ravensthorpe), and Radio Hill and Mount Sholl (west Pilbara). At RAV8, about 25 km east-southeast of Ravensthorpe, the resource previously defined by WMC and North consists of 110 000 t at 6.6% Ni. Tectonic Resources NL has undertaken further drilling and announced plans to begin mine development early in 1998. Nickel mining in the Pilbara also moved a step closer after metallurgical testing showed that the sulfide ore at Radio Hill was amenable to biological oxidation. Titan Resources NL recently purchased the deposit and plan to start mining operations as soon as possible, handling 200 000 t of ore per year and producing a Ni–Cu–Co concentrate.

Chromium

The Coobina chromite deposit, managed by Valiant Consolidated Ltd and located 57 km east-southeast of Newman, contains Australia's only source of hard, lumpy chromite ore. Danelagh Resources Pty Ltd, with an option to acquire 70% of the project, shipped 6000 t of chromite ore in early 1996 to a Chinese ferro-alloy plant for assessment. The first commercial shipment was in early 1997 and consisted of 20 000 t of chromite ore, again destined for the Chinese market.

Manganese

Woodie Woodie deposit was purchased by Valiant Consolidated from Portman Mining during 1996, and Stage 1 development of the Big Mack pit commenced in September 1996. The preliminary measured resources at Woodie Woodie were 1.2 Mt at 39% Mn, 2.8% Fe, 19.7% SiO_2 and 1% Al_2O_3. During 1996–97, Valiant Consolidated extended the gravity surveys in the area and drilled gravity anomalies, but the company reported a loss of $13.6 million for the year to 31 December 1996 as a result of manganese ore prices falling 30% during 1996. Road haulage costs of the ore from Woodie Woodie to Port Hedland represent 40% of total operating costs, and the announced $45 million major upgrade of the Ripon Hills road in late 1997 is expected to significantly reduce haulage costs. Major disruptions to exploration, production, and road haulage occurred during early 1997 after the heaviest rains on record in the east Pilbara. Efforts to keep the mine operating failed, and in October 1997 Valiant went into voluntary administration and suspended all mining operations.

A possible breakthrough in the treatment of manganese ore from the Ant Hill deposit (previously known as Balfour Downs), 150 km east of Mount Newman, was made during the year. Ant Hill contains low-grade and ferruginous manganese ore, with indicated resources estimated of 1.42 Mt at 25% Mn, which is not suitable for direct shipping ore for ferro-alloy production. Metallurgical testing and a preliminary scoping study during 1996–97 indicated that the ore is amenable to leaching to produce manganese sulfate, and a small-scale leaching plant in Port Hedland is proposed. Manganese sulfate is used as a fertilizer and stock feed, as well as a base to produce electrolytic-grade manganese dioxide. A feasibility study, expected to be completed by the end of 1997, is examining the option to mine 20 000 tpa, with some supergene gold as a by-product. With manganese sulfate selling for about $450/t, gross sales revenue would potentially be $9 million per year.

Tantalum

In 1996–97, Gwalia Consolidated produced a record 671 122 pounds of tantalite concentrates from its mines at Wodgina (Pilbara) and Greenbushes (southwest Yilgarn). Gwalia Consolidated remains the world's largest producer of tantalite concentrates, and all production for the next five years is sold under long-term contracts. An attempt to produce a saleable mica product by dry separation techniques, from its tantalum processing plant at Greenbushes, has apparently failed.

Vanadium

Renewed interest was shown in the vanadium-bearing magnetite deposits at Wagoo Hills (Windimurra project), 75 km east-southeast of Mount Magnet, in what is reported by Precious Metals Australia Ltd to be the largest undeveloped vanadium deposit in the world. Indicated resources of oxide material are 44 Mt at 0.56% V_2O_5, with inferred resources of unoxidized material at 60 Mt at 0.56% V_2O_5. Following the recovery in vanadium prices, a 1992 feasibility study is being updated, incorporating advances in magnetic-separation techniques and the availability of cheap clean fuel (gas) that in the roasting process produces a vanadium pentoxide product with fewer contaminants. An updated reserve model and mine plan are being prepared, and a bankable feasibility study is expected to be completed in late 1997. The current proposal is to develop a mine and processing plant to produce 15.8 million pounds of V_2O_5 per annum, over a mine life of 30 years. The $80 million project could reach production in 1999. Windimurra will need to be a low-cost producer to succeed because, notwithstanding the current strong market for vanadium and the good outlook for vanadium demand growth, Windimurra's initial production will be more than 10% of world production and it will need to displace other producers. Developments at Windimurra should encourage further exploration and a reassessment of other vanadium deposits in the Yilgarn and Pilbara.

Heavy-mineral sands

Western Australia remains the major focus of exploration expenditure in Australia for heavy-mineral sands, with $7.9 million spent in Western Australia during 1996–97. This represents 57% of the Australian total. Exploration expenditure for heavy-mineral sands in both Western Australia and Australia has doubled in the last two years, and expenditure in Western Australia is now at a level equal to the previous record expenditures in 1988–89 and 1990–91.

Exploration for heavy-mineral sands has a low public profile, and competing land-use is a major obstruction to additional exploration and further developments. However, since 1992, exploration activities and gaining access to land have been successful in retaining the State's resource inventory of more than 100 Mt of contained heavy minerals.

The relatively buoyant market, with high prices for most of the mineral-sands products, especially zircon, and the need to replace operations with depleted reserves, have led to a number of new developments proceeding, particularly Beenup, where BHP owns one of the largest economic titanium mineral resources in the world suitable for treatment by the chloride process. Beenup will consolidate Australia's position as a major international supplier of titanium minerals.

The Beenup heavy-mineral sands deposit, located 17 km northeast of Augusta, was discovered in 1987, but a slump in world titanium mineral markets delayed commencement of the project until December 1994, despite the project receiving environmental approval in 1991. Site works began in late 1994 and plant construction followed in 1995 and 1996. Production began in late 1996 and the first shipments of concentrate in early 1997. In full production, Beenup is expected to produce 600 000 t of ilmenite and 20 000–30 000 t of zircon each year. BHP Titanium Minerals Pty Ltd is also in joint venture with Tinfos Titan and Iron K/S in a titanium smelter operation at Tyssedale, Norway. Most of the ilmenite is exported directly, rather than being upgraded into synthetic rutile, because of the intensive energy requirement for processing into high-quality titanium dioxide pigment feedstock.

Developments near Capel include the Maidment and Higgins deposits. RGC's Maidment mine came on stream during the year and is to be the main source of ore as nearby reserves are depleted. Plans are in progress to re-open the original Yoganup mine and develop two new operations farther to the north, near Roelands and Yarloop.

Westralian Sands Ltd is constructing a second, stand-alone, plant at North Capel, which should lift annual production of synthetic rutile from 122 000 t (in 1996) to a total of 230 000 tpa. The first plant was built in 1986 and had a design output capacity of 100 000 tpa of synthetic rutile. Westralian Sands decided in March 1995, after improvement in the international markets for titanium mineral products following the depressed prices in 1991–1993, to expand production of synthetic rutile, and commissioning of the new $135 million plant is expected in late 1997. Westralian Sands is also undertaking research and development studies into converting iron oxide waste from the synthetic rutile plant into marketable pig iron.

Losses during 1996 for Ticor Ltd, the parent company to Tiwest that runs the Cooljarloo heavy-mineral sands mine and a pigment plant at Kwinana, have caused a delay in the planned $160 million expansion of the Kwinana plant, but detailed engineering studies on the expansion are continuing.

Diamonds

Expenditure on diamond exploration in 1996–97 totalled $38.6 million, an increase of $4.9 million or 14.5% from 1995–96. The increase mostly represents a greater appreciation of the diamond potential of the Yilgarn Craton, with keen activity by numerous companies, both large and small, and the emergence of the Leonora–Menzies region as a potentially new kimberlite province. Although interest by investors in the diamond sector is still very weak, and has been so for several years, there was sufficient interest for a successful float of Western Diamond Corporation NL. Another feature for the year has been the very large number of joint ventures, with diamond explorers farming into ground currently being explored for other minerals.

The lack of significant kimberlite discoveries to date in the Yilgarn Craton is now being regarded by many companies as an exploration problem, rather than a geological problem. Exploration for diamonds in the Yilgarn is technically difficult for several reasons.

- Kimberlitic rocks in the craton are generally deeply weathered and partly leached, making petrographic classification difficult.
- Some of the kimberlitic rocks have unusual features and are difficult to categorize.
- Poor drainage over many parts of the craton means that heavy-mineral sampling of drainages is not the optimum method, even though it may be the preferred method of reconnaissance exploration for many companies.
- Extensive lateritization produces noisy background in the shallow wavelength magnetic data, which can easily mask the expected responses of some kimberlites, hence problems also exist for remote sensing exploration techniques.

The need to develop more effective diamond exploration techniques for this deeply weathered terrain is leading to fresh research and development.

Industry speculation suggests that Stockdale Prospecting Ltd has made a significant discovery in the Yilgarn in the vicinity of Lake Ballard, near Menzies, but no details are available. Stockdale has struck deals with several gold tenement holders in the Leonora to Menzies region to explore exclusively for diamonds. Other companies active in the area include Astro Mining NL, Western Diamond Corporation NL and Diamond Ventures NL. Western Diamond Corporation NL, after acquiring tenements from Kalgoorlie prospector Mr Mel Della-Costa, floated on the ASX in February 1997 and raised $4 million. The focus of attention for Western Diamonds was initially the Sturt Meadows prospect, 60 km west of Leonora, where previous work by Stockdale Prospecting Ltd between 1991 and 1995 had recovered two diamonds and numerous kimberlite indicators. Stockdale had conducted three drilling programs, recovering the two diamonds from one hole near Turkey Well. Following bulk sampling by Western Diamonds in early 1997, Turkey Well was confirmed as a kimberlite. The company has also located chromite source rocks, believed to be kimberlite, at its Perrinvale project, northwest of Menzies.

In the Sandstone area, Astro Mining NL located 49 anomalies in their magnetic data, from a survey of 9400 line km. RC drilling by Astro Mining of anomalies in the Merredin area has commenced, intersecting possible alkaline syenite in one of the anomalies. A low-level airborne magnetic survey, covering 170 km^2 at Kununoppin, 50 km northwest of Merredin, generated 17 magnetic anomalies considered to be highly prospective.

Elsewhere in the Yilgarn, Astro Mining continues to explore within the Narryer Gneiss Complex, locating alkaline mafic to ultramafic rocks with lamproitic affinities in the Mount Gould area.

Stockdale views the Yilgarn Craton southern extension as prospective, following identification of 25 high-priority magnetic anomalies in Pan Australian Resources NL's airborne magnetic data. Stockdale is earning a 60% interest in any diamond discovery within wholly-owned tenements of Pan Australian by spending $2 million within three years. Helicopter-borne magnetic surveys and ground sampling commenced in late January 1997.

In the Kimberley, exploration success continues at the Beta Creek project, and this project shows commercial promise. During 1996 and 1997, Striker Resources NL delineated the diamond-bearing Ashmore 1 and 2 pipes and discovered the diamond-bearing Ashmore 3 pipe (with magnetic and EM data strongly suggesting an additional pipe nearby). Striker Resources has commenced an evaluation program involving a 5 t/hour heavy-media separation plant and results to date indicate the likelihood of economic grades being obtained, with Ashmore 1 and 2 containing the tonnage potential to support a five-year mine life. The average grade for all drillholes in Ashmore 2 is 215 ct/100t. The largest diamond recovered so far weighs 2.4 carats, and numerous stones are of high quality. A mining and exploration agreement has been signed with the Balanggarra native title claimants, and covers an area of 27 000 km^2.

An important geological feature of Beta Creek, applicable to broader exploration in the Kimberley, is that the kimberlitic indicator minerals and niobium in soils exhibit very little dispersion away from each Ashmore pipe. Available data suggest that the Ashmore pipes tend to be Group-2 kimberlites, and are interpreted to be much younger than the nearby Lower Bulgurri and Seppelt kimberlites.

Exploration continues at other prospects in the Kimberley, with further encouraging results from Blina prospect and Mad Gap Yard, the latter 70 km northeast of Halls Creek. Diamonds continue to be recovered from bulk samples of the Blina palaeochannel in the west Kimberley, and the likelihood of a commercially viable deposit of alluvial diamonds improved during 1996–97. Kimberley Diamond Corporation NL recovered 61 diamonds totalling 12.45 carats from the palaeogravels at the Blina prospect, with the largest three stones weighing 3.34, 2.31 and 1.44 carats. About 20 Mm^3 of palaeogravels exist at Blina, and current attempts are directed at isolating areas of more than 1 ct/100t, as well as trying to locate the source rocks. The search has narrowed down to an area of radius 5 km.

The current ore reserves at Argyle, Australia's only diamond mine, are expected to last to about 2003. However, the mine life could be extended with positive results from a multimillion dollar study into underground mining and expanded open-cut mining at Argyle that was completed in early 1997. Ashton Mining Ltd announced in mid-1997 that underground mining may be postponed in favour of deepening the existing open-pit operation. That option is regarded as more cost effective and could be funded from operating cashflow, whereas underground mining would require fresh capital, an option the joint venture partner Rio Tinto is apparently unwilling or reluctant to take. A decision on the style of expansion is expected in late 1997. Production for calendar 1997 is expected to be about 36 million carats, a decrease from the 42 million carats produced in 1996. Production during the first half of 1997 was lower because of heavy rain in the Kimberley, and a decision to produce larger stones, leaving a large volume of smaller, low-grade and low-value stones in the waste, in order to improve project economics in this the world's largest diamond mine (by production).

Four lamproite pipes, discovered at Ellendale (E04/813) in late 1996 by Auridiam Consolidated NL and Diamond Ventures NL, were confirmed by drilling. The four new lamproite pipes are all small, 1–4 ha in surface area, and were found using high-resolution, airborne magnetic surveys.

Stockdale remains active in the Kimberley region, having joint ventures with Burdekin Resources NL and with Precious Metals of Australia Ltd to explore for diamonds near Palm Springs.

Kimberlite Resources International NL, a public unlisted company, has pegged tenements north and northeast of the Aries pipe in the Phillips Range kimberlite province, with the tenements along three structural corridors perceived to host kimberlite pipes.

Diamond exploration continued in the Pilbara, with Stockdale Prospecting Ltd farming into five tenements held by Haoma Mining NL, and into tenements (totalling 1415 km^2) in the west Pilbara held by Dragon Mining NL.

At the Ullawarra prospect within the Bangemall Basin, Astro Mining NL and Diamin Resources NL have located several possible kimberlite pipe structures not found previously by Stockdale, and these will be drilled during 1997–98.

Cambridge Gulf Exploration NL acknowledged its past mistakes in attempting to explore offshore using the inadequately equipped and unsuitable marine vessels *Lady S* and *Java Constructor*, but was confident that the company-owned *Gulf Explorer* was technically suited to the task, including the capacity to drill 1.5m diameter holes for bulk sampling. Another vessel commenced trial drilling in lease areas offshore from the Ord River in November 1996; however, by May 1997, Cambridge Gulf announced that its diamond exploration equipment, including the barge *Gulf Explorer*, was for sale, and that Cambridge Gulf was seeking a joint venture partner to continue the exploration program. Before ceasing drilling, Cambridge Gulf had drilled seven holes, rather than the 30 holes apparently required under a settlement contract from earlier litigation with Australian Kimberley Diamond (AKD), on their adjoining tenements. Three of the holes were within AKD's interpreted prospective palaeoshoreline apron, with a surface extent of 9 x 1 km and thickness of up to 20 m, apparently confirming the model, but further work is necessary to locate sites most favourable for deposition of diamonds.

Energy minerals

Coal

Coal production in the State is centred on the Collie Basin, 200 km south of Perth, and during 1996–97, 5.6 Mt was produced. Coal is used locally for electricity generation and metallurgical purposes in the mineral sands and alumina industries. The transition from underground and small-scale openpit mining to large-scale openpit mining, along with minimization of overheads, over the past three years, is beginning show dividends, with costs decreasing and more competition between the only two operators in the State. Wesfarmers Coal Ltd beat Griffin Coal Mining Co. Pty Ltd to supply 1.2 Mt per annum from July 1999 to Western Power's new, 300 megawatt power station due for completion at the end of 1998. Although this was a setback for Griffin, that company is gearing up to supply coal for the predicted expansion in mineral-sand and alumina operations.

Uranium

A Commonwealth Government policy change during early 1996, effectively abandoning the 'three mines policy', has enabled other uranium projects to be considered for development. In addition, during May 1997, the Senate Select Committee on Uranium Mining and Milling supported the principal findings of the 1977 Fox Inquiry that there should be no unreasonable impediment to developing Australia's uranium mining industry. Consistent with this was the Commonwealth's environmental approval for mining at Jabiluka (Northern Territory), owned by Energy Resources of Australia Ltd.

Although the 1996 demand for uranium far exceeded production, leading to early forecasts by ABARE of steadily rising prices, and to media speculation about the industry in general, spot prices for uranium declined sharply during 1996–97 from $US16 per pound to about $US10 per pound. As a result, there are few signs at present of renewed exploration for uranium in Western Australia, and uranium exploration expenditure remains at historically low levels of $2–3 million per year, the lowest level for at least twenty years. There is interest in the uranium exploration sector, however, which is yet to be shown in official estimates of current exploration expenditure. Acclaim Uranium NL, a subsidiary of Acclaim Exploration NL, registered a prospectus with the Australian Securities Commission in August 1997. This is the first uranium float for many years and is an attempt to raise $5 million for exploration, much of which would be spent on Acclaim's numerous uranium prospects in Western Australia.

The large Kintyre deposit in the Rudall River area is an advanced prospect which could be considered for development in the short term. However, although exploration continues, a decision by Rio Tinto on whether to develop has been put on hold until the uranium market improves. A go-ahead by WMC for the deposit at Yeelirrie, 110 km northwest of Leinster, is unlikely following WMC's commitment to the expansion of Olympic Dam in South Australia. A merger of the uranium interests of Uranium Australia NL (formerly Noble Resources NL) and Paladin Resources NL is likely to lead to further exploration, particularly at the Paterson project (north-northeast of Kintyre) and the Ponton prospect (east-northeast of Kalgoorlie). There was minimal exploration activity at other prospects, e.g., Manyingee, Onslow and Lake Maitland.

Industrial materials

Attapulgite

Attapulgite (or palygorskite) is mined by Hudson Resources Ltd (formerly Mallina Holdings Ltd) at Lake Nerramyne, approximately 165 km northeast of Geraldton. The deposit contains measured and indicated resources of 4 Mt, in addition to an inferred resource of 100 Mt. Although the material at present is mainly sold for domestic and overseas pet-litter markets, to use this vast resource in a more productive manner, the company is carrying out more research on the suitability of the material for other applications.

Dimension stone

Although the dimension stone industry in the State has not shown strong growth during the last few years, during 1997 a number of producers appear to be showing signs of recovery. For example Fraser Range Granite NL, which produces a range of products such as 'Verde Austral', 'Gold Leaf Black', and 'Garnet Ice', shows signs of improving production in a significant way with new technological developments in mining. 'Verde Austral' has been specified by the Sydney City Council as one of the materials to be used in the upgrading of public areas, such as sidewalks, as Sydney prepares for the Olympic Games in the year 2000.

Feldspar

Total production of feldspar in the State during 1996–97 was 63 066 t, all of which is currently exported to Asia. Most of the output, 57 808 t, was by Commercial Minerals Ltd from a deposit at Pippingarra, 30 km southeast of Port Hedland. Imdex Ltd produced the remainder from a new deposit at Calcaling, located approximately 20 km northeast of Mukinbudin. In recent years Commercial Minerals has carried out exploration activities in the Londonderry area and Imdex Minerals in the Mukinbudin area to identify more feldspar deposits.

Gypsum

In June 1997, Dampier Salt Pty Ltd officially opened a gypsum operation at Lake MacLeod, 70 kilometres north of Carnarvon. The company has delineated a measured resource of 25 Mt of gypsum of uniform particle size and chemical quality by drilling and sampling at Lake MacLeod. According to Dampier Salt, gypsum of similar quality extends over 150 km^2 of the lake complex, and an inferred resource of 280 Mt has been estimated. In 1995 the company signed a long term contract with Yoshino Corporation, the major wallboard producer in Japan, for a significant proportion of the project's initial output, and a further contract was signed covering supply to the cement industry in Japan. The first shipment to Yoshino is scheduled for the latter part of 1997. With the commissioning of this operation the State re-emerges as an exporter after a lapse of about 10 years. The rise in gypsum production, to about 1.76 Mtpa when Lake MacLeod Gypsum is in full production, should lift Australia to about the world's twelfth largest producer.

Kaolin

CRA Exploration Pty Ltd (now Rio Tinto) has discovered a large deposit of kaolin at Kerrigan (350 km east of Perth) probably suitable for paper coating and fillers. Although CRA's aim was to spend up to $70 million developing a mine and processing plant to produce up to 500 000 t per annum of kaolin, development of the deposit will probably be determined by a more global view from Rio Tinto in London. Another constraint on the future of these deposits will be international competition from newly discovered kaolin deposits in Brazil.

Limestone

Cockburn Cement Ltd has installed an additional (sixth) kiln to its existing facilities at Kwinana, increasing production of lime by 400 000 tpa. Production from all six kilns at present amounts to 1.4 Mt of cement clinker and lime. Cockburn Cement also has plans for a 100 000 tpa facility at Dongara, with production likely to begin in April–May 1998. Westlime

(WA) Ltd has plans to produce 120 000 tpa of lime, with the commissioning of a plant at Dongara scheduled toward the end of 1997. David Mitchell Ltd plans to expand its Loongana lime operation with a new operation at Rawlinna to supply the growing lime markets of the Eastern Goldfields region. The company intends to add a new large capacity kiln to the existing facility in Kalgoorlie. The reported production of limestone in the State during 1996–97 was 2.4 Mt and most of this is material suitable for manufacture of cement and metallurgical grade lime.

Lithium

The lithium carbonate industry worldwide changed in late 1996 following the commencement in Chile of the first commercial-scale crystallization of lithium carbonate from brines. Its plant capacity is 40 million pounds per annum of lithium carbonate, and output is expected to undercut the two main producers of lithium carbonate on the world market by $US0.90 per pound. The impact on the world lithium carbonate market was felt during 1996–97 by Gwalia Consolidated Ltd, which was forced to place its Greenbushes lithium carbonate plant on care and maintenance.

Meanwhile, the lithium minerals (spodumene) business is on-going, continuing to produce at budgeted levels. Lithium minerals (spodumene) Production for 1996–97 was 114 934 t, exceeding the 1995–96 production of 92 462 t.

Pigments

Imdex Ltd is currently mining micaceous iron oxide (MIO) at Mount Gould, about 400 km northeast of Geraldton. The current mining is from the G6 MIO lens, which has indicated and inferred resources of 117 000 t. After preliminary crushing on site, the silver-grey ore is trucked to the company's Perth facility for specialized milling to customer specifications. Tests on the Mount Gould ore indicate it is >90% Fe_2O_3, with a natural plate length of about 70 µm and thickness of around 5 µm, making it at least equal to world standard material from Austria. MIO is used as a pigment in anti-corrosive paints used for coating steel structures such as large bridges, industrial plants and offshore oil rigs.

Salt

Akzo Nobel NV of the Netherlands, including its controlled subsidiary Onslow Salt Pty Ltd, is establishing a low-cost, sea-salt processing operation on the Exmouth Gulf coast at Onslow. Production, initially designed to be 2.5 Mtpa, is aimed at the growing chlor-alkali markets in the region. Akzo Nobel is undertaking a feasibility study of the operation, which, with a final theoretical capacity of 6 Mtpa, would be one of the largest sea-salt operations in the world. Construction of the first salt ponds and levee banks commenced in June 1997, and the whole project is scheduled for completion by the end of 1999. The State already produces more than 90% of the national production and that in 1996–97 was 7.5 Mt.

Silica

Kemerton Silica Sand Pty Ltd commenced mining and processing of silica sand at its Kemerton site, 12 km southwest of Harvey, in April 1996. Mining is from resources expected to last 10 to 15 years. Plans to expand the operation have been released under provisions of the Environmental Protection Act 1986 for public scrutiny and comment. In late 1995, TT Sand, a joint venture between Tomen Australia Ltd and Tochu Ltd, commenced production of silica sand from a deposit at Mindijup, located 40 km northeast of Albany. Production continued in 1996–97, with an output of 73 889 t. The deposit is estimated to contain 20 Mt of silica sand. The production of silica sand in the State during 1996–97 was 700 204 t. Operations continue at Jandakot, producing high-grade silica sand for both the domestic and international markets.

Talc

In 1996, Gwalia sold 50% of its holdings of the Mount Seabrook deposit to Industrial Mineraria Italiana Fabi Sri, which increased the output of talc from the deposit from 4556 t (in 1995–96) to 16 174 t in 1996–97. The production of talc in the State shows a progressive increase from 112 724 t in 1994–95 to 177 540 t in 1996–97. The Three Springs deposit, owned by WMC, is the major producer and produced 161 366 t in 1996–97.

Other

Another development in the industrial minerals sector is that the $50 million gallium extraction plant at Pinjarra, owned by Rhône Poulenc, ceased production from July 1997 despite the fact that it was only commissioned a year ago. The decision to place the gallium plant on a care-and-maintenance basis is because of the dumping of 50 t of gallium metal on the world market by Russia. Once that world surplus has been absorbed the gallium plant is likely to be reactivated by Rhône Poulenc.

Other industrial mineral deposits continue to be evaluated. These include diatomite deposits in the North Perth Basin, a graphite deposit at Munglinup River (70 km east of Ravensthorpe), a fluorspar deposit at Speewah (Kimberley region), saponite or bentonite deposits at Watheroo (40 km north of Moora), and phosphate and rare earth deposits at Mount Weld (250 km northeast of Kalgoorlie).

Discussion

Despite the boom in mineral exploration in Western Australia, problems of land access, and the perceived uncertainty of security of tenure in respect to native title throughout Australia, continue to be put forward as reasons restricting exploration and for an increased proportion of exploration budgets of Australian-based companies being directed overseas. But does uncertainty surrounding the Wik High Court decision on Native Title really deter potential investors?

The following table clearly shows that the number of Prospecting and Exploration Licences and the area held under tenure under the 1978 Mining Act have increased during the last three years, but that the growth rate between 1995–96 and 1996–97 is definitely slowing (Table 3). This contrasts with the surge in exploration expenditure in Western Australia during 1996–97, which increased by 33% over one year. The only slight increase in the number of exploration tenements and area held under tenure is consistent with there being little ground considered prospective that is available for pegging. The large number of diamond joint ventures entered into during the year supports that view.

For mining leases under the 1978 Mining Act, the distinct trend is for fewer tenements, but about the same area under tenure. However, the number of mining leases under application as at 30 June 1997, has increased by 69% between 1995–96 and 1996–97. These statistics certainly add weight to the argument that Australia might have experienced a greater exploration boom or seen more development as a result of the exploration boom if the native title uncertainty were not present.

A related aspect is whether, during this current exploration boom, there has been increased exploration effort on ‘brownfield’ sites, i.e., essentially

Table 3. Western Australian mineral tenements in force as at 30 June 1997

	1994–95		*1995–96*		*1996–97*	
	No.	*Area (ha)*	*No.*	*Area (ha)*	*No.*	*Area (ha)*
Tenements in force as at 30 June 1997 (1978 Mining Act)						
Prospecting Licence	7 991	1 109 662	8 111	1 098 339	8 212	1 099 671
Exploration Licence	3 950	34 943 253	4 417	37 845 997	4 718	38 279 436
Mining Lease and others	6 934	2 008 018	7 373	2 134 622	6 717	2 135 806
Tenements in force as at 30 June 1997 (1904 Mining Act)						
Mineral Claims and others	325	34 123	320	34 090	310	34 133
Tenement applications yet to be granted as at 30 June 1997						
Prospecting Licence	–	–	–	–	985	–
Exploration Licence	–	–	–	–	2 060	–
Mining Lease	1 785	–	1 871	–	3 167	–
Others	–	–	–	–	357	–

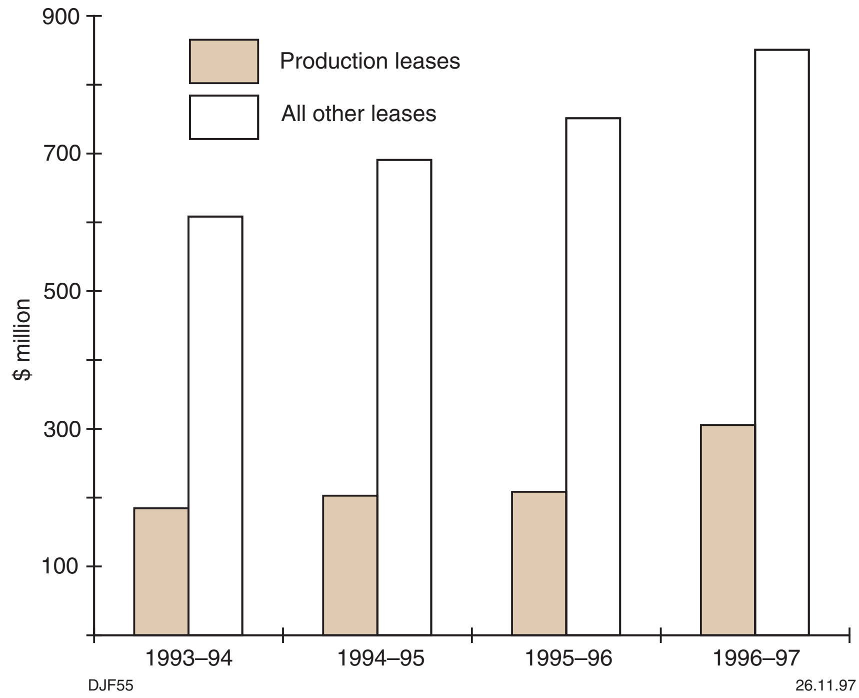


Figure 4. ***Australian mineral exploration expenditure (excluding petroleum), by lease type (dollars of the day, original figures)***

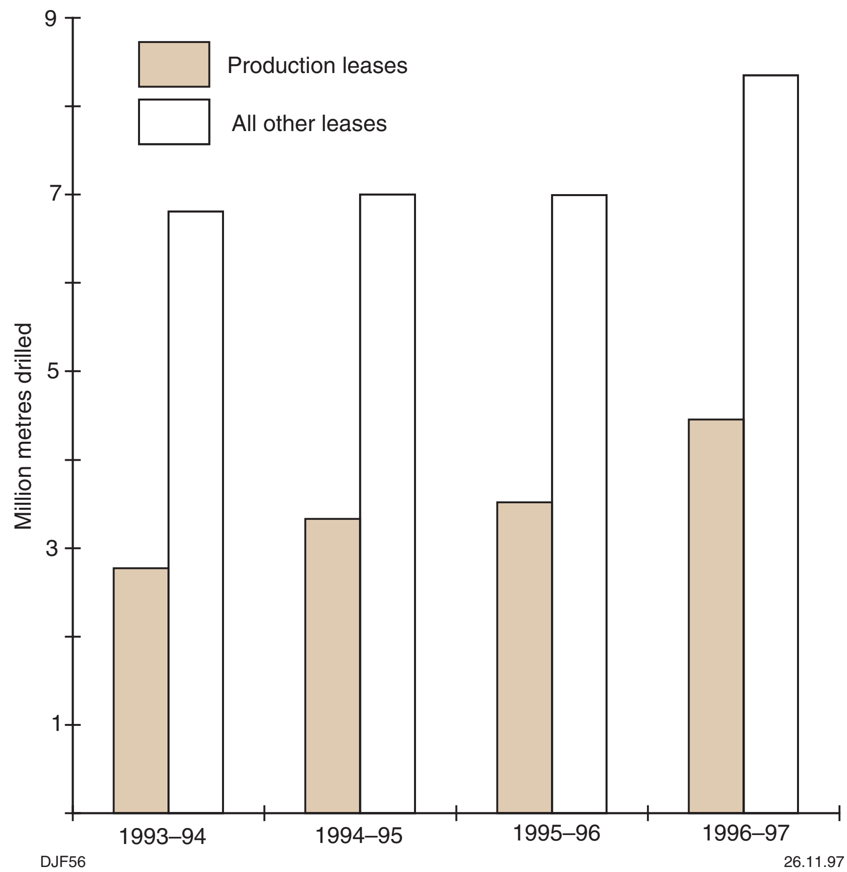


Figure 5. ***Australian mineral exploration drilling (excluding petroleum), by lease type (million metres drilled)***

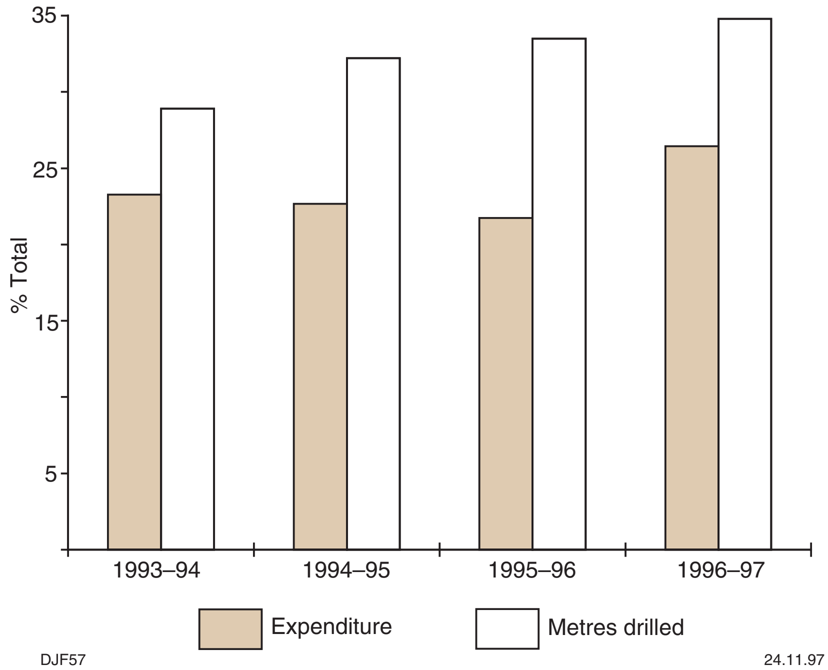


Figure 6. Australian mineral exploration expenditure and metres drilled (excluding petroleum) on production leases as a percentage of all leases

on mining leases at and immediately around existing mines, rather than on exploration or prospecting tenements ('greenfield' sites). The following comments are based on Australia-wide statistics, sourced from the Australian Bureau of Statistics, as detailed data for Western Australia are not available. Note, however, that Western Australia has attracted 50–60% of all Australian exploration expenditure during the last decade, so the Australia-wide statistics should give a good guide to the trends in Western Australia.

Figure 4 shows a steadily rising trend since 1993–94 of exploration expenditure (excluding petroleum) on exploration tenements throughout Australia, whereas exploration expenditure (excluding petroleum) on production tenements has risen significantly only over the last year. Also note that in Western Australia at least, there were fewer mining leases in existence at 30 June 1997, hence the increased expenditure is being spent on fewer production tenements. For metres drilled (excluding petroleum drilling), rather than exploration expenditure, the situation is similar but subtly different (Fig. 5). Metres drilled on production tenements have been increasing steadily over at least the last four years, whereas drilling on exploration tenements has increased sharply during the last year only. The proportion of Australia-wide exploration drilling (excluding petroleum drilling) that has taken place on production tenements has been steadily rising for at least the last four years — from about 28% of the total in 1993–94 to 35% in 1996–97 (Fig. 6).

Another measure of whether during this current exploration boom there has been increased exploration effort on 'brownfield' sites is to examine trends in the type of drilling (Table 1). This uses the simple premise that most RAB drilling is during grassroots exploration, most RC drilling is anomaly evaluation, and most diamond drilling is for advanced evaluation and development. Exploration drilling activity in Western Australia (Table 1) clearly shows a very large increase (47%) in diamond drilling during 1996–97, which exceeds the large increase (20%) also recorded for RAB drilling. Note that data in Table 1 is extracted from the Department's WAMEX database and relates to mineral exploration reports received by the

Department during the period, but may refer to work carried out up to one year earlier.

These statistics support the anecdotal evidence and argument that there has been greater focus on ‘brownfields’ exploration, but whether this is because of greater perceived geological prospectivity, Native Title uncertainty and delays, or other factors, are still points for further discussion.

Inside the GSWA

Steve Sheppard

Steve was approached to work for the Survey late in 1993 at a time when we were urgently looking for suitably qualified geologists to fill positions created by the New Initiatives mapping program. As he was working as an exploration geologist with Placer at the Granny Smith mine in the northern Eastern Goldfields, he might have expected to work with the team set up to map that area. However, he was hijacked by the Kimberley mapping team and was given the task of completing the mapping of felsic igneous rocks of the King Leopold and Halls Creek Orogens, which had been ongoing since the mid-1980s.

Steve was an undergraduate at ANU, completing his Honours thesis on Palaeozoic gold mineralization in the Lachlan Fold Belt. After a brief period as an exploration geologist in the Pilbara, he went to the Key Centre at UWA and carried out a PhD with Nick Rock and David Groves on gold mineralization associated with Palaeoproterozoic alkaline intrusive rocks and lamprophyres from Toms Gully in the Northern Territory.

Steve's good-humoured determination made him an excellent choice for the Kimberley team because he was given some of the most rugged and difficult to access areas in the East Kimberley. His regional mapping work in the granites and gabbros of the Bow River batholith and its associated felsic volcanic rocks have combined well with his knowledge of igneous geochemistry and petrogenesis, and he has made important contributions to the development of tectonic models for the Palaeoproterozoic rocks of the Kimberley. At last Steve has moved out of the Kimberley — to the southern Gascoyne Complex, where his geological experience is being broadened into the realms of structural and metamorphic geology.

Steve is married to Mel, and has two young children. He is an avid soccer fan, and has followed Southampton in the English Premier League since their 1976 FA Cup win. He is a qualified referee, although field work has enforced his retirement for the time being.

Ian Nowak

Ian Nowak, wordsmith, blacksmith and sometime geophysicist, retires from the GSWA in late 1997, some 28 years after first joining. This long association alone deserves recording but Ian's unique career is certainly worthy of exploring further.

Born in England, Ian became a '10 pound tourist' at age ten. University of Sydney educated, he joined the Snowy Mountains Authority in 1967 after completing an MSc on seismic wave propagation. Ian put his knowledge of matters seismic to work in the study of dam foundations and as there have been no dam failures to date in the Snowy Mountains, he must have known his subject.

Following the obligatory overseas working trip through Europe when Ian undertook some North Sea seismic reflection interpretation to sustain body and soul, the lure of once again examining dam foundations proved irresistible and Ian joined the GSWA in 1969. At this time the future water supply in WA was under scrutiny and the GSWA was closely involved in dam construction and the ultimately successful exploration and delineation of substantial quantities of underground water chiefly in the Pilbara and the South West. Ian's geophysical input into these programs was critical to their success. He worked closely with both the hydrogeologists and the drillers and was known as 'plunger', a reference to some interesting seismic tests he performed after he and John Watt became licensed shot firers. His shot-firing skill was to prove useful in later life too when it came to clearing stumps from sections of a country block of land he and his wife Margaret had purchased.

This was the early 70s, when the Survey had a particularly vibrant social scene and Ian and Margaret had a well-deserved reputation for friendly, fluid dinner parties. The gregarious nature of the man, his keen wit, acute memory, his depth of knowledge and interest in politics and in his fellow man led him to acquire a network of friends amongst present and former members of the Survey.

In 1977, while on long service leave, Ian and his family travelled back to the UK where he became fascinated with blacksmithing. He took it up as a hobby when he returned to Australia. This hobby became something more, and in 1980 Ian resigned from the Survey to become a full-time artistic blacksmith at the Bannister Street Workshops in Fremantle. Several of Ian's works were exhibited in galleries both in WA and interstate and a pair of convict manacles he made adorns a wall of the Greenough Museum. During this period Ian held a solo exhibition of work at the Fremantle Arts Centre.

In 1987 Ian rejoined the geoscience profession as a consultant in mineral exploration, becoming involved in mapping, drilling, and magnetics. Over the years he has enjoyed the craft of writing, and has had several pieces published in art review magazines. In 1991 he was able to combine this love of writing with his knowledge of geoscience by rejoining the GSWA as a text editor. Since that time he has appointed himself guardian of the English language, which he considers to be under assault on many fronts. He initiated *Pandinotes*, a series of irregular offerings to Survey authors bemoaning their lack of precision (or is it accuracy?) in their use of consist of or comprise, cajoling them away from 'occurs', and explaining once more the merits of the Oxford comma.

Ian and his wife of 36 years, Margaret, enjoy travelling and cricket; they are members of the WACA. They share with the Royal family a love of corgis and over the years corgis have come and gone and been sources of companionship, destruction, and conversation. Ian still blacksmiths in his spare time — keeping a forge in operation at Denmark where he and Margaret have a small house to which they retreat whenever possible.

Ian then has much to occupy his time in retirement and was heard once to remark that ageing is a small price to pay for the pleasures of having independent grown-up offspring.

Marianna Brzusek

Marianna Brzusek was born in Moniaki near Lublin in Poland in 1947. She completed a Diploma in Teaching in 1966 and for the next three years taught mathematics and chemistry in Rzeszow. In 1969 Marianna migrated to Australia, leaving the cold weather and misery of Poland for the sunshine and wide-open spaces of Australia. She soon found work at the Regional Hospital in Northam, as a laboratory assistant. These first few years in Australia were a steep learning curve for Marianna as she learnt the way of life in a new country and worked hard at learning the language.

Marianna moved to Perth in 1973 and joined Mineralogical and Geochemical Laboratories. The laboratories were sold to Analabs in 1977, and with them Marianna further developed her laboratory skills and took part in setting up a new laboratory in the eastern Pilbara at the Telfer gold mine.

In 1979 Marianna joined the GSWA to work in the laboratory, becoming the first female to work in a previously all male workplace. In 1984 after two years study, mostly in her own time, she completed a Certificate in Geoscience. She was promoted to Laboratory Technician in the following year, and in 1991 gained the position of Senior Laboratory Technician.

Marianna is well-known throughout the Survey for her energetic approach to all that confronts her. Deadlines are to be met, and short of the building burning down, all tasks are completed on time without fail. It is not surprising that Marianna is so highly regarded by all of her colleagues in the Survey.

On a personal note, Marianna enjoys working about her home and, in particular, is an avid gardener. For a rose bush, Marianna's garden must be Utopia. Marianna also provides assistance to charity organizations, providing transport to and from hospitals and medical centres for sick and elderly people. Because of her own early struggle to adapt to life in Australia, she worked for many years in a voluntary capacity as an interpreter for migrant groups.

Marianna still maintains close ties with her family back in Poland and makes regular visits to catch up with them.

Staff list (30 June 1997)

GUJ, Pietro (Director)

Regional Geoscience Mapping Branch

GRIFFIN, Tim (Assistant Director)
MYERS, John (Chief Geoscientist)

Bangemall Basin
BAGAS, Leon
COPP, Iain
THORNE, Alan

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

Eastern Goldfields/Southern Cross
CHEN, Shefa
FARRELL, Terry
WYCHE, Stephen

Gascoyne/Kimberley
OCCHIPINTI, Sandra
SHEPPARD, Steve
TYLER, Ian

Pilbara
HICKMAN, Arthur
KOJAN, Chris
SMITHIES, Hugh
VAN KRANENDONK, Martin
WILLIAMS, Ian

Lennard Shelf
PLAYFORD, Phillip

Geochronology
NELSON, David

Geochemical Mapping
FAULKNER, Joan
MORRIS, Paul
SANDERS, Andrew

Geophysics
WATT, John

Geochemistry and Regolith Geology
MATTHEWS, Leon (CRC-AMET)

Mineral and Petroleum Resources and Organizational Development Branch

BLIGHT, David (Deputy Director)

Basin Studies (Petroleum Initiative)
APAK, Sukru (Neil)
CARLSEN, Greg
CHAKRABORTY, Kalyan
CROSTELLA, Angelo[1]
DE LEUW, Lorraine
GHORI, Ameed
HAVORD, Peter
IASKY, Robert
MORY, Arthur
SCILLIERI, Roger
SHEVCHENKO, Sergey
STEVENS, Mark
SVALBE, Andrew
YASIN, Raza

Mineral Prospectivity
ABEYSINGHE, Pathmasekara (Abey)
COOPER, Roger
FERGUSON, Kenneth
FRANCOIS, Annick
HASSAN, Lee
LANGFORD, Richard
LESIAK, Irena
PEIRIS, Elias
ROGERSON, Rick
RUDDOCK, Ian

Resource Assessment and Advice
FLINT, Don
PAGEL, Jutta
TOWNSEND, David

Palaeontology support
BACKHOUSE, John
GREY, Kath

Executive support
BAILEY, Elizabeth
CRESSWELL, Brian
STOYANOFF, Nell

Stores and Transport
FAIR, John
LOCKYER, Stuart
MOORE, Brian

Administration
BRADSHAW, Brian
BURNETT, Elaine
ELLIOT, Ian
LAPTHORNE, John

[1] Consultant or fee for service support

Geoscientific and Exploration Information Group

ANNISON, Les (Assistant Director)

Field and Technical support
BONER, Peter
CAREW, Eugene
CLARKE, Dean
HOLMES, Mario
TAYLOR, Ben
URBINI, Simon

I.T. support
GOZZARD, Bob
McGRATH, Bob[1]
LENNOX-BRADLEY, Shaun[1]

Laboratory
BRZUSEK, Marianna
DOMBROWSKY, Peter
WILLIAMS, Gary
WILLIAMS, John

WAMEX/WAPEX
ARATHOON, Claudette
ARDEN, Lorraine[1]
BELL, Ann[1]
BRADLEY, John
COOPER, Christella
DEUTSCHMAN, Anthony[1]
ELLIS, Margaret
EMMS, Rosie[1]
FETHERSTON, Michael
GOSS, Andrew
HAWORTH, Jeffrey
HUGHES, Bernard
JONES, Katherine
KARNIEWICZ, George
LOPEZ, Annabelle
MASON, Jan Sandra
McCORQUODALE, Fiona
McGORRIN, Yvonne
NAGY, Pearl
SAINT, Joan
SMITH, Daniel
STAPLETON, Gladys
WONG, Henrietta

Publications and Information
APIDOPOULOS, Fiona
DAVIS, Angela[1]
DAY, Lyn[1]
FERDINANDO, Darren
FORBES, Alex
GOZZARD, Margie
JOHNSTON, Jean
LOAN, Geoff
MIKUCKI, Jennifer
NOONAN, Kathleen
NOWAK, Ian
STRONG, Caroline
THEEDOM, Erica

Library
CHEUNG, Eunice
CROSS, Robert
KNYN, Brian

Cartographic services
BARTLETT, Clive
BRIEN, Cameron
CARROLL, Peter
COLLOPY, Sean
COSGROVE, Lisa
DAWSON, Brian
DOWSETT, Suzanne
EDWARDS, Tara
FOX, Alistair
GREEN, Ellis
GREENBERG, Kay
HOFFMAN, Arthur
JONES, Murray
LADBROOK, David
LENANE, Tom
PRAUSE, Michael
SUTTON, Dellys
TAYLOR, Peter
WILLIAMS, Brian

GIS
BANDY, Stephen
BURDEN, Phillip
JOSE, Geoffrey
KIRK, John
KUKULS, Liesma (Les)
VAN BURGEL, Gerrit

[1] Consultant or fee for service support

Staff movements (1 July 1996 to 30 June 1997)

Internal appointments

BANDY, Steve — to Level 7
CARROLL, Peter — to Level 6
COLDICUTT, Shaun — transfer from POD
COPP, Iain — to Level 5
CRESSWELL, Brian— to Level 5
DAWSON, Brian — to Level 6
ELLIOTT, Ian — to Level 5
FARRELL, Terry — to Level 5
FETHERSTON, Mike — to Level 7
FORBES, Alex — to Level 7
GOSS, Andrew — to Level 5
HAWORTH, Jeff — to Level 6
HICKMAN, Arthur — to Level 8
HOFFMAN, Arthur— to Level 5
PAGEL, Jutta — to Level 6
SHEPPARD, Steve — to Level 5
WYCHE, Steve — to Level 6
WILLIAMS, Gary — to Level 6

Internal reclassifications

BRADSHAW, Brian — to Level 2
MOORE, Brian — to Level 4

Commencements
(*payroll*)

APIDOPOULOS, Fiona
BURDEN, Phillip
CHEN, Shefa
CHEUNG, Eunice
COOPER, Roger
EDWARDS, Tara
ELLIS, Margaret
FLINT, Don
FRANCOIS, Annick
GREEN, Ellis
GREY, Nicola
HUGHES, Bernard
JENKINS, Wayne
LEBEL, Andre
MATHEWS, Leon
OATES, Jodie
PEIRIS, Elias
VAN KRANENDONK, Martin
WARD, Ian

(*fee for service*)
BELL, Ann
DAY, Lyn
DAVIS, Angela
DEUTSCHMAN, Anthony
EMMS, Rosie
LENNOX-BRADLEY, Shaun
National Workforce
(for temporary field hands)

Resignations

ANDREWS, Tim
BARRETT, Kevin
BRADLEY, Jason
BROOKS, Chris
CAREW, Ross
CATALANO, Paul
GREY, Nicola
JENKINS, Wayne
KEEP, Myra
LEBEL, Andre
LENNOX-BRADLEY, Sean
LUFFMAN, Tim
OATES, Jodie
PAPICCIO, Marlene
PEIRIS, Elias
PERINCEK, Dogan
SMITH, Daniel
SUBRAMANYA, Anil
SWAGER, Cees
VANN, Delma
WITT, Wally
WESTAWAY, Jane
WHITFORT, Mathew

Retirements

GRIEW, Jane
LEWIS, John

Voluntary redundancies

DURR, Kathryn

Transfers out
(*to Mineral Titles*)

MAYER, Ian

(*to Petroleum Operations Division*)

O'BRIEN, Richard

(*to other agencies*)

PRESTON, Bill

On secondment with GSWA
(*from Land Access Unit*)

KOJAN, Chris

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DIRECTOR
Pietro Guj

ASSISTANT DIRECTOR
Tim Griffin

REGIONAL GEOSCIENCE MAPPING BRANCH

- *Chief Geologist* — John Myers
- *Chief Geophysicist/Terrane Custodianship Facilitator* — David Howard
- *Chief Geochemist* — Paul Morris
- *Geochronologist* — David Nelson
- *Terrane Custodian Goldfields* — Ivor Roberts
  - *Southern Cross* — Steve Wyche
  - *Eastern Goldfields* — Bruce Groenewald
- *Lennard Shelf* — Phillip Playford
- *Glengarry/Earaheedy* — Franco Pirajno
- *Pilbara* — Arthur Hickman
- *Gascoyne/Kimberley* — Ian Tyler
- *Bangemall* — Alan Thorne

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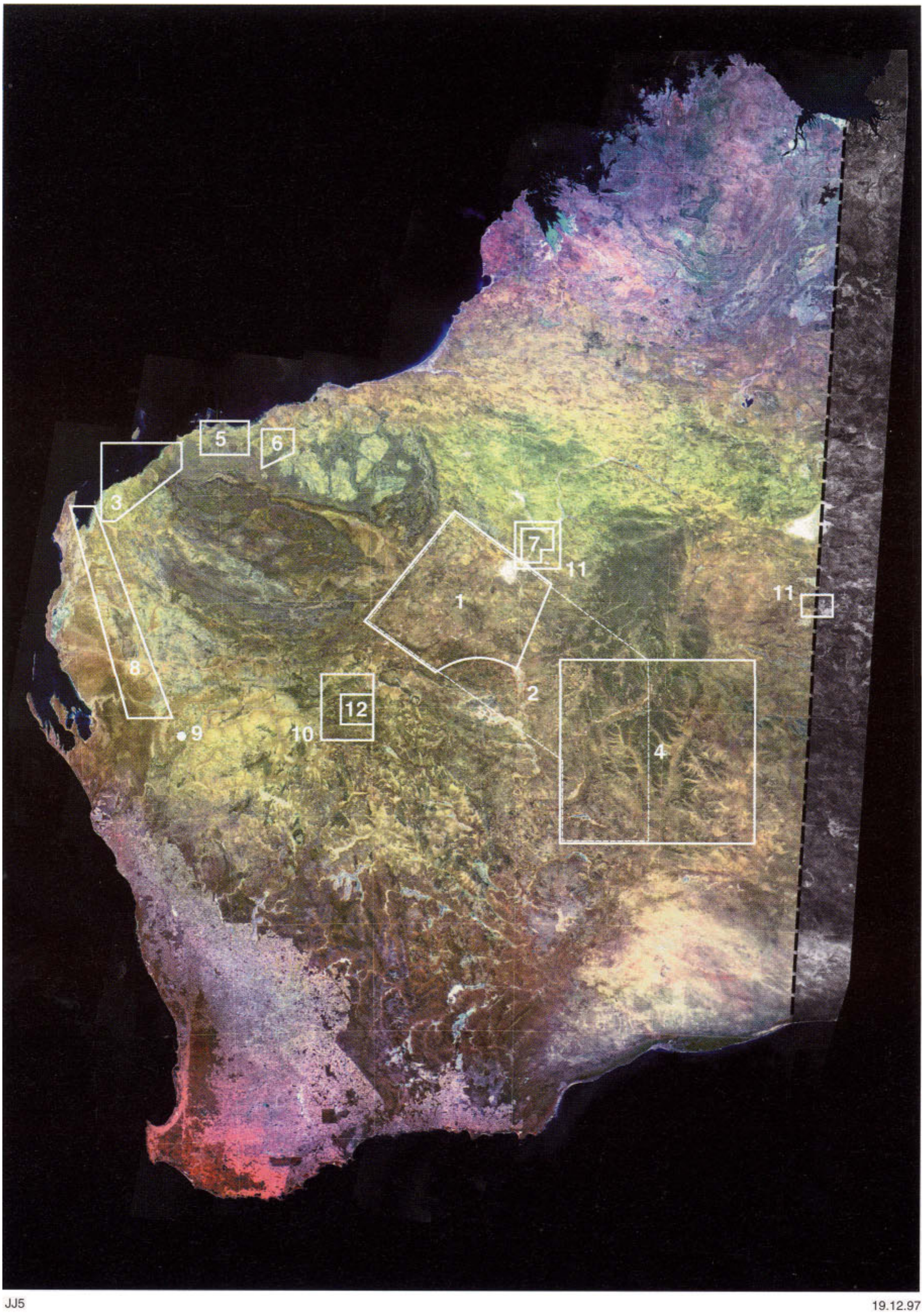


Map of Western Australia showing the location of the twelve (12) technical papers on the following pages. Landsat MSS data supplied by ACRES. Mosaic courtesy of Geoimage.

Technical papers

Neoproterozoic palynomorphs of the Savory Sub-basin, Western Australia, and their relevance to petroleum exploration

by K. Grey and M. K. Stevens

Abstract

Neoproterozoic palynomorphs from the Savory Sub-basin are proving useful for biostratigraphic correlation and preliminary estimation of thermal maturity. Abundant, well-preserved palynomorphs have been recovered from several shallow bores. Both the Tarcunyah Group and part of the Cornelia Formation, previously considered to be older than the Savory Group, contain typical Neoproterozoic assemblages that indicate that they are the same age as the older part of the Savory Group. Organic thermal maturity levels for the Tarcunyah Group in the upper part of LDDH 1, and for the lower units of the Savory Group in several boreholes, are consistent with the more mature phase of liquid petroleum generation, and range into the dry gas generation phase.

KEYWORDS: Neoproterozoic palynology, acritarchs, cyanobacteria, benthic microbial communities, hydrocarbons, Savory Sub-basin, Officer Basin

As part of the evaluation of the hydrocarbon potential of the Savory Sub-basin by the Geological Survey of Western Australia (GSWA), fifteen shallow rotary air blast holes were drilled to provide water supplies for stratigraphic wells (Fig. 1). Diamond corehole GSWA Trainor 1 was subsequently drilled to a TD of 709 m, but the proposed stratigraphic well GSWA Bullen 1 was not drilled. In addition, two samples were examined from diamond corehole LDDH 1, drilled by Normandy Poseidon through the Tarcunyah Group, in an area previously assigned to the Paterson Orogen. The Tarcunyah Group is now considered to be part of the Savory Sub-basin (Bagas et al., 1995). Core and cutting samples were processed by a modified palynological technique designed to recover delicate organic-walled microfossils. Several samples yielded abundant organic residues that included some well preserved palynomorphs. Results from these palynological investigations led to a reinterpretation of parts of the sub-basin, and provide information on the thermal maturity and, to a more limited extent, the environment of deposition.

Geological setting

The geology of the Savory Sub-basin was described in detail by Williams (1992, 1994) and correlations were refined by Walter and Gorter (1994), Walter et al. (1994), Grey (1995a), Bagas et al. (1995), and Perincek (1996). The Savory Basin as defined by Williams (1992) is now considered to be a sub-basin of the Officer Basin (Perincek, 1996). A major problem in understanding the sub-basin has been the lack of adequate stratigraphic control. Outcrop is poor: Williams (1994) estimated it at no more than eight per cent of the 53 000 km^2 occupied by the basin, and prior to 1995 no diamond coring had taken place.

Improved correlation both within and between the principal areas of Neoproterozoic rocks in Australia (i.e. the Centralian Superbasin and the Adelaide Geosyncline) is now possible with the use of a variety of techniques such as sequence analysis, isotope chemostratigraphy, palynology, stromatolite biostratigraphy, macropalaeontology, seismic interpretation, magnetostratigraphy, and limited radiometric dating (Walter et al., 1995). Correlation between parts of the Savory Sub-basin and other Neoproterozoic successions is now feasible using a similar integrated approach (Walter et al., 1994; Grey, 1995a; Stevens and Grey, 1997, fig. 3).

Detailed seismic interpretation has led to improved correlation within the Officer Basin (Perincek, 1996), and correlation between this basin and the Savory Sub-basin is now possible using stromatolites (Stevens and Grey, 1997; Grey, unpublished data). Palynological results are generally consistent with these recent revised interpretations, and all productive palynological assemblages are from Neoproterozoic Supersequence 1 in the sense of

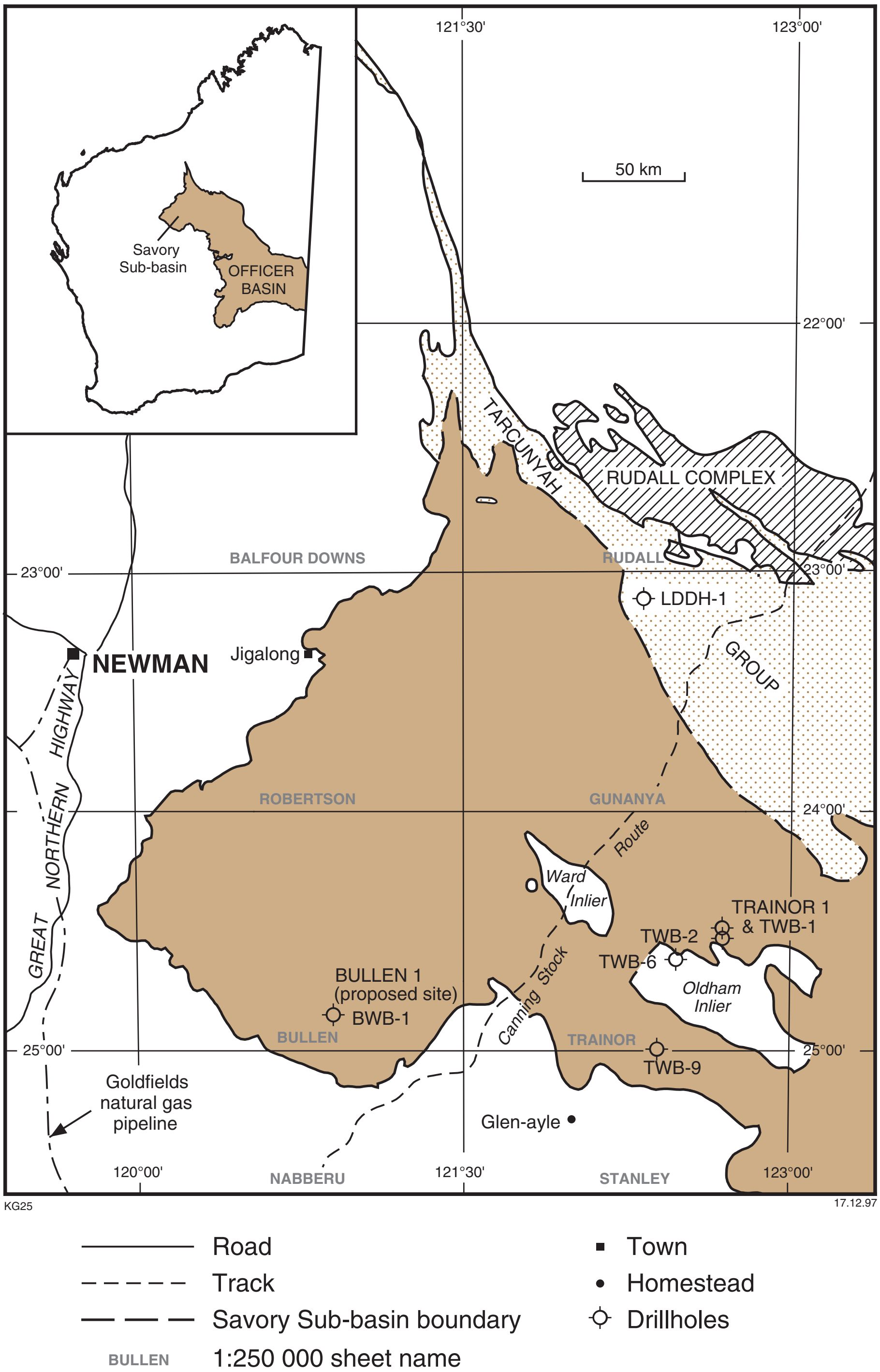


Figure 1. Part of the Officer Basin, Western Australia, showing drillholes examined for palynological studies

Table 1. Drillhole locations

Drillhole	*Mapsheet (1:250 000)*	*Easting*	*Northing*
BWB 1	BULLEN	287337	7245861
TWB 1	TRAINOR	473692	7287406
TWB 2	TRAINOR	473195	7285767
TWB 6	TRAINOR	457013	7274352
TWB 9	TRAINOR	437219	7235905
Trainor 1	TRAINOR	473642	7287403
LDDH 1	GUNANYA	431148	7443826

Note: Eastings and northings are for Zone 51, AGD 84

Walter et al. (1995). The location of drillholes discussed here is shown in Table 1 and Figure 1.

Palynology

Results of palynological studies from Savory drillholes are summarized in Table 2. Advances in our understanding of Neoproterozoic acritarchs and microfossil assemblages in Australia (Zang and Walter, 1992; Zang, 1995; Grey and Cotter, 1996; various unpublished reports) have made it feasible to identify and date isolated samples of the type discussed here, although the limitations of such an approach must be taken into consideration. Documentation of late Neoproterozoic palynomorph assemblages is at an early stage, but the biostratigraphic framework is becoming more tightly constrained as a result of continuing studies.

Assemblages from the Savory Sub-basin can be compared with those from the Western Australian Officer Basin (Grey, 1995b; Grey and Cotter, 1996) and elsewhere in Australia (Zang, 1995; Cotter, in press). Preliminary results indicate that certain palynomorphs are useful index fossils, and will thus aid assessment of the hydrocarbon potential of the Officer Basin.

Palynomorphs from the Savory Sub-basin are mainly of two types: acid-insoluble microfossils and, more rarely, acritarchs. Acid-insoluble microfossils are mostly the remains of coccoids and filaments of the cyanobacteria (blue-green bacteria) that grew as benthic microbial communities (BMCs) at the sediment–water interface, whereas the acritarchs are a polyphyletic group of uncertain affinities, consisting mainly of the resting cysts of prasinophyte algae (marine phytoplankton that lived mainly in the photic zone).

The Thermal Alteration Index (TAI) provides an indication of the depth of burial and thermal maturity based on the wall colour of palynomorph vesicles (Traverse, 1988). Values for TAI less than 2^+ indicate that sediments are immature. Values between 2^+ and 3^+ correspond to the oil generation window (i.e. equivalent to vitrintite reflectance (VR) values of 0.5% to 1.3%), and those over 3^+ fall in the gas-generation phase (VR >1.3%). This index is well established for the Phanerozoic, but must be used with caution for Proterozoic fossils (Grey and Cotter, 1996). The limited data for the Savory Sub-basin indicate that at least some samples have values close to the boundary between the oil- and gas-generation windows (between TAI 3 and 3^+).

Palaeoenvironmental control is evident in some assemblages, particularly those dominated by BMCs. Many taxa are morphologically conservative and of simple form; nevertheless, some forms are more complex (Fig. 2) and show restricted ranges, and are therefore useful for biostratigraphy. Biostratigraphic control improves in the upper part of the Neoproterozoic, especially above the Marinoan glacial succession, but even pre-Sturtian strata may yield biostratigraphically useful assemblages. Grey and Cotter (1996) recorded four preliminary assemblages in Supersequence 1 of the Officer Basin, and of these assemblages the oldest (Assemblage 1) has been recognized in the Savory Sub-basin. Palynological results are summarized in Table 2. Only the more significant results are discussed here.

Trainor water bores 1 to 10

Trainor water bores (TWB) 1, 2, 3, 6, 8, 9, and 10 penetrated rocks of presumed Proterozoic age, but only TWB 1, 2, 6, and 9 contained lithologies considered suitable for palynology. No identifiable palynomorphs were found in TWB 1 or TWB 2, although biogenic material was present.

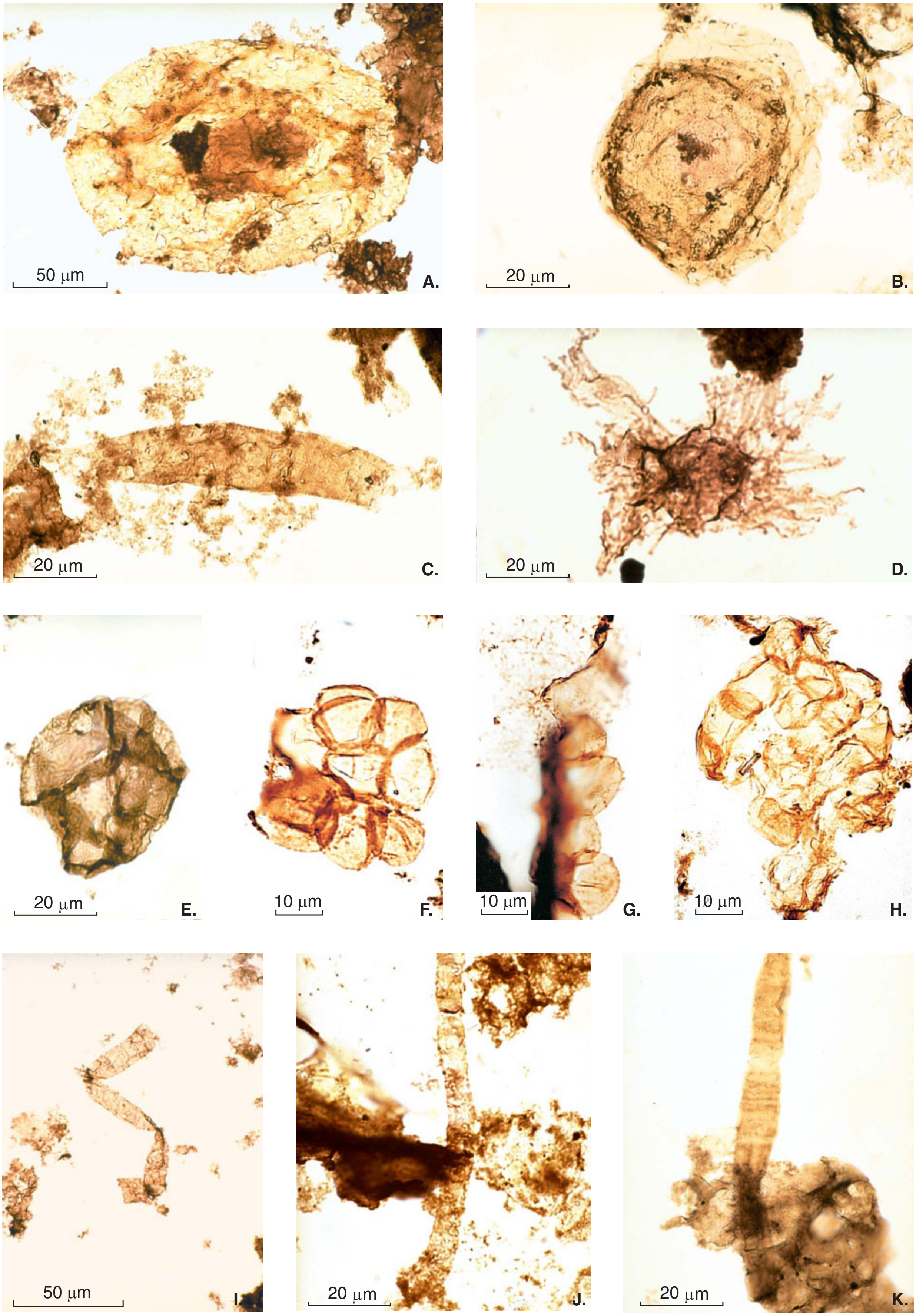
Identifiable palynomorphs and abundant biogenic material were recovered from TWB 6 and TWB 9. Palynomorphs from these samples are generally long-ranging, conservative species, but are consistent with an Assemblage 1 age of Supersequence 1. The species present suggest a mixed assemblage of benthic mat communities and planktonic forms, probably intermediate between near- and off-shore environments. Thermal maturity levels from most samples are within the oil–gas window (TAI = 3^+).

Samples from TWB 9 from the Brassey Range Formation indicate,

Table 2. Summary of palynological results

Drillhole	*Depth (m)*	*F no.*[(a)]	*GSWA no.*	*Lithology*	*Formation*	*Assemblage*	*TAI*[(b)]
BWB 1	74–75	F49668	135741	dark-grey siltstone	Jilyilli	?	>5
BWB 1	98–100	F49669	135742	dark-grey siltstone	Jilyilli	?	>5
BWB 1	121–122	F49670	135743	dark-grey siltstone	Jilyilli	?	>5
TWB 1	86–87	F49671	135631	dark-grey siltstone	McFadden	?	3+
TWB 1	104–105	F49672	135632	dark-grey siltstone	Cornelia	?	3+
TWB 1	121–122	F49673	135633	dark-grey siltstone	Cornelia	?	4
TWB 2	14–15	F49674	135634	dark-grey siltstone	Skates Hills	?	3+
TWB 6	49–50	F49675	135675	dark-grey siltstone	?Cornelia	1	3+
TWB 9	49–51	F49676	135704	dark-grey siltstone	Brassey Range	1	3+
Trainor 1	374.97–375.09	F49733	138939	black mudstone with light-grey siltstone	Cornelia	?	5
Trainor 1	380.9	F49734	138940	dark-grey and black laminated mudstone	Cornelia	?	4-
Trainor 1	417.0	F49735	138941	black unlaminated mudstone	Cornelia	?	4-
Trainor 1	495.0	F49851	139501	dark-grey indurated siltstone	Cornelia	?	5
Trainor 1	603.2	F49852	139502	dark- and light-grey indurated siltstone	Cornelia	?	5
Trainor 1	643.4	F49853	139503	greenish indurated finely laminated siltstone	Cornelia	?	5
LDDH 1	270	F49678	138934	dark-grey siltstone interbeds in ?enterolithic evaporite	Waters Tarcunyah Gp	1	3+
LDDH 1	277	F49679	138935	dark-grey siltstone in cavity in ?enterolithic evaporite	Waters Tarcunyah Gp	1	3+

Notes:
(a) GSWA Fossil Catalogue number
(b) TAI = Thermal Alteration Index of Traverse (1988, plate 1)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as expected, a Neoproterozoic age. However, TWB 6, drilled in the Cornelia Formation, also contained a Neoproterozoic assemblage that includes *Leiosphaeridia* sp., clusters of *Synsphaeridium* sp., *Arctucellularia ellipsoidea*, ?*Satka* sp., ?*Goniosphaeridium alinyum*, *Simia annulare*, and a few filaments, including *Oscillatoriopsis* sp. Most of the recorded species are common in the Neoproterozoic. The assemblage is consistent with assemblages previously recorded from the Browne Formation of the Officer Basin (Grey, 1995b; Grey and Cotter, 1996) and the Gillen Member of the Bitter Springs Formation, Amadeus Basin (Zang and Walter, 1992). Several of these species have previously been reported from the Alinya Formation of the South Australian Officer Basin (Zang, 1995).

On this basis, the assemblage from TWB 6 is considered to be of Supersequence 1 age (younger than c. 0.85 Ga), and considerably younger than the 1.2 Ga Bangemall Group to which the Cornelia Formation is currently assigned. Examination of Landsat imagery and recent field investigations suggest that two separate stratigraphic units may be present: a steeply dipping black siltstone and quartzite succession belonging to the Bangemall Group and having a more restricted distribution pattern than previously thought, and a moderately dipping sandstone unit of Neoproterozoic age. It now seems that much of the Oldham and Ward Inliers should be reassigned to the Savory Group.

Normandy Poseidon LDDH 1

Normandy Poseidon LDDH 1 is a stratigraphic diamond drillhole, cored from 112 to 701 m TD, which was drilled 150 km east of Balfour Downs Homestead on the GUNANYAH* 1:250 000 map sheet (Busbridge, 1994). Abundant identifiable palynomorphs were recovered from two samples in the Tarcunyah Group, and amorphous biogenic material was also plentiful in both samples. The abundance of filamentous and coccoid mat fragments indicates a benthic microbial community in a near-shore environment. Based upon visual TAI assessment, thermal maturity lies within the oil–gas window (TAI = 3^+). These values are consistent with results obtained from geochemical analysis (Ghori, in prep.). Taxa present include *Leiosphaeridia* sp., clusters of *Synsphaeridium* sp. (very abundant), *Arctucellularia ellipsoidea*, a variety of single filaments, including *Oscillatoriopsis* sp. and *Siphonophycus* sp. A Zang 1982, and tangles of filaments of *Eomycetopsis robusta* and *Archaeotrichion contortum*.

These palynomorphs are generally long-ranging, conservative species, but are equivalent to assemblages in the Browne and Bitter Springs Formations of the Officer and Amadeus Basins respectively, and therefore coeval with Supersequence 1 of the Centralian Superbasin. The palynological evidence substantiates correlation of the Tarcunyah Group with the older part of the Savory Group, and separation from the remainder of the Yeneena Group as proposed by Bagas et al. (1995). Correlation of the Tarcunyah and Savory Groups has subsequently been supported by stromatolite biostratigraphy (Stevens and Grey, 1997).

* Capitalized names refer to standard map sheets

Trainor 1

Trainor 1 is a fully cored stratigraphic hole drilled by GSWA on the TRAINOR 1:250 000 sheet (Stevens and Adamides, in prep.). Stratigraphic interpretation of Trainor 1 is still uncertain, but horizontally dipping rocks above an angular unconformity at 83 m are correlated with the McFadden Formation, and rocks below the unconformity are correlated with the Cornelia Formation. As discussed above, it is unclear whether all or parts of the Cornelia Formation are part of the Neoproterozoic Savory Group. Although several samples were processed from this hole, all were barren of palynomorphs, and the contained amorphous organic matter in samples correlated with the Cornelia Formation was overmature (TAI 4^- to 5).

Bullen water bores 1 to 5

Bullen water bores (BWB) 1, 4, and 5 penetrated rocks of presumed Proterozoic age. Only samples from BWB 1 were submitted for palynological processing and no identifiable palynomorphs were recovered. Biogenic material was sparse, and indicated high levels of thermal maturity (TAI = 5). These high thermal-maturity levels in BWB 1 are most probably the result of the effects of contact with basaltic intrusives, and the effects are considered to be of local extent.

Subsequently, thin-section investigation of the cuttings showed that they were largely basaltic in origin. The identification of abundant mafic rocks in the area of the proposed stratigraphic well, Bullen 1, led to the decision not to drill this well.

Figure 2. Selected palynomorphs from the Savory Sub-basin. Identifications are tentative pending further systematic analysis but specimens are typical of Assemblage 1 of Grey and Cotter (1996). Slides are held in the GSWA fossil collection. England Finder coordinates are given for each specimen. All specimens are from LDDH 1, 277.0 m, except (e), (f) and (g) which are from TWB 6, 49–50 m
(a) zoned sphere, H-43-1
(b) zoned sphere, C-39-2
(c) tubular filament, N-31-0
(d) cluster of fine filaments, R-57-3
(e) **Actucellularia ellipsoides**, *P-58-3*
(f) **Synsphaeridium** *sp., G-49-4*
(g) **Satka** *sp., P-58-3*
(h) **Leiosphaeridia** *sp., C-46-1*
(i) broad filament, C-31-0
(j) broad filament, X-48-2
(k) banded filament, W-57-4

Conclusions

Palynology, combined with other correlation tools, shows good potential for elucidating relationships between Neoproterozoic sedimentary rocks that cover a significant area of Western Australia. Neoproterozoic palynological zonation is still at a preliminary stage, and caution must be exercised when interpreting rotary air blast cuttings because of the potential for down-hole contamination. Nevertheless, palynological investigations have already provided significant results in terms of stratigraphic reassessment and investigation of thermal maturity.

Inconsistencies in previous stratigraphic interpretations, first identified through biostratigraphic analysis, have led to further investigations and subsequent reinterpretation of units such as the Cornelia Formation and Tarcunyah Group. The Cornelia Formation in the Ward and Oldham Inliers is now considered to be at least in part of Neoproterozoic age, and may require future subdivision. Palynomorphs provided the first indication that the Tarcunyah Group is Neoproterozoic in age, and this has been confirmed by recent stromatolite studies (Stevens and Grey, 1997; Grey, unpublished data).

TAI values in a small number of widely spaced wells range from 3^+ to 5. These TAI values correspond to late oil generation through gas generation to overmaturity. The thermal maturity indicated by TAI in samples from LDDH 1 has now been confirmed by organic geochemistry, with samples above 500 m down-hole depth mature for oil generation, and samples below this depth mature for gas only (Ghori, in prep.). Thermal maturities in TWB 6 and TWB 9 based on TAI values are similar to the upper part of LDDH 1 (Table 2). The data from these wells suggest that the northeast and southeast parts of the Savory Sub-basin currently lie within the oil–gas generation window, and warrant further investigation.

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Skates Hills Formation and Tarcunyah Group, Officer Basin — carbonate cycles, stratigraphic position, and hydrocarbon prospectivity

by M. K. Stevens and K. Grey

Abstract

Measured Neoproterozoic sections from the Savory and Gibson Sub-basins can be tied to revised Officer Basin stratigraphy using lithostratigraphy and stromatolite biostratigraphy. Stromatolitic dolomite, clastic sedimentary rocks and minor evaporites in a 70 m-thick composite section in the Skates Hills Formation, and a 35 m-thick section in the Tarcunyah Group indicate shallow-water and sabkha environments. The Skates Hills Formation contains the *Acaciella australica* stromatolite assemblage that is also found in the Browne and Woolnough Formations of the Officer Basin. An unnamed unit in the Tarcunyah Group is younger, and contains the *Baicalia burra* stromatolite assemblage, previously found in the Neale and Kanpa Formations.

Modern saline lakes, as typified by Lake Thetis, Western Australia, may provide a better model for Neoproterozoic shallow-marine environments than do current marine counterparts. In Lake Thetis, organic-rich muds derived from microbial communities are deposited in anoxic conditions, and are juxtaposed with porous stromatolitic marginal reefs. These facies, representing source, seal and reservoir, are analogous to palaeoenvironments identified in the Neoproterozoic of the Officer Basin.

KEYWORDS: Officer Basin, Neoproterozoic, Skates Hills Formation, Tarcunyah Group, hydrocarbon potential, stromatolites, biostratigraphy

The Officer Basin remains underexplored and the stratigraphic framework of the basin is still poorly defined. Recent seismic interpretation (Perincek, 1996), together with studies outlined here, has further clarified correlations within the Neoproterozoic.

During the 1996 field season, a reconnaissance field trip was made to the generally poorly exposed outcrops of the Gibson, Yowalga, and Savory Sub-basins with one of the aims being to locate and measure significant outcrops of Neoproterozoic stromatolitic dolomites. Three sections were measured where stratigraphic thickness was greater than 30 m. Two of these provide a composite section through much of the Skates Hills Formation of the Savory Group in the Skates Hills area at about 24°34'S, 123°05'E (Fig. 1). A third section was measured in an unnamed unit of the Tarcunyah Group near Constance Headland at 24°07'S, 123°12'E. Stromatolites in the measured sections can be used to determine stratigraphic positions relative to other units in the Officer Basin. Stromatolitic correlations are based on continuing biostratigraphic studies that include Australia-wide Neoproterozoic correlations (Grey, 1995, unpublished data).

Measured stratigraphic sections

Stratigraphic sections were measured using a Jacob's staff in areas of good outcrop, and a combination of chain, compass and clinometer where there were significant gaps.

Skates Hills measured sections

Two sections, 1.48 km apart, were measured in the Neoproterozoic Skates Hills Formation to the north of Skates Hills on the MADLEY* 1:250 000 sheet where the strata dip north-northeasterly at about 10°. The western section, MDL96/1, is 36.7 m thick and consists of poorly outcropping mudstone interbedded with thin sandstone, overlain by 3m of dolomite. The eastern section, MDL96/2, is 41.8 m thick and grades from dolomite, mudstone, and chert at the base to mudstone and sandstone at the top. Together

* Capitalized names refer to standard map sheets

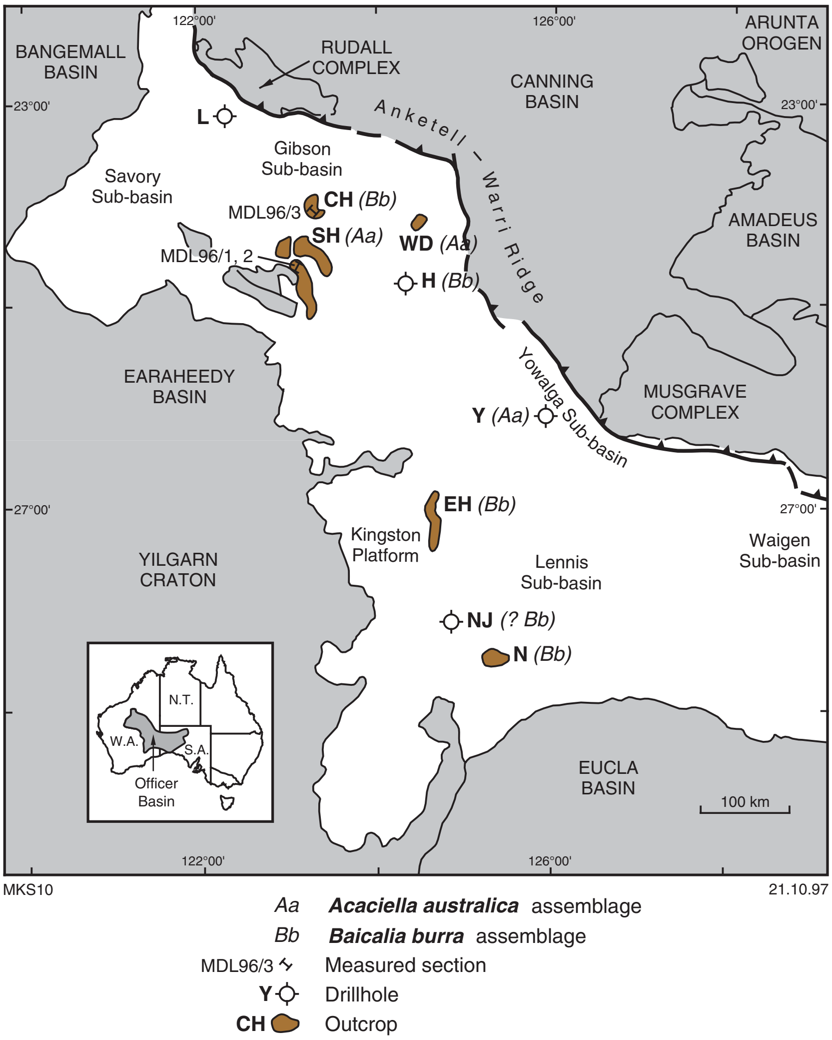


Figure 1. Location map of the Officer Basin. Localities referred to in text: CH, Constance Headland; EH, Eagle Highway localities; N, central NEALE *localities; SH, Skates Hills localities; WD, Woolnough Hills Diapir. Drillholes referred to in text: H, Hussar 1; L, LDDH 1; NJ, NJD 1; Y, Yowalga 3*

the sections form a 70 m-thick composite section, comprising a basal western part (Section MDL96/1) and an upper eastern part (Section MDL96/2).

The base of section MDL96/1 is taken at the angular unconformity between the underlying Cornelia Formation and the Skates Hills Formation (Figs 1, 2, and 3). The first 33.6 m of MDL96/1 consists of poorly outcropping mudstone with minor fine sandstone interbeds. The upper 3m contains rare chert and poorly preserved stromatolites, tentatively identified as *Acaciella australica* (Howchin 1914) Walter 1972. From 33.6 m to 36.7 m the section consists of light-grey micritic dolomite that is laminated and stromatolitic and contains well-preserved *Basisphaera irregularis* Walter 1972. This dolomite is resistant to weathering and forms a cliff that outcrops as low ridges to the north of Skates Hills.

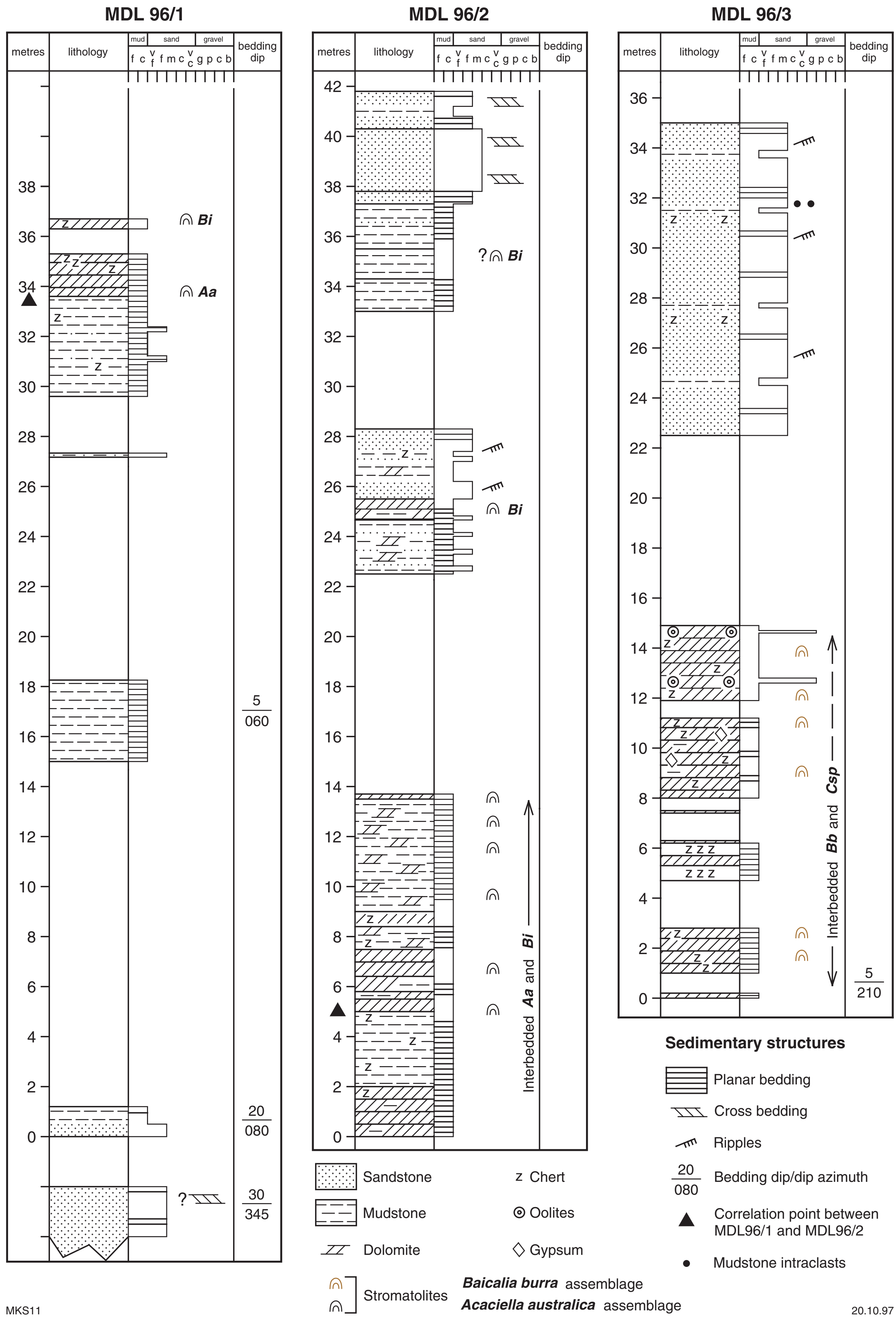
The base of the cliff-forming unit (at 33.6 m in section MDL96/1) is correlated along strike with the base of a resistant unit at 5 m in section MDL96/2 (1.48 to the southeast) because of similar lithology and topographic expression.

In the second section, MDL96/2 (Fig. 2), the basal 5 m of section comprises poorly exposed micritic dolomite and mudstone with common bedded and nodular chert. From 5 to 9 m the section consists of grey, white, red, and green micritic dolomite with silicified stromatolitic bioherms and minor chert, and from 9 to 13.5 m, of poorly outcropping stromatolitic dolomite and light-red mudstone that is partly evaporitic. Both *A. australica* and *B. irregularis* are present. The section from 13.5 to 22.5 m is devoid of outcrop, but from 22.5 to 28.3 m contains interbedded sandstone, mudstone and dolomite with rare poorly preserved stromatolites, probably *B. irregularis*. Again, outcrop is absent from 28.3 to 33 m. The uppermost unit from 33 to 41.8 m consists of a coarsening-upwards cycle ranging from carbonaceous mudstone and siltstone at the base to thickly bedded and cross-bedded sandstone at the top.

The Skates Hills Formation contains lithologies and sedimentary structures indicative of a shallow-marine environment. Grey (1995) gave detailed descriptions of the stromatolites and geological setting of this group of outcrops. The Skates Hills Formation records an increasing input of coarse clastic sediments that coincides with a change from *A. australica*-dominated dolomites to sandstones containing *B. irregularis*. Bioherms are frequently truncated and their growth habit indicates shallow-water conditions. Stromatolite growth was eventually terminated by increasing clastic input.

The Cornelia Formation, which underlies the Skates Hills Formation, was previously considered to be an inlier of the Mesoproterozoic Bangemall Basin. Recent palynological evidence (Grey and Stevens, 1997) suggests that it could be at least partly of Neoproterozoic age and therefore part of the Savory Group.

Figure 2. Measured sections MDL96/1 and MDL96/2, Skates Hills Formation, and MDL96/3, Tarcunyah Group. **Aa, Acaciella australica; Bi, Basisphaera irregularis (Acaciella australica** *assemblage);* **Bb, Baicalia burra; C** *sp,* **Conophyton** *sp. Nov.* **(Baicalia burra** *assemblage)*


MDL 96/1
MDL 96/2
MDL 96/3
metres
lithology
mud
sand
gravel
f c vf f m c vc g p c b
bedding dip
Bi
Aa
?Bi
Interbedded Aa and Bi
Interbedded Bb and Csp
5/060
20/080
30/345
5/210
Sandstone
Mudstone
Dolomite
Stromatolites
z Chert
Oolites
Gypsum
Baicalia burra assemblage
Acaciella australica assemblage
Sedimentary structures
Planar bedding
Cross bedding
Ripples
20/080 Bedding dip/dip azimuth
Correlation point between MDL96/1 and MDL96/2
Mudstone intraclasts
MKS11
20.10.97

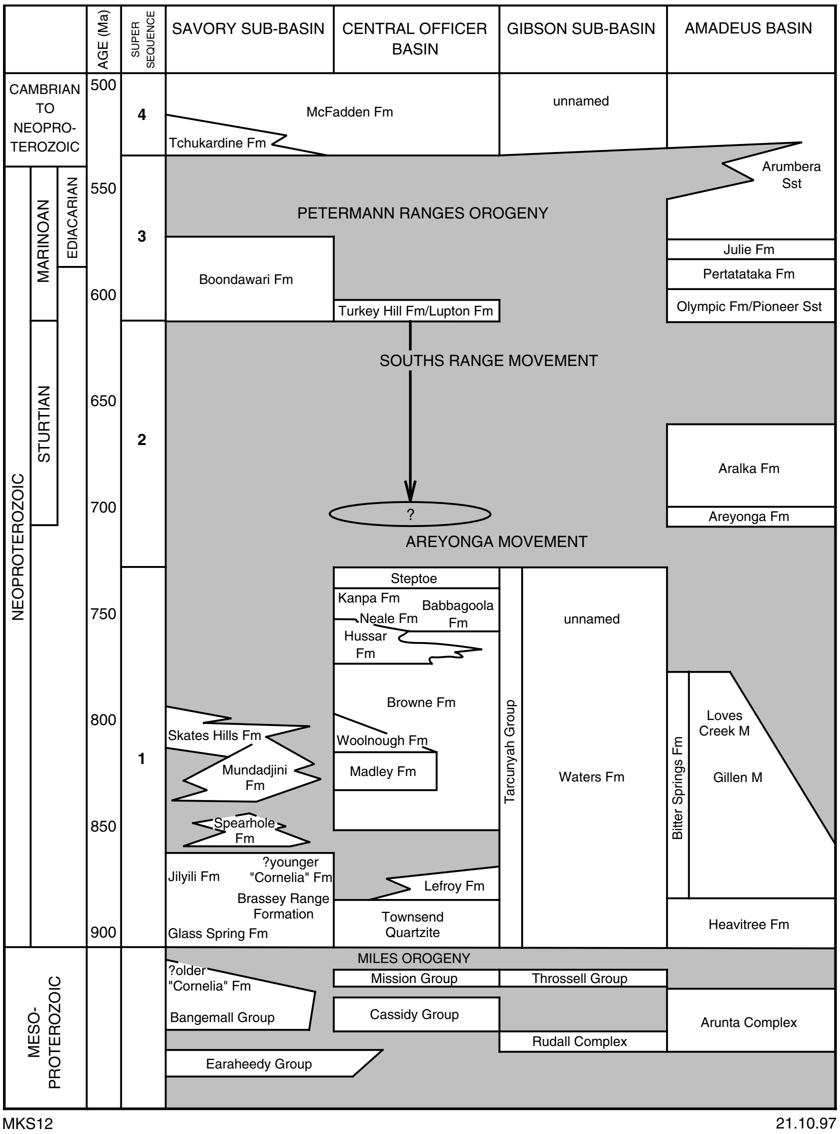


Figure 3. Correlation of formations in the western Officer and Amadeus Basins Fm = Formation; Sst = Sandstone; M = Member

Constance Headland measured section

The third section, MDL96/3, was measured on a small hill 16 km southeast of Constance Headland on MADLEY. Constance Headland lies at the northwestern point of an outcrop of the Neoproterozoic Tarcunyah Group, which was recently recognized as being part of the Officer Basin (Bagas et al., 1995), and within the Gibson Sub-basin (Fig. 2). The Neoproterozoic, which consists predominantly of quartz sandstones, outcrops in a syncline that plunges gently to the southeast and covers an area of approximately 30 by 10 km.

Basal units consist of poorly exposed sandstone, chert and probable evaporite with outcrop too discontinuous to allow a section to be measured. About 1 km northwest of Constance Headland stromatolites are present in chert, but these are too poorly preserved to be identified. The upper part of the succession constitutes some of the best outcrop in the western Officer Basin, and a section was measured near the stratigraphic top of the outcrop through dolomite and sandstone. Stromatolites in the dolomite consist of *Baicalia burra* Preiss 1992 and a new form of *Conophyton* Maslov 1937.

The basal unit of section MDL96/3 is 15 m thick and consists predominantly of micritic dolomite. The dolomite is stromatolitic, has a mudstone component and includes cauliflower chert. Gaps of 0.5–2 m in the outcrop are interpreted as extremely weathered mudstone and contain white, powdery gypsum. Both gypsum and cauliflower chert indicate deposition in evaporitic conditions. Oolites up to 5 mm in diameter are present at the top of this unit. There is no outcrop from 15 to 22.5 m. The top of the section from 22.5 to 35 m consists of medium-grained sandstone with minor interbedded mudstone and lenses of cauliflower chert. The sandstone contains thin horizontal bedding and ripple-cross laminations.

Lithology and sedimentary structures observed in this section indicate a shallow-marine environment, somewhat similar to that of the Skates Hills Formation.

Age, depositional environment, and cyclicity

Measured sections MDL96/1 and MDL96/2 in the Skates Hills Formation contain the stromatolites *Acaciella australica* and *Basisphaera irregularis*. These forms are widely distributed throughout the Centralian Superbasin (Grey, 1995), and have been referred to as the *Acaciella australica* assemblage Grey (1996). This assemblage appears to be slightly older than 800 Ma (Grey, unpublished data), and is restricted to the middle part of Supersequence 1 as defined by Walter et al. (1995).

The stromatolites *Baicalia burra* and a new form of *Conophyton* from section MDL96/3 in the Tarcunyah Group are referred to as the *Baicalia burra* assemblage (Grey, 1996). From comparison with the Adelaide Geosyncline, the age of this assemblage is considered to be slightly younger than 800 Ma (Grey, unpublished data). It is therefore younger than the *Acaciella australica* assemblage and occurs in the upper part of Supersequence 1.

Depositional environments of both the Skates Hills Formation and the part of the Tarcunyah Group in section MDL96/3 seem to be broadly similar. Both are interpreted as shallow-marine settings in which the stromatolites grew in an episodically high-energy environment within the photic zone. The presence of cauliflower chert indicates evaporative and possibly sabkha environments in both units. Cross-bedding and ripple marks in the associated clastic units provide further evidence for a shallow-marine depositional environment.

Both the Skates Hills Formation and Tarcunyah Group demonstrate upward shallowing with lithologies ranging from mudstone, through dolomite, to sandstone. These show environments that range from below wave base, through high-energy shallow marine, to near shore, possibly supratidal. The sequence of lithologies in both the measured sections indicates cyclic deposition.

Regional correlations

The *Acaciella australica a*ssemblage recorded in the measured sections is widespread in the Skates Hills Formation (Grey, 1995). The Skates Hills Formation can also be correlated with the Woolnough Formation in the Woolnough Diapir in the Gibson Sub-basin, and with the Browne Formation at 2390 m in Yowalga 3 borehole in the Yowalga Sub-basin. All contain elements of the *Acaciella australica* assemblage (Grey, 1996). The formation can also be correlated with the Loves Creek Member of the Bitter Springs Formation of the Amadeus Basin and the Yackah beds of the Georgina Basin (Walter et al., 1994; Grey, 1995).

The measured section in the Tarcunyah Group at Constance Headland correlates with the Neale Formation and an unnamed carbonate equivalent to the Neale Formation outcropping west of the Eagle Highway on the Kingston Platform, and with the Kanpa Formation at 891.34 m, 892.81 m and 895.2 m in Hussar 1 in the Gibson Sub-basin (Fig. 1). All contain elements of the *Baicalia burra* assemblage (Grey, 1996). The occurrence of *B. burra* indicates correlation with the Burra Group in the northern Adelaide Geosyncline of South Australia (Grey, unpublished data).

A small columnar stromatolite found in corehole NJD-1 (Fig. 1) at around 150–160 m is similar to an unnamed form that occurs associated with *Baicalia burra* at one of the Eagle Highway localities. This interval in NJD-1 therefore also appears to belong to the *Baicalia burra* assemblage.

The mudstone–dolomite–sandstone shoaling cycle observed in section MDL96/3 is similar both lithologically and in thickness to cycles recognized in the Kanpa Formation, and both contain *B. burra.* Mudlog and wireline log data for the Kanpa Formation between 881 and 1040 m in Hussar 1 shows evidence for four shallowing-upwards cycles. Three of these cycles contain the mudstone–dolomite–sandstone succession and one contains a mudstone–dolomite succession. Evaporites occur in three of the four cycles. The total cycle thickness varies from 26 to 51 m. Dolomite units range in thickness from 15 to 30 m, and are comparable with the 15 m-thick dolomite unit in section MDL96/3. Thus the Tarcunyah Group cycle is probably equivalent to one of the four Kanpa Formation cycles.

Relevance to hydrocarbon prospectivity

Stromatolite bioherms are widespread in the Officer Basin, indicating extensive microbial activity that may have produced abundant organic matter. Modern saline lakes that have stromatolitic rims and restricted floras and faunas may provide a better analogue for Neoproterozoic hydrocarbon systems than is found in modern marine environments. Typical of these lacustrine environments is Lake Thetis near Cervantes, Western Australia (Grey et al., 1990). Abundant production and local preservation of organic matter from microbial activity in this lake is coupled with porosity development in marginal stromatolite reefs. Lake Thetis is characterized by a highly evaporitic environment resulting in high-salinity and high-pH lake waters. Anoxic bottom waters and organic-rich sediments are juxtaposed with evaporitic deposits that provide seal potential.

In the Officer Basin there is evidence of erosion of organic matter from the extensive benthic microbial communities that formed stromatolitic fringing reefs. Bioherm surfaces show evidence of erosion, and fragmented columns occur in breccias adjacent to more-intact bioherms. Ripped-up fragments of filaments and coccoid mats are common components of palynological assemblages from drillholes. If eroded and transported as a result of storm activity, and then redeposited under anoxic conditions, this material could form significant source-rock intervals without requiring a deep-water basinal setting. Seawater stratification would encourage the growth of mats similar to the Lake Thetis purple sulfur bacterial mat. The association of stromatolitic dolomite and evaporitic conditions interpreted from the presence of cauliflower chert and the occasional presence of poorly outcropping gypsum beds indicates the potential for evaporitic intervals to form significant sealing horizons. Judging from the preferential silicification observed in outcrop, some stromatolite bioherms probably had significant primary porosity. Sandstones associated with the dolomites could be good reservoirs if porosity is preserved or secondary porosity generated.

The Neoproterozoic Alinya Formation of the eastern Officer Basin, which is of similar age to the Supersequence 1 successions in the western Officer Basin, contains up to 0.62% total organic carbon (Zang and McKirdy, 1994). This unit was deposited in subtidal shelf to coastal sabkha environments that are similar to those described here for the western Officer Basin. The oldest known Siberian oil and gas fields were probably sourced from Neoproterozoic carbonate–evaporite successions (Zang, 1995), and in Oman most petroleum originated from Neoproterozoic salt-related kerogenous rocks (Zang, 1995). These environments are also similar to those recorded from parts of the Officer Basin.

Conclusions

The stratigraphic sections measured in stromatolitic dolomites of the Skates Hills Formation and an unnamed unit of the Tarcunyah Group show evidence that these units were deposited in shallow water; both are associated with evaporitic environments. Both units consist of a mudstone–dolomite–sandstone succession that is interpreted as an upward-shallowing marine cycle.

The recognition of two stromatolite assemblages, an older *Acaciella australica* assemblage and a younger *Baicalia burra* assemblage has improved biostratigraphic correlation of outcrops in the Officer Basin. Both assemblages can be recognized in the field, given good preservation, and their occurrence in the measured sections described here allows correlations to be made from these sections to drillhole successions and seismic sections. The correlations based on stromatolite biostratigraphy are supported by preliminary palynological results from drillholes (Grey and Cotter, 1996; Grey and Stevens, 1997).

If the analogy with modern high-alkaline, high-salinity lacustrine environments such as Lake Thetis is relevant to Neoproterozoic marginal-marine settings, then significant volumes of organic matter produced by microbial communities could have been locally buried under anoxic conditions. It is likely that storm erosion of microbial communities would have resulted in the deposition of organic-rich deposits in a marginal-marine to shelfal environment. Organic matter would have been preserved if bottom waters were anoxic.

Most of the limited hydrocarbon exploration effort in the Officer Basin has so far been concentrated on models based on the association between deeper water shale units as a source rock and overlying sandstone as a reservoir. Field observations discussed herein suggest that source potential in the Officer Basin is not restricted to deep-water deposits. Marginal-marine, shelfal and sabkha carbonate environments, such as those found in the Skates Hills Formation, Neale Formation and its equivalents, and in the Tarcunyah Group have good potential because of the proximity of source, reservoir, and sealing units.

The 1996 field program provided important ties between isolated carbonate outcrops and subsurface control in the deeper parts of the Officer Basin and provides encouragement for further investigation of basin margin play types.

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Triassic correlations on the Peedamullah Shelf, Carnarvon Basin

by A.R. Yasin

Abstract

Ten Triassic sequences have been identified in seven key wells on the Peedamullah Shelf from gamma and sonic log signatures and palynology. Sequences 1–4 are Scythian to Anisian and lie within the Locker Shale, except in Candace 1, where the top of the Locker Shale is older and does not extend to the top of Sequence 4. Sequences 5–10 are Anisian to Rhaetian and lie within the Mungaroo Formation. The lower part of the sequence stratigraphic scheme of Gorter (1994), in which he proposes the Sholl and Cunaloo Formations in the basal part of the Locker Shale, is not consistent with the available palynology. Specifically, the Sholl Formation is not considered a valid lithostratigraphic unit. In Observation 1 and Long Island 1, the Locker Shale was not penetrated as both wells terminated within the Mungaroo Formation. The type section of the Mungaroo Formation in Long Island 1 (749–1992 m), therefore, should be extended to 2158 m, which is the total depth of this well.

KEYWORDS: Triassic, Mungaroo Formation, Locker Shale, Cunaloo Member, correlation, sequences, palynology, Peedamullah Shelf, Carnarvon Basin

The Peedamullah Shelf lies mainly between the Flinders and the Sholl Fault Systems in the east of the hydrocarbon-producing Barrow Sub-basin (Fig. 1). The shelf consists of faulted and folded lower Neocomian (Lower Cretaceous), Jurassic, Triassic, and Palaeozoic rocks overlain by a relatively undeformed blanket of Cretaceous (Upper Neocomian to Campanian) and Tertiary rocks.

The Triassic succession (Fig. 2) is an important part of the stratigraphy of the Peedamullah Shelf and is found only in the subsurface. It consists of a lower shaly component (Locker Shale) of Scythian to Anisian age, conformably overlain by a sandy section (Mungaroo Formation) of Anisian to Rhaetian age (Hocking et al., 1987). The Triassic succession was deposited in offshore-marine, deltaic, and fluvial environments (Hocking et al., 1987). These rocks underlie much of the Northwest Shelf and contain potential source-rock intervals especially in the Locker Shale (Scott, 1994), whereas the Mungaroo Formation is a reservoir in several oil–gas fields (Vincent and Tilbury, 1988; Bauer et al., 1994).

To determine the depositional history of any area it is important to establish sound regional correlations and to define objective stratigraphic subdivisions. On the Peedamullah Shelf, palynology is the main control for regional correlation of the Triassic succession. In previous work on the shelf, Hocking (1985) defined a limestone in the basal Locker Shale (the Cunaloo Member) but did not establish its regional extent. Gorter (1994) attempted a regional correlation of the Locker Shale and the Mungaroo Formation using conodonts and palynological data. He renamed the Cunaloo Member as the Cunaloo Formation and suggested another, stratigraphically lower unit, the ‘Sholl Formation’ in the basal part of the Locker Shale. An alternative regional correlation of the Triassic of the Peedamullah Shelf, based on palynological data and gamma-sonic signatures, is outlined below. The seven wells selected to illustrate this correlation have relatively complete Triassic sections and good palynological control (Fig. 3).

Stratigraphic correlation

The Cunaloo Member (Table 1) is identified in Chinty 1, Onslow 1, Sholl 1, and Candace 1, and is used as the datum for Figure 3. Based on palynology and log signatures, the ‘Sholl Formation’ of Gorter (1994) in Sholl 1 and Candace 1 is not recognized. The intervals representing the ‘Sholl Formation’ in Sholl 1 and Candace 1 are now correlated with the Cunaloo Member (discussed below). Ten informal Triassic sequences have been recognized in the seven key wells on the Peedamullah Shelf based on log signatures, lithology, and palynology, which are also valid in the sequence stratigraphic context.

Sequence 1 lies at the base of the Locker Shale within the *Kraeuselisporites saeptatus* zone. Its

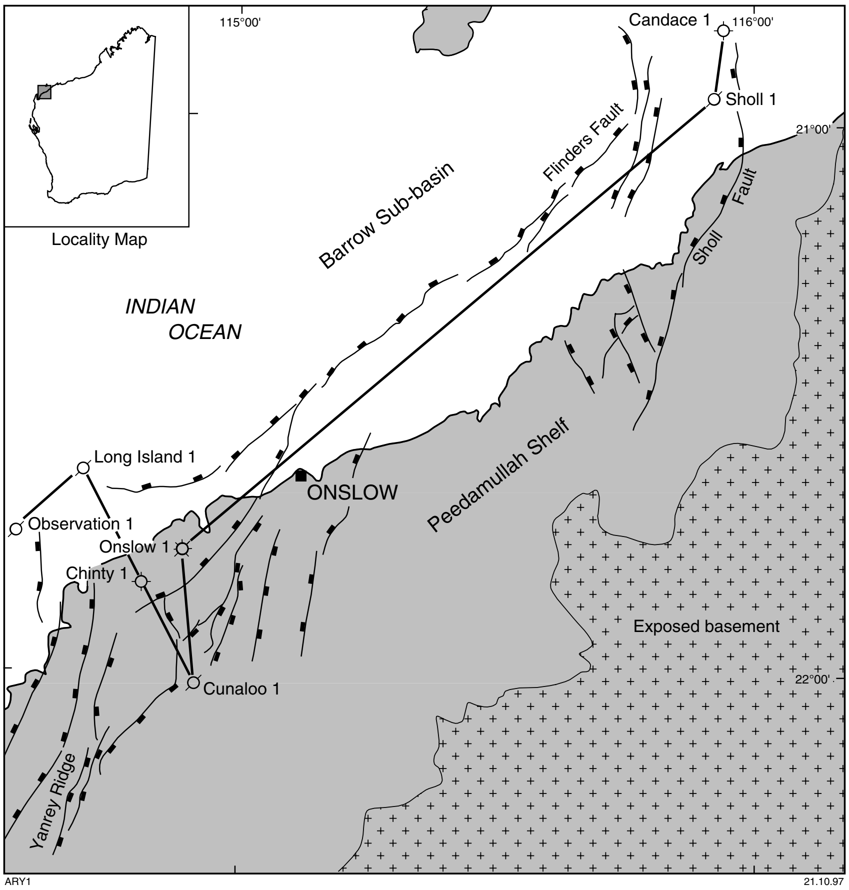


Figure 1. Main faults in the Peedamullah Shelf at the Lower Cretaceous breakup unconformity and the wells used in the Triassic correlation

base is a prominent radioactive shale overlain by a widespread limestone, the Cunaloo Member (Fig. 3). Sequence 1 overlies the Upper Permian Chinty Formation, and in Onslow 1 this contact is considered conformable or slightly disconformable (Parry and Smith, 1988). The basal part of Sequence 1 is transgressive and the Cunaloo Member (mainly limestone) near the top is probably a highstand deposit. Sequence 1 of this paper is equivalent to the lower part of Sequences 1 (in Sholl 1 and Candace 1) and 2a (in Cunaloo 1 and Onslow 1) of Gorter (1994).

Sequence 2 consists of shale and lies within the *K. saeptatus* and the *Tigrisporites playfordii* zones above the Cunaloo Member of the Locker Shale. A widespread horizon is identified within this sequence, dividing it into Sequences 2a and 2b. Sequence 2a fines upward and Sequence 2b coarsens upward, to fine- to very fine-grained feldspathic sandstone (Australian Occidental Petroleum, 1983; Brownhill, 1967a) in its upper part. The radioactive shale at the top of this sequence is probably a marine-flooding surface.

Sequence 3, which consists largely of shale with minor limestone and sandstone, overlies widespread radioactive shale at the top of Sequence 2 (Fig. 3) and is subdivided into Sequences 3a, 3b, and 3c. At the top of Sequence 3a, a limestone (L_2) is present in Candace 1 and Chinty 1 whereas a calcareous horizon is developed in Cunaloo 1 (Meath, 1972). In Sholl 1, limestone is absent from this interval (Brownhill, 1967a) and the top of Sequence 3a correlates to a carbonaceous bed. The tops of Sequences 3b and 3c are sandstone horizons in all wells.

Sequence 4 lies mainly within the *T. playfordii* zone with a thin but extensive sandstone horizon at its base (Fig. 3). In Chinty 1, Onslow 1, and Sholl 1 this sequence consists mainly of shale (Locker Shale), whereas in Candace 1 it is mainly sandstone (Mungaroo Formation). The boundary between the two formations is time transgressive from Candace 1 (*T. playfordii* zone) to Onslow 1 and Chinty 1 (*Staurosaccites quadrifidus* zone). Candace 1 is adjacent to the Sholl Fault (Fig. 1), which has a long history of movement, starting in the Palaeozoic (Bentley, 1988; Delfos and Dedman, 1988). The sands were probably derived from the upthrown Precambrian block east of the Sholl Fault (Fig. 1) and deposited in the Candace 1 area earlier than in the Onslow 1 and Chinty 1 areas.

Sequence 5 in the *S. quadrifidus* zone, is penetrated in Candace 1, Onslow 1, and Chinty 1. Within this sequence a radioactive shale in Onslow 1 (1525 m) correlates to a similar shale in Candace 1 (510 m) and Chinty 1 (970 m) and is used to define Sequences 5a and 5b (Fig. 3). This widespread radioactive shale, also, is considered to be a marine-flooding surface. The base of Sequence 5a is a Type 1 unconformity (Gorter, 1994). Sequence 5a consists largely of sandstone in Candace 1 and Chinty 1, and sandstone with scattered pebbles in Onslow 1. In Candace 1 it shows a coarsening-upward character on the gamma log. Sequence 5b consists of sandstone at the base, and fines upward to shale, suggesting a retrogradational character.

Sequence 6 (shale and sandstone) also lies within the *S. quadrifidus* zone. It fines upward in Onslow 1 and Chinty 1, and is recognized in the basal parts of the succession in Long Island 1 and Observation 1. The basal sandstone in this sequence abruptly overlies shale of Sequence 5, which probably suggests an unconformity. In Onslow 1 this sandstone also contains scattered pebbles at its base. This fining-upwards sequence has a retrogradational character.

Sequence 7 occupies the uppermost interval of the *S. quadrifidus* zone and consists of sandstone with minor shale in Onslow 1. The abrupt basal contact, with scattered pebbles in Onslow 1 and Chinty 1,

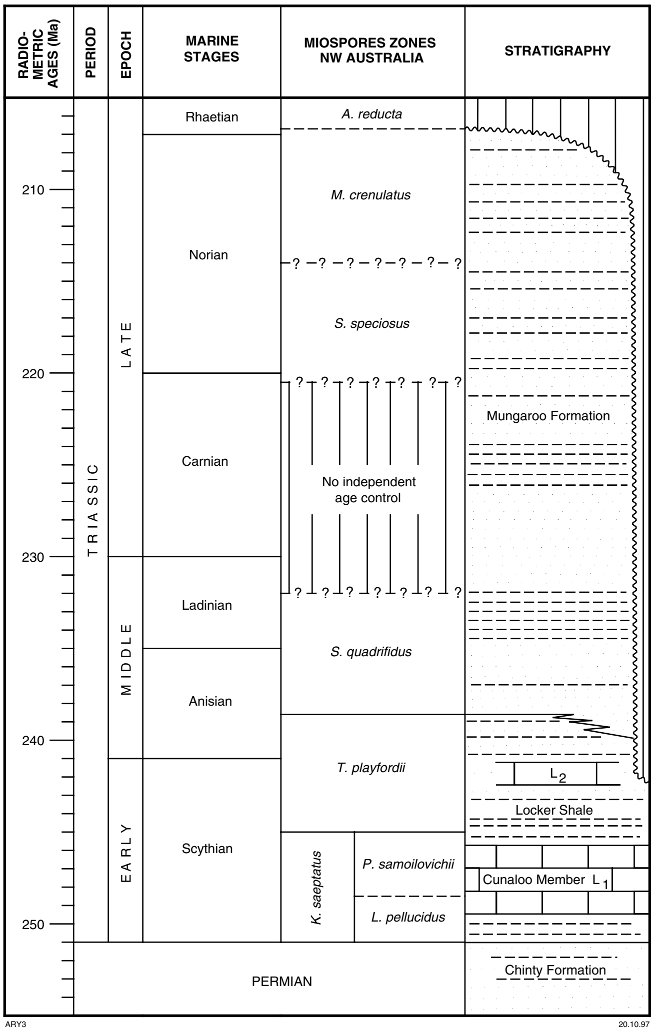


Figure 2. Triassic stratigraphy of the Peedamullah Shelf. The radiometric ages and the miospore zones are from Young and Laurie (1996). The **Lunatisporites pellucidus** *and* **Protohaploxypinus samoilovichii** *zones are after Helby et al. (1987)*

may indicate a local unconformity. A thin sandstone overlain by a prominent shale occurs near the base of the sequence in Onslow 1, Chinty 1, and Long Island 1 (Fig. 3); this may be a transgressive sandstone. Sequence 7 is more shaly in Long Island 1 and Observation 1 than in Chinty 1 and Onslow 1, which are closer to the basin margin.

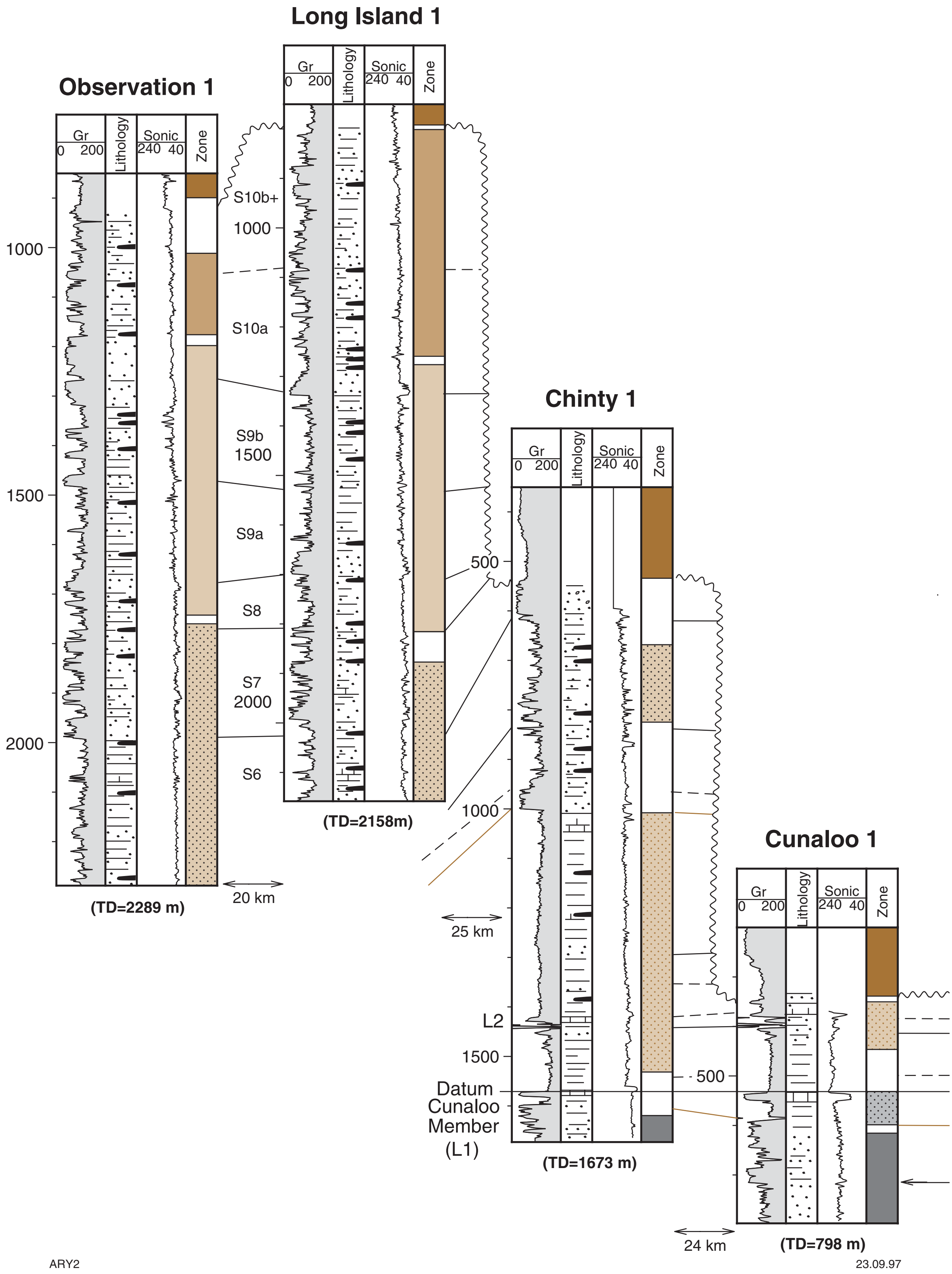
Sequence 8 (lower *Samaropollenites speciosus* zone) is best developed in Long Island 1, where it has a fining-upwards trend followed by a coarsening-upwards trend to its top, perhaps because of relative sea-level change. In both Long Island 1 and Observation 1 carbonaceous beds are present near the base and top of the sequence. This sequence consists largely of shale in Observation 1, which lies basinwards of Onslow 1 where sandstone is dominant.

Sequence 9 lies largely in the *S. speciosus* zone, and is tentatively divided into 9a and 9b after Gorter (1994). In Observation 1, Sequence 9 consists of sandstone near the base followed by a shale-dominant interval and a sandstone near the top. This sequence is mostly shale in Long Island 1 and mostly sandstone towards the basin margin in Onslow 1.

Sequence 10 (*S. speciosus* to *Minutosaccus crenulatus* zones) is subdivided into Sequences 10a and 10b (Fig. 3). In Long Island 1, Sequence 10a consists of sandstones near the base and top, separated by a thick shale-dominated interval. In Observation 1, Sequence 10a consists mainly of sandstone with a relatively thin shale in the middle. Sequence 10b is terminated by the Lower Cretaceous breakup unconformity.

Discussion

Sequences 5–10 in this paper generally correspond to those of Gorter (1994), but Sequences 1–4 differ significantly. These differences are due to the addition by Gorter (1994) of the 'Sholl Formation' near the base of the Locker Shale in Sholl 1 and Candace 1. Gorter (1994) recognized two limestones (here differentiated as L_1 and L_2 in Figure 3) in Sholl 1 and Candace 1 and one limestone (L_1) in Cunaloo 1 and Onslow 1 in the lower Locker Shale. In Sholl 1 he considered the upper limestone (L_2) to be the Cunaloo Formation and correlated it to the limestone (L_1) in Cunaloo 1 and Onslow 1. On conodont data he suggested that the lower limestone (L_1) in Sholl 1 was older than both the limestone beds in Cunaloo 1 and Onslow 1, and named the lower limestone


Long Island 1
Observation 1
Chinty 1
Cunaloo 1
Gr
0 200
Lithology
Sonic
240 40
Zone
S10b+
S10a
S9b
S9a
S8
S7
S6
1000
1500
2000
500
L2
Datum
Cunaloo
Member
(L1)
(TD=2289 m)
(TD=2158m)
(TD=1673 m)
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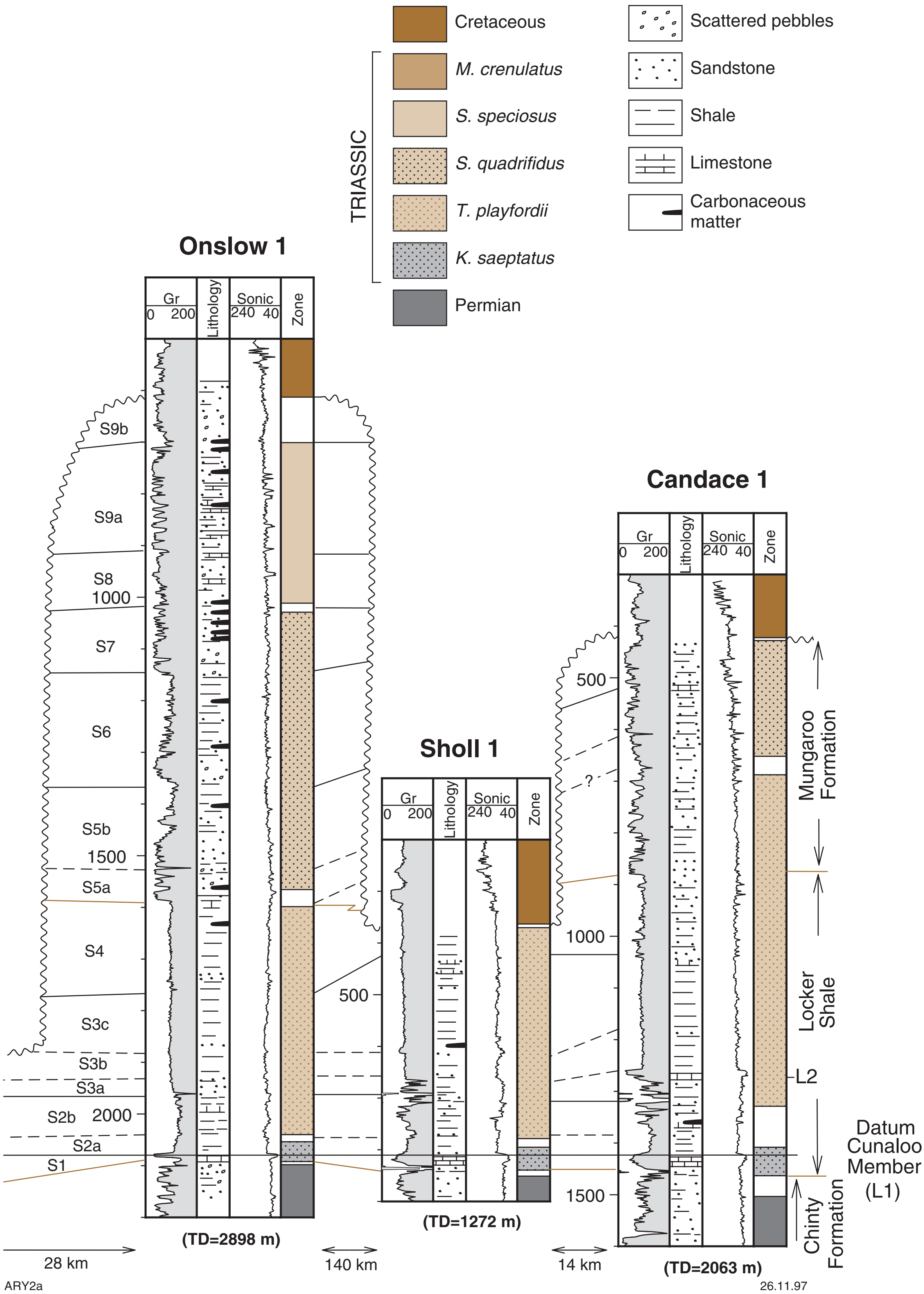

Figure 3. Well correlation of the Triassic of the Peedamullah Shelf. Palynological details for individual wells are summarized in Table 2

Table 1. Triassic stratigraphic units on the Peedamullah Shelf

Unit	*Type section*	*Lithology*	*Stratigraphic relationships*	*Author*
Mungaroo Formation	Long Island 1 749–2158 m [(a)] Latitude: 21°37'10" Longitude: 114°41'10"	Interbedded sandstone, claystone, siltstone with thick sandy intervals, minor coal and conglomerate, areally variable	Conformable on Locker Shale	Parry (in Jones, 1967) amended by Playford et. al., (1975)
Locker Shale	Onslow 1 1587–2096 m Latitude: 21°45'17" Longitude: 114°52'17"	Dark pyritic shale with local sandstone interbeds and basal limestone (Cunaloo Member)	Apparently conformable on Chinty Formation, unconformable on older rocks	Parry (in Jones, 1967)
Cunaloo Member	Cunaloo 1 534–548.6 m Latitude: 22°00'48" Longitude: 114°53'47"	White, pale brown or grey lime mudstone, locally recrystallized, calcareous siltstone, near the base pyritic black shale	Conformable within Locker Shale	Hocking (1985)
Sholl Formation	Sholl 1 806–850 m [(b)] Latitude: 20°57'00" Longitude: 115°53'50"	White, fine-medium grained crystalline calcarenite and pink sucrosic limestone (Brownhill, 1967a)	Conformable within Locker Shale	Gorter (1994)
Cunaloo Formation	Cunaloo 1 534–548.6 m [(b)] Latitude: 22°00'48" Longitude: 114°53'47"	Same as the Cunaloo Member	Conformable within Locker Shale	Gorter (1994)

Notes:
(a) Modified herein
(b) Estimated, as not specified in original paper

unit (L_1) in Sholl 1 the 'Sholl Formation'.

Gorter (1994) noted that the palynological zones of Helby et al., (1987) are broad and suggested that conodonts provide the most precise control for the correlation of basal Triassic rocks in the Carnarvon Basin. However, the conodont data used to distinguish the 'Sholl Formation' in Sholl 1 are poor. The presence of the *Neospathodus dieneri* conodont zone in Sholl 1 is based on two composite ditch cuttings that yielded only three specimens of the zonal species (McTavish, 1973). As there are no conodont data from Candace 1, the correlation of the 'Sholl Formation' between Sholl 1 and Candace 1 was based entirely on lithology and log character and is not supported by current palynological data.

Palynologically, the 'Sholl Formation' in Sholl 1 and Candace 1 and the Cunaloo Member (Cunaloo Formation of Gorter, 1994) in Cunaloo 1, and Onslow 1 fall within the *K. saeptatus* zone (Fig. 3). Gorter (1994, fig. 7) correlates intervals within the *K. saeptatus* zone in Cunaloo 1 and Onslow 1 with intervals within the *T. playfordii* zone in Candace 1 and Sholl 1. The palynological correlation is referred to here (Table 1), and the 'Sholl Formation' of Gorter (1994) is not recognized. The lower limestone (L_1) in Sholl 1 is identified as the Cunaloo Member of Hocking (1985). Because of lateral variation in its lithology from limestone (Candace 1, Chinty 1, Cunaloo 1) to sandstone (Sholl 1, Onslow 1), the upper (L_2) horizon, in the lower part of the Locker Shale, is not named. The two limestones or their equivalent horizons (L_1 and L_2) are identified in Chinty 1, Onslow 1, and Cunaloo 1 in addition to Sholl 1 and Candace 1. The resulting correlation (Fig. 3) honours the palynological data and is supported by log signatures.

The interval now assigned to Sequence 6 was originally referred to the Locker Shale in Long Island 1 (Brownhill, 1967b) and Observation 1 (Watson, 1968). This sequence lies within the *S. quadrifidus* zone, and in Chinty 1 and Onslow 1, well above the base of the Mungaroo Formation. As these wells are close (Fig. 1) it is likely that the sand-rich Sequence 5 of Chinty 1 and Onslow 1 (Mungaroo Formation) is also present in the vicinity of Observation 1 and Long Island 1, although it was not penetrated in either well. The Locker Shale (Sequences 1 to 4) in Chinty 1 and Onslow 1 falls within the *T. playfordii* zone. As it is unlikely that the Locker Shale is markedly time transgressive over such a short distance (25 km), Long Island 1 and Observation 1 probably did not reach this unit and were still in what should be properly regarded as Mungaroo Formation at their total depths. Consequently, the interval 749–1992 m in Long Island 1, designated as the type section

Table 2. Palynological zones for wells from the Peedamullah Shelf (data from Dolby and Balme, 1976; Morgan and Ingram, 1990)

Well	*Depth (m)*	*Zone*
Candace 1	418.5–629	*S. quadrifidus*
	665–1320	*T. playfordii*
	1404.9–1457.5	*K. saeptatus*
Chinty 1	674–827	*S. quadrifidus*[(a)]
	1003–1512	*T. playfordii*[(b)]
Cunaloo 1	356.5–429.8	*T. playfordii*
	530.4–584.6	*K. saeptatus*
Long Island 1	795.5–1270.7	*M. crenulatus*
	1285.6–1604.5	*S. speciosus B*
	1637.7–1803.5	*S. speciosus A*
	1858.7–1877	*S. quadrifidus B*
	1886.1–2157.9	*S. quadrifidus A*
Observation 1	1015–1234.4	*M. crenulatus*
	1260.7–1766.6	*S. speciosus*
	1781.8–2289	*S. quadrifidus*
Onslow 1	695.6–716.9	*S. speciosus B*
	737.9–994.3	*S. speciosus A*
	1005.8–1563.6	*S. quadrifidus*
	1600.2–2023.6	*T. playfordii*
	2051.3–2090.7	*K. saeptatus*
Sholl 1	341.4–776.3	*T. playfordii*
	792.8–837.3	*K. saeptatus*

Notes:
(a) Backhouse, J., 1996, pers. comm.
(b) Fell (1985)

(Table 1) of the Mungaroo Formation (Playford et al., 1975) should be extended to 2158 m (the total depth of the well).

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Calculating depth to basement from magnetic and gravity data, with an example from the western Officer Basin

by S. I. Shevchenko and R. P. Iasky

Abstract

A procedure for calculating depth to crystalline basement in sedimentary basins is demonstrated by integrating interpretations from aeromagnetic and gravity datasets from the Officer Basin. The initial step in this procedure is to calculate depths to magnetic basement by deconvolving aeromagnetic data with the Euler method. This method provides geologically plausible depth solutions only where there are magnetic sources at the top of basement. The depths to magnetic basement then provide constraints to determinations of subsurface topography of crystalline basement from the gravity data, thereby producing a detailed picture of depth to basement.

In the poorly explored western Officer Basin, depth to crystalline basement calculated using this integrated procedure shows good correlation with seismic mapping of a horizon near the base of the sedimentary succession. In the Officer Basin, the top of basement is difficult to interpret from seismic data, and potential-field data provide a more reliable way to generate such a map.

KEYWORDS: Bouguer gravity, basin structure, Euler deconvolution, magnetics, Officer Basin, residual gravity.

Potential-field data can be used to provide estimates of the thickness of sedimentary strata and the geometry of basins. These are important parameters in understanding the evolution of basins. Potential-field data have been used by the petroleum industry since the 1920s as preliminary reconnaissance programs in frontier areas. In the absence of seismic data, petroleum companies estimated the thickness of sedimentary basins by modelling depth to magnetic basement. More recently, with superior computers, such calculations can be made over large areas using automated depth-to-source techniques on profile data (Naudy, 1971) or gridded data (Reid et al., 1990). The calculations of depth to magnetic basement, however, may provide a range of solutions which do not necessarily represent the base of the sedimentary succession. This is because magnetic anomalies may be present at any level within either the sedimentary or basement rocks. Also, reliable solutions for depth to magnetic basement are normally too sparse to define basement topography.

Generally, the petroleum industry has preferred aeromagnetic data to gravity data in determining depth to basement because, for similar costs, aeromagnetic surveying is logistically easier to conduct and provides a greater density of data than ground gravity surveying. In contrast to magnetic data, the gravity field is more suitable for mapping basement topography as there is usually a significant density contrast between crystalline and sedimentary rocks. The accuracy in determining depth to crystalline basement from gravity data depends on the accurate estimation of the regional gravity field and the density contrast between crystalline and sedimentary rocks. Deep crustal structures largely determine the regional gravity field, which is critical in modelling depths to basement from gravity data. Inaccuracies in determining depth to basement from gravity data may also arise by assuming a homogeneous sedimentary section or a constant density contrast between basement and sedimentary rocks. The inaccuracies inherent in making these assumptions are generally accepted because inhomogeneous bodies are impractical to model.

Depth to basement calculations integrating both gravity and magnetic interpretations are more accurate than using either method separately. A procedure integrating these interpretations is applied to data from the western Officer Basin, where the results are compared with those of previous attempts to caculate depth to basement from either magnetic or seismic data.

Calculating depth to basement

The initial step of the procedure is to calculate depths to magnetic basement by deconvolving gridded aeromagnetic data with Euler's equation (Reid et al., 1990). The Euler deconvolution method is an automatic depth estimate to magnetic sources that can locate or outline confined sources and contacts with remarkable accuracy. In this method, the position of the source is determined by the gradient of the anomaly, and the depth to the source is determined from the wavelength. An important input to the Euler equation is the structural index (ranging from 0 to 3), which is a measure of the rate of change of the potential field with distance, and dictates the degree of homogeneity of the field (Reid et al., 1990).

The grid cell size of the aeromagnetic data is critical in determining the frequencies of anomalies to be processed by the Euler deconvolution, but the range of depths to basement must first be known. In the absence of well or seismic data, an initial estimate of depth to basement can be modelled across short distances from gravity data. Grid cell size for the aeromagnetic data is then chosen by trial and error until the Euler deconvolution produces a geologically plausible depth range. In addition, with the Euler method, threshold depths can be used to discriminate solutions outside the expected depth range. The structural index to be used in sedimentary basins normally lies between 0 and 1, being closer to 0 in the case of a broad, relatively unfaulted sag and closer to 1 in the case of highly irregular terrains containing faults with extremely large throws. A structural index of 0.5 is generally a reasonable compromise because it best defines anomalies generated by faults (Reid et al., 1990). The Euler deconvolution method statistically analyses and determines confidence levels for depth solutions. Depth solutions including a broad range of reliabilities should be chosen to confidently identify structural features of interest.

The Euler deconvolution displays linear clusters of depth solutions where there are magnetic sources such as basement faults (Reid et al., 1990). Depths to these features are assumed to be reliable only where they correspond to structures identified from outcrop, seismic or gravity data. Where there is no outcrop or seismic control, coincidence of the Euler depths with lineaments identified on the first vertical derivative of Bouguer gravity may be used as a guide for depth to basement. These depths are gridded as reliable solutions of depth to magnetic basement (D_{mb}), and are assumed to represent the top of crystalline basement.

Assuming a constant density contrast between sedimentary and basement rocks, the gravity field can provide good definition of basement topography. The initial step in determining basement topography from gravity is to calculate residual gravity (G_{res}), by subtracting the regional (G_{reg}) from the Bouguer (G_{bou}) gravity (Equation 1) using gridded data. The Bouguer gravity is produced from a regional gravity coverage over the basin, and the regional gravity is calculated by using Bouguer gravity values from locations where depths to crystalline basement have been previously estimated. These gravity points are obtained from lineaments defined by the Euler depth solutions, outcrops, or wells that penetrated basement.

$$G_{res} = G_{bou} - G_{reg} \quad (1)$$

The gravity effect of the basin (G_{dgb}) is calculated, using the equation for an infinite slab with a constant density contrast (Telford et al., 1976; Equation 2).

The gravity effect (Δg) of an infinite slab of a constant density contrast is:

$$\Delta g = 2\pi d\gamma\Delta\delta \ (\mu m\ sec^{-2}) \quad (2)$$

where

d = thickness of the body (m)
γ = gravity constant (6.67×10^{-8} cm^2 gm^{-1} sec^{-2})
$\Delta\delta$ = density contrast (g cm^{-3})

The total gravity effect of a sedimentary basin is calculated by adding the Euler deconvolved depths to magnetic basement (G_{dgm}) to the residual gravity (Equation 3):

$$G_{dgb} = G_{dgm} + G_{res}$$

where

$$G_{dgm} = 2\pi D_{mb}\gamma\Delta\delta \quad (3)$$

Finally the depth to basement (D_b) is calculated from the equation for an infinite slab (Equation 4):

$$D_b = G_{dgb}/2\pi\gamma\Delta\delta \quad (4)$$

Western Australian Officer Basin

The western Officer Basin is an episutural basin that covers about 330 000 km^2, and contains approximately 1000 m of Mesoproterozoic rocks, and up to 7000 m of Neoproterozoic strata underlying a maximum of 1000 m of Phanerozoic sedimentary rocks. The main sub-basins can be identified on the gravity image as gravity lows (Fig. 1). The total sedimentary succession overlies predominantly granitic and metamorphic rocks of the Musgrave Complex to the northeast and granitic rocks of the Yilgarn Craton to the southwest. The basin is asymmetric with its deepest part along the north-northeastern boundary adjacent to the Musgrave Complex. Detailed accounts of the structure and stratigraphy of the basin are in Jackson and van de Graaff (1981), Townson (1985) and Perincek (1996).

The western Officer Basin has been underexplored for petroleum and minerals. However, the Australian Geological Survey Organisation (AGSO), formerly the Bureau of Mineral Resources, covered the entire basin with regional gravity (11 km grid) in the early 1960s, and aeromagnetics with traverse line spacing of 1.5–3 km in 1960 and 1975–1977. Two phases of petroleum exploration in the basin were conducted from the 1960s to early 1980s by a number of companies including Hunt Oil, CRA Exploration, Eagle Corporation Ltd, Shell Company of Australia and News Corporation Ltd. During this exploration approximately 6200 km of seismic lines were recorded and nine wells drilled. In 1995–1996, the Japan National Oil Corporation (JNOC) conducted the latest phase of petroleum exploration by carrying out 86 854 km of high-resolution aeromagnetic surveying, and reprocessing numerous seismic lines.

Townson (1985) and JNOC (1997) determined depth to magnetic basement using different automated

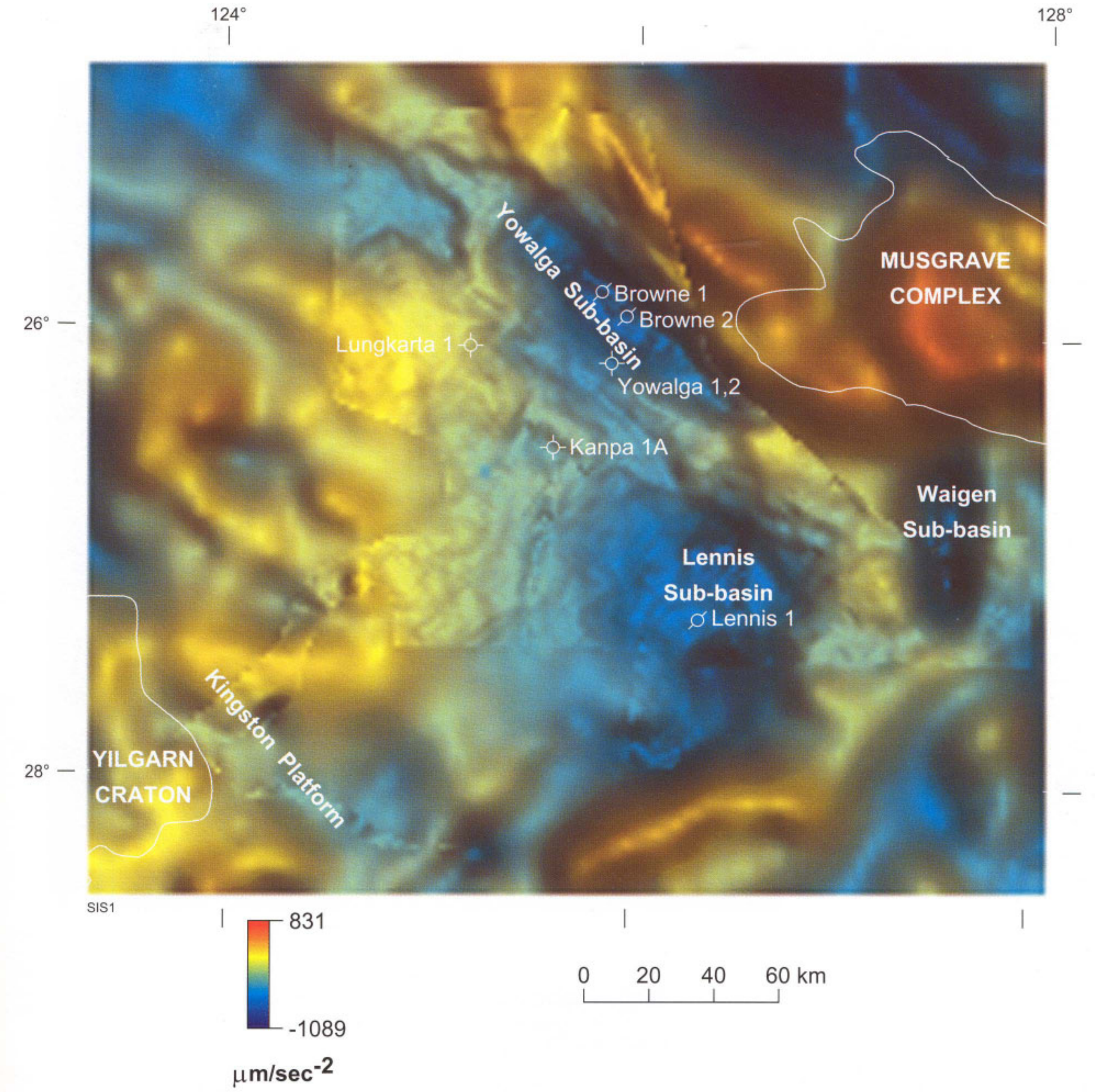


Figure 1. Bouguer gravity image of the western Officer Basin

techniques and achieved, in places, contrasting results. The results are similar in areas where there are strong magnetic sources at basement level, but elsewhere the correlation is poor. In particular, basement gradually shallows towards the outcropping Yilgarn Craton to the southwest but in this area, the JNOC (1997) contours are perpendicular to the expected trend (Fig. 2).

In the procedure described above, depth solutions from magnetic sources in the western Officer Basin were calculated by deconvolving the regional AGSO aeromagnetic data (Fig. 2) gridded at 1 km with the Intrepid ® Euler deconvolution module. The Euler deconvolution parameters applied to the data include a structural index of 0.5, operating window of 15 grid cells, and reliability coefficients from 3 to 80%. A depth threshold range of 1–30 km was used to exclude very high and very low frequencies and to include intermediate and low frequency anomalies. Depth solutions were averaged over a 1 km radius and displayed in a colour range as grid cells of 1 km (Fig. 3). Generally, linear clusters of consistent depth solutions are reliable and tend to correspond to gravity lineaments or seismically mapped faults. Depth solutions along these prominent lineaments or clusters (circled in black in Fig. 3) were contoured and the results are similar to the earlier attempt by Shell (Fig. 2). On these maps

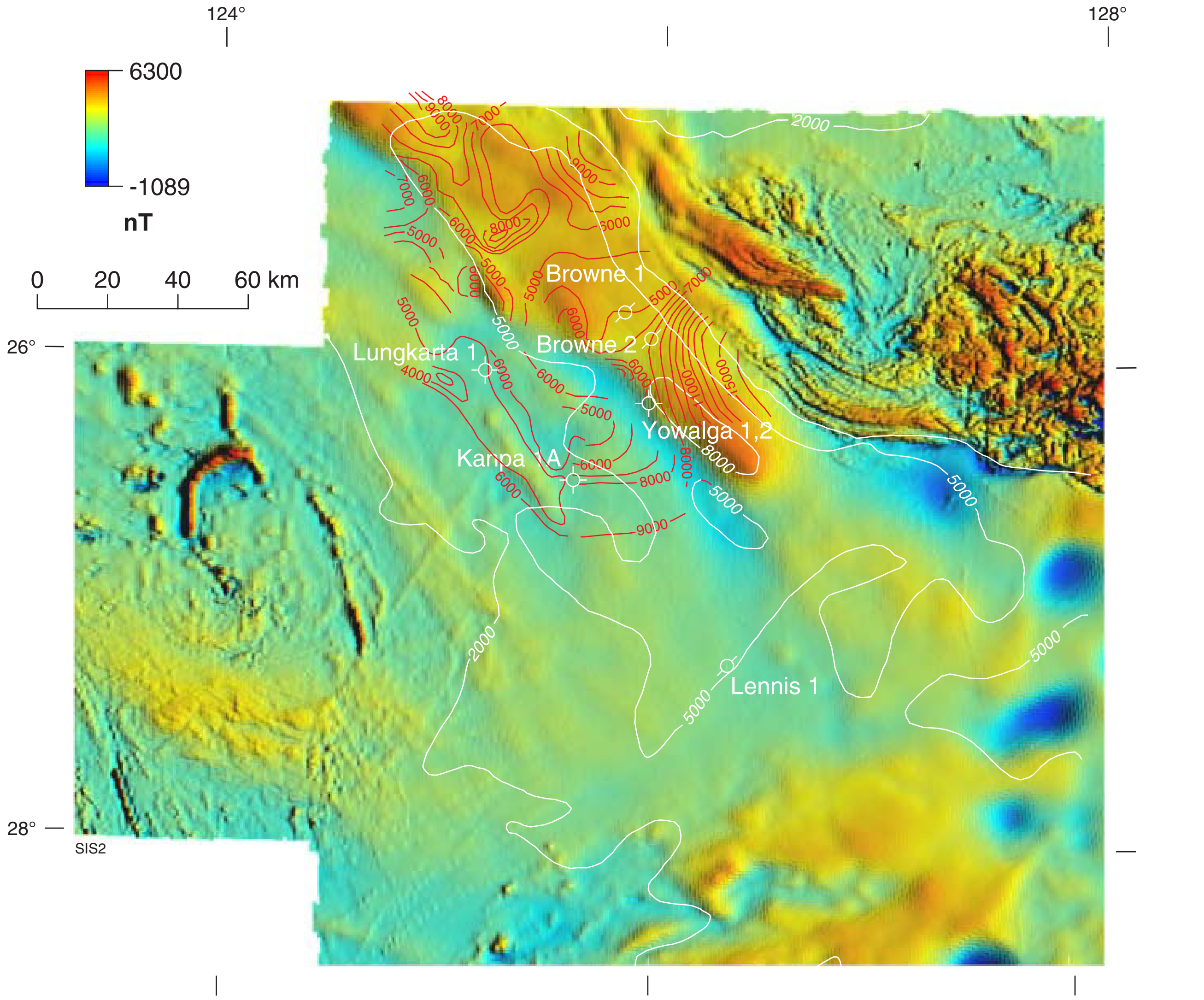
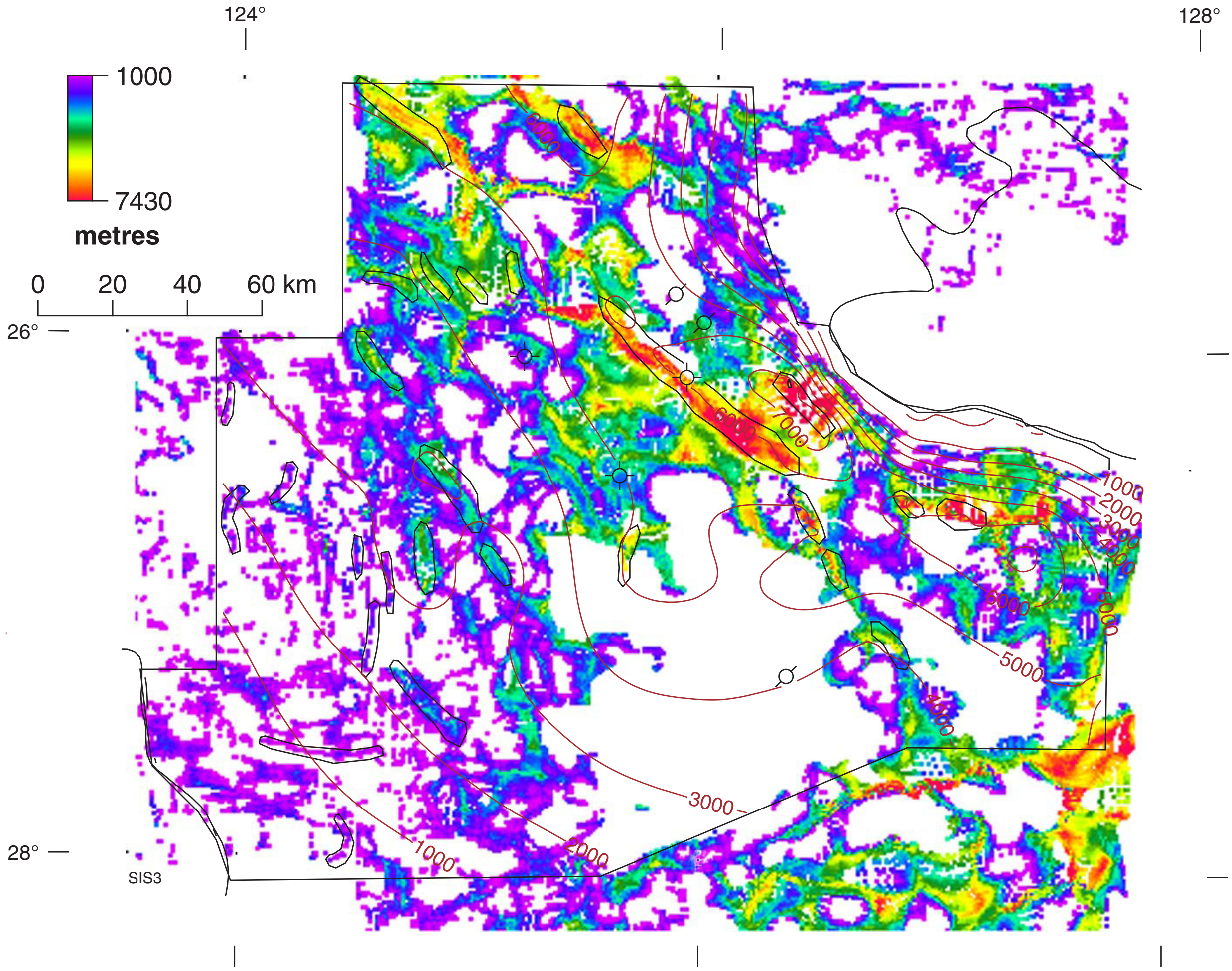


Figure 2. TMI image of the western Officer Basin with depth to magnetic basement contours (white from Townson, 1985; red from JNOC, 1997)

basement is deepest in the northeast next to the Musgrave Complex, and shallowest to the southwest towards the Yilgarn Craton. The depth to magnetic basement solutions, and the position of the troughs, however, do not show a good correlation with the seismic mapping by JNOC (1997).

The interpreted base of the Neoproterozoic succession (base of Townsend Quartzite) was mapped by JNOC (1997) from seismic data as acoustic basement. Because of the structural complexity of the basin and the poor seismic response at depth, this map is inaccurate and it is unclear whether the mapped horizon represents crystalline basement or some intra-Mesoproterozoic horizon. A more accurate definition of basin geometry is provided by the top of the Townsend Quartzite seismic horizon (Fig. 4), which was mapped by JNOC (1997) with greater confidence. This horizon is approximately 250 m above the base of the Neoproterozoic (Jackson and van de Graaff, 1981).

The depth to crystalline basement of the western Officer Basin was calculated from the gravity data using Equations 1–4 with a density contrast of 0.2 g/cm^3 (Fig. 5). This contrast was based on an average density of 2.47 g/cm^3 for the sedimentary succession, obtained from the density logs of two deep petroleum exploration wells (Kanpa 1A and Yowalga 3), and 2.67 g/cm^3 for crystalline basement. Because basement density in the Kingston Platform on the western margin of the basin (Fig. 1) is not homogeneous, only Euler-deconvolved solutions were used to define depth to crystalline basement in this area. The contours of the depth to crystalline basement determined from the potential field data for the whole basin (Fig. 5) are consistent with those of the depth to the top Townsend Quartzite (Fig. 4). The depth values from potential-field data are greater than the depths to the top of this unit by some 1000 m, which is approximately the thickness of the Mesoproterozoic strata. Because the detailed



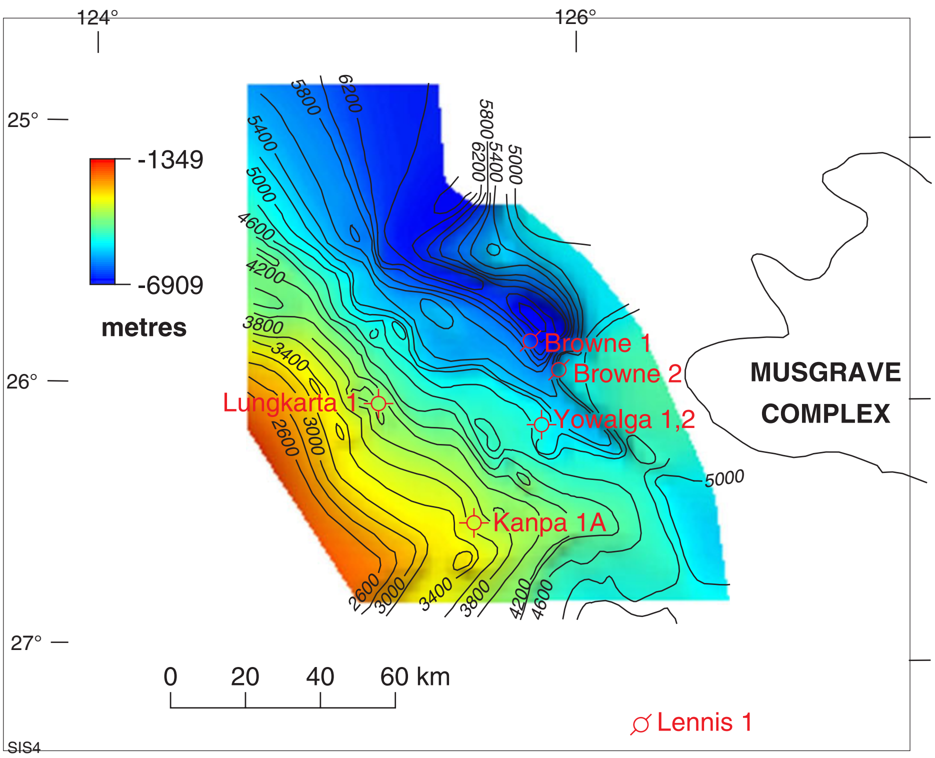


Figure 3. Euler-deconvolved depths to magnetic basement of the western Officer Basin. Depth solutions along well-defined lineaments are circled in black and contoured

Figure 4. Seismic depth to top of Townsend Quartzite (JNOC, 1997)

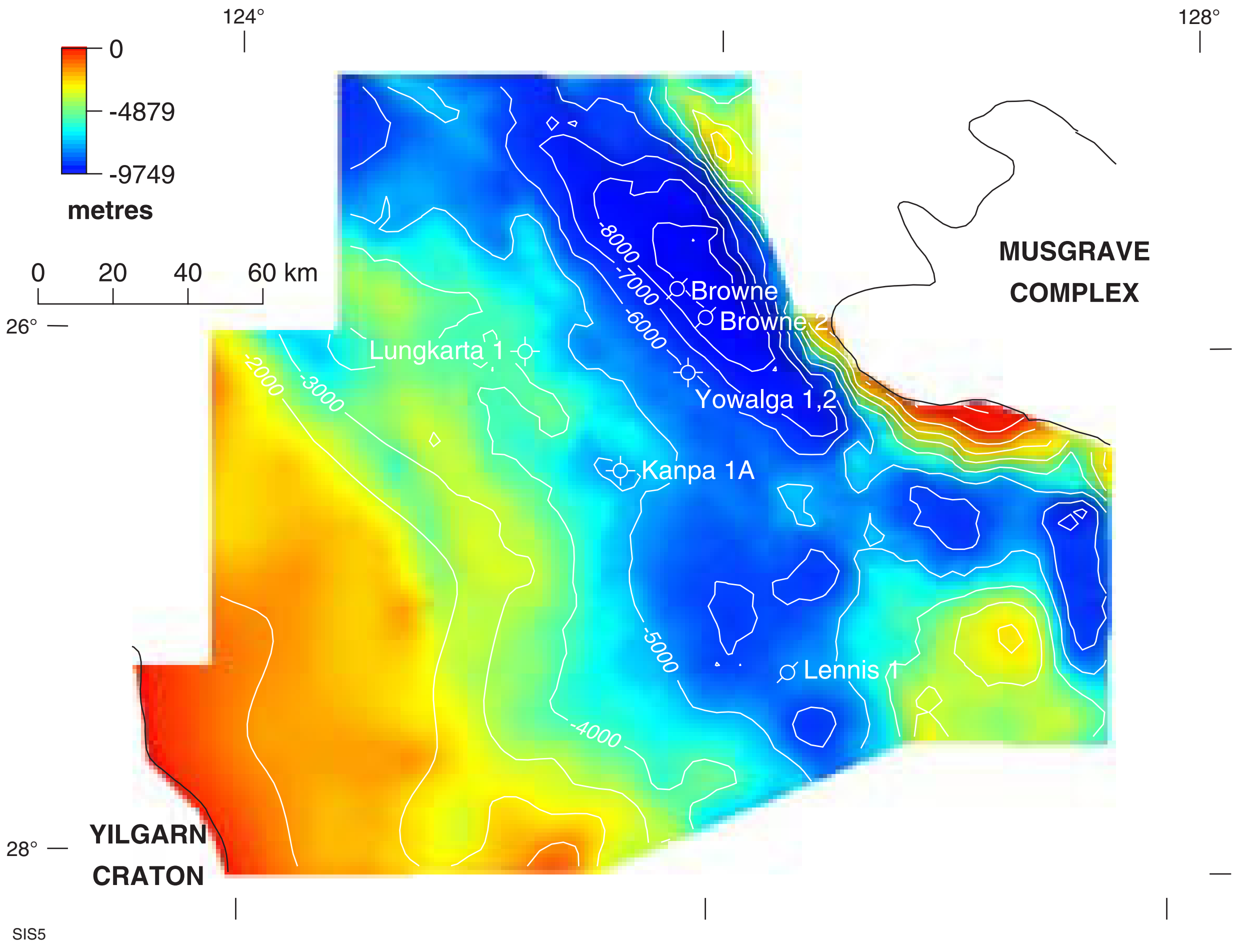


Figure 5. Depth to basement of the western Officer Basin interpreted from both gravity and magnetic data

basement topography was calculated from the gravity data, the geometry of the final result (Fig. 5) is broadly similar to the Bouguer gravity image (Fig. 1).

The procedure described herein defines basement topography in detail and accurately locates major troughs, whereas previous attempts only broadly delineated basement.

Discussion

Calculating depth to crystalline basement using either magnetic or gravity data can be inaccurate because basement may have few magnetic sources, the regional gravity field is difficult to define, and the sedimentary section can be inhomogeneous. The procedure presented here for calculating depth to crystalline basement from potential-field data minimizes such inaccuracies and, in the western Officer Basin, gives results broadly comparable to the seismic mapping. Where seismic data are sparse, absent, or of poor quality, this procedure can provide a simple and reliable technique to determine the thickness and geometry of a basin.

The accuracy of the above procedure depends on the accuracy of the depth solutions from the Euler-deconvolved magnetic data, and on the sedimentary section and basement densities being relatively homogeneous. In the procedure, calculating the gravity effect of the sedimentary basin was simplified by using the infinite slab equation with a constant density contrast. A further refinement in calculating the gravity effect of the sedimentary basin, however, could be made by using an equation that allows for the effects of surrounding topography, and increasing density with depth.

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A revision of the stratigraphy of Archaean greenstone successions in the Roebourne – Whundo area, west Pilbara

by A. H. Hickman

Abstract

New field and geochronological data require a complete revision of the greenstone stratigraphy of the Roebourne – Whundo area, and establish that previous stratigraphic correlations between the east and west Pilbara were incorrect. A major crustal fracture of the west Pilbara, the Sholl Shear Zone, separates volcanic and sedimentary successions of differing stratigraphy, metamorphic grades, and ages. Greenstones north of the Sholl Shear Zone were deposited between 3270 (or older) and 3020 Ma, and are assigned to the Roebourne Group and the Cleaverville Formation. Greenstones south of the shear zone were deposited between 3125 and c. 2925 Ma, and are now assigned, from older to younger, to the Whundo Group, the Cleaverville Formation, the Whim Creek Group, the Louden Volcanics, and the Kialrah Rhyolite. Recognition of the Cleaverville Formation on both sides of the Sholl Shear Zone shows this to be a major fault rather than a suture.The new data have important implications for tectonic models and regional stratigraphic correlations.

KEYWORDS: West Pilbara, greenstone stratigraphy, Roebourne Group, Whundo Group, Whim Creek Group, Regal Formation, Woodbrook Formation, Cleaverville Formation, Louden Volcanics, Kialrah Rhyolite, geochronology

Current geological mapping in the western part of the Pilbara Craton is rapidly improving our understanding of the stratigraphy, structure, tectonic evolution, and mineral potential of the granite–greenstone terrain in this area. When the project began in late 1994, differences between the three main stratigraphic interpretations for the west Pilbara (Hickman, 1983; Horwitz, 1990; Krapez, 1993) reflected an inadequacy of data. In this paper, a summary of the revised greenstone stratigraphy is presented, based on new data from recent mapping and geochronology. More detailed descriptions and complete formal definitions will be provided in subsequent publications.

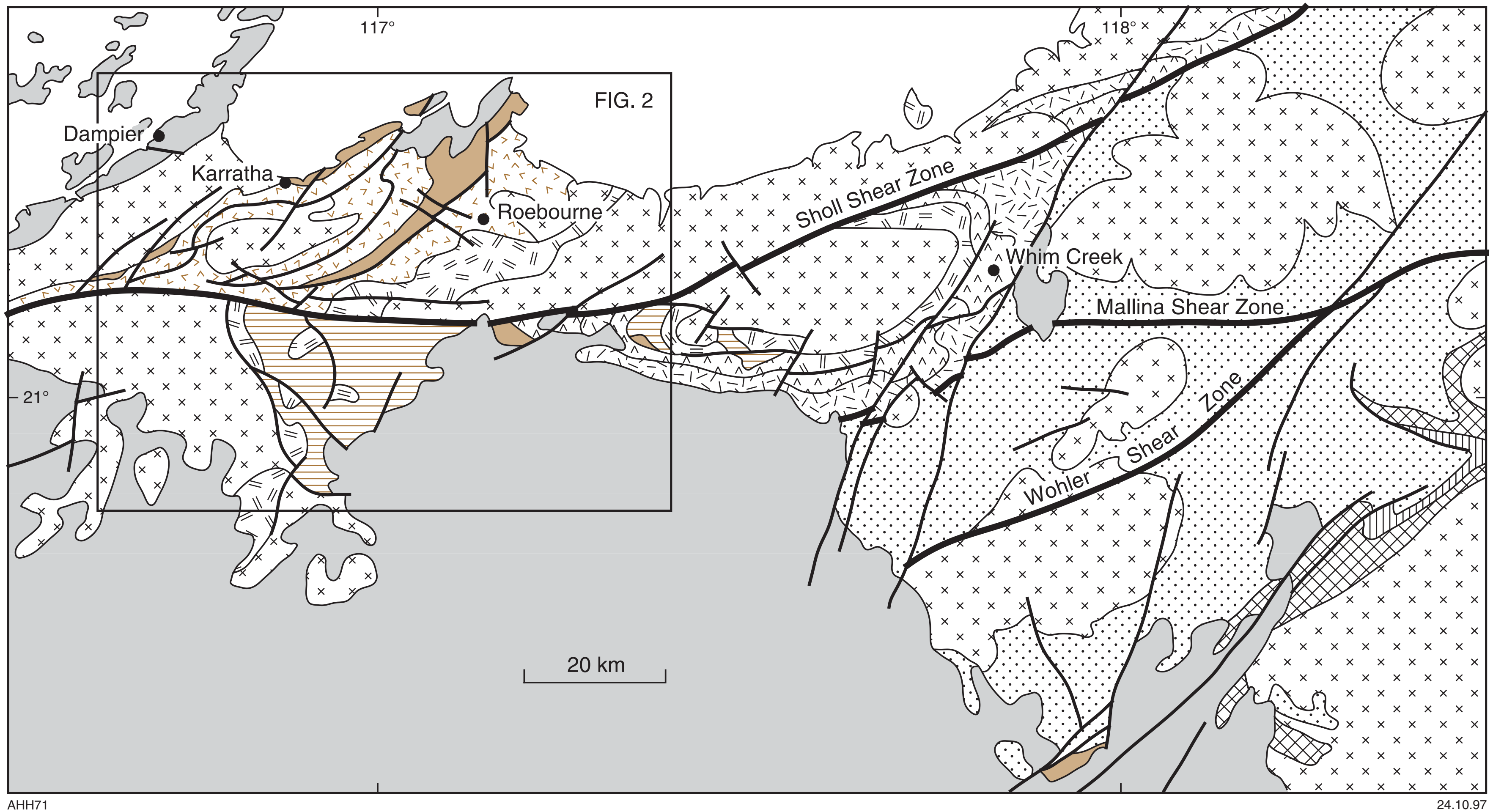
Stratigraphy

This, and other recent studies (Nelson, 1996, 1997, in prep.; Smith et al., in press), have indicated that the Warrawoona Group (c. 3500–3430 Ma) of the east Pilbara is absent from the west Pilbara succession (Fig. 1). Current data suggest that the oldest greenstones in the west Pilbara were deposited at about 3270 Ma, and that these are restricted to the area north of the Sholl Shear Zone between Roebourne and Karratha (Fig. 1). The greater part of the greenstone succession north of the shear zone belongs to the redefined Roebourne Group (Table 1), whereas the greenstones south of the shear zone are now assigned to a more complex stratigraphic succession (Table 2). Figure 1 shows the regional setting of the area described in this paper.

Roebourne Group

The name Roebourne Group was originally used by Ryan (1964) to refer collectively to all greenstones of the west Pilbara, but subsequent recognition of internal unconformities has invalidated this application. As now redefined, the Roebourne Group is composed of three formations, with a combined stratigraphic thickness of approximately 4000 m (Table 1).

The contact between the Nickol River and Regal Formations is mylonitized throughout most of the area, but important lithological differences preclude the Regal Formation from being a tectonic repetition of the Ruth Well Formation. Extrusive peridotite is much more thickly developed in the Ruth Well Formation than in the Regal Formation, which has only a laterally discontinuous basal ultramafic unit. Moreover, there is no equivalent of the Nickol River Formation above the Regal Formation. Competency differences between the pelitic upper part of the Nickol River Formation and the relatively massive volcanics of the lower Regal Formation probably induced layer-parallel shear along



West Pilbara succession

- Layered mafic intrusion (c. 2925 Ma)
- Louden and Mount Negri Volcanics
- De Grey Group (c. 3000 Ma)
- Whim Creek Group (c. 3010 Ma)
- Cleaverville Formation (c. 3020 Ma)
- Whundo Group (c. 3120 Ma)
- Roebourne Group (c. 3270–3050 Ma)

East Pilbara succession

- De Grey Group (c. 3000 Ma)
- Gorge Creek Group (< 3240 Ma)
- Warrawoona Group (> 3430 Ma)
- Late Archaean rocks
- Granitoids
- Major shear zone
- Shear zone/ fault

Figure 1. Regional setting of the Roebourne–Whundo area

Table 1. Revised stratigraphy of the Roebourne Group

Formation	*General thickness (m)*	*Lithology and relationships*
Regal Formation (revised name)	2000	Basal peridotitic komatiite overlain by pillow basalt and local chert units. Intruded by microgranite and felsic porphyry (not dated)
		Tectonized contact
Nickol River Formation (revised name)	100–500	Banded chert, iron-formation, ferruginous clastic sedimentary rocks, quartzite, felsic volcanic, volcanogenic sedimentary rocks and local conglomerate. Locally intruded by peridotite. Contact with Regal Formation is generally tectonic. Rhyolite near Mount Regal dated at 3251 ± 6 Ma
Ruth Well Formation (revised name)	1000–2000	Basalt and extrusive peridotite with thin chert units. Intruded by Karratha granodiorite dated at 3261 ± 4 Ma

Table 2. Stratigraphy of greenstones south of the Sholl Shear Zone, Roebourne–Whundo area

Group/Formation	*General thickness (m)*	*Lithology and relationships Age*
Kialrah Rhyolite (new name)	1000	Feldspar-phyric, commonly flow-banded rhyolite. Age 2972 ± 2 Ma
Louden Volcanics	300	Komatiitic basalt and pillow tholeiite
~~*Low-angle unconformity*~~~		
Whim Creek Group		
Cistern Formation	100	Felsic tuff and volcanogenic sedimentary rocks; minor quartzite and chert. Age c. 3010 Ma
Warambie Basalt	300–500	Vesicular, pyroclastic, and amygdaloidal basalt, with hyaloclastite and local pillow basalt. Basal polymictic conglomerate and sandstone
~~*High-angle unconformity*~~~		
Cleaverville Formation	1500	Banded iron-formation, chert, fine-grained clastic sedimentary rocks, and dacite–rhyolite ?sills. Age c. 3020 Ma
~~*?Low-angle unconformity*~~~		
Whundo Group		
Woodbrook Formation (new name)	1000	Rhyolite tuff and agglomerate; minor basalt and thin banded iron-formation. Age 3117 ± 3 Ma
Bradley Basalt (new name)	3000–4000	Pillow basalt, massive basalt, and minor units of felsic tuff and chert. Age 3115 ± 5 Ma
Tozer Formation (new name)	500–2500	Calc-alkaline volcanics, including felsic pyroclastic units. Age c. 3120 Ma
Nallana Formation (new name)	2000	Dominantly basalt, but includes minor ultramafic and felsic units. Felsic tuff dated at 3125 ± 4 Ma. Base of formation truncated by Maitland Shear Zone

the contact during tight upright folding.

The Ruth Well Formation has been intruded by the Karratha Granodiorite, dated by Smith et al. (in press) at 3261 ± 4 Ma. Rhyolite in the Nickol River Formation was dated at 3251 ± 6 Ma by Nelson (1997), and a volcanogenic sedimentary unit returned an age of 3269 ± 2 Ma. The age of the Regal Formation is poorly constrained between 3250 Ma and c. 3050 Ma. Local conglomerate and sandstone at the top of the Nickol River Formation could mark a long time break. The minimum age for the Regal Formation is provided by new geochronological data from the overlying Cleaverville Formation. A maximum depositional age for the Cleaverville Formation is indicated by clastic zircons dated at 3015–3020 Ma from samples collected at Cleaverville (Nelson, 1997), Wickham, and Mount Ada (Nelson, in prep.).

Whundo Group

The Whundo Group, which is restricted to the area south of the Sholl Shear Zone, forms the bulk of the succession referred to by Krapez (1993) as the Sholl Supersequence. It is approximately 8000 m thick and is composed of four formations (Table 2). U–Pb zircon dating (Horwitz and Pidgeon, 1993; Nelson, 1996) indicates an age range from 3125 Ma in the upper part of the Nallana Formation to 3117–3115 Ma in the Bradley Basalt and the Woodbrook Formation. The Maitland Shear Zone (Fig. 2) defines the base of the group, and the top of the group is overlain by the Cleaverville Formation. Apart from a basal zone of amphibolite-facies metamorphism immediately above the Maitland Shear Zone, the metamorphic grade of the Whundo Group is generally lower greenschist facies. This contrasts with the upper greenschist to lower amphibolite facies metamorphism throughout most of the Roebourne Group. The newly recognized Woodbrook Formation is best exposed west of Woodbrook, 14 km south of Roebourne, but also occurs in De Witt Hill north of Warambie (Fig. 2). On its northern side the formation is truncated by the Sholl Shear Zone, whereas to the south it is unconformably overlain by the Mount Roe Basalt of the Fortescue Group (Fig. 2). It is clearly overlain by the Cleaverville Formation in the Woodbrook area, but the contact is covered by Mount Roe Basalt. Geochronology (Nelson, in prep.) has established an age difference of c. 100 Ma between the Woodbrook Formation and the Cleaverville Formation, although no major angular unconformity is evident.

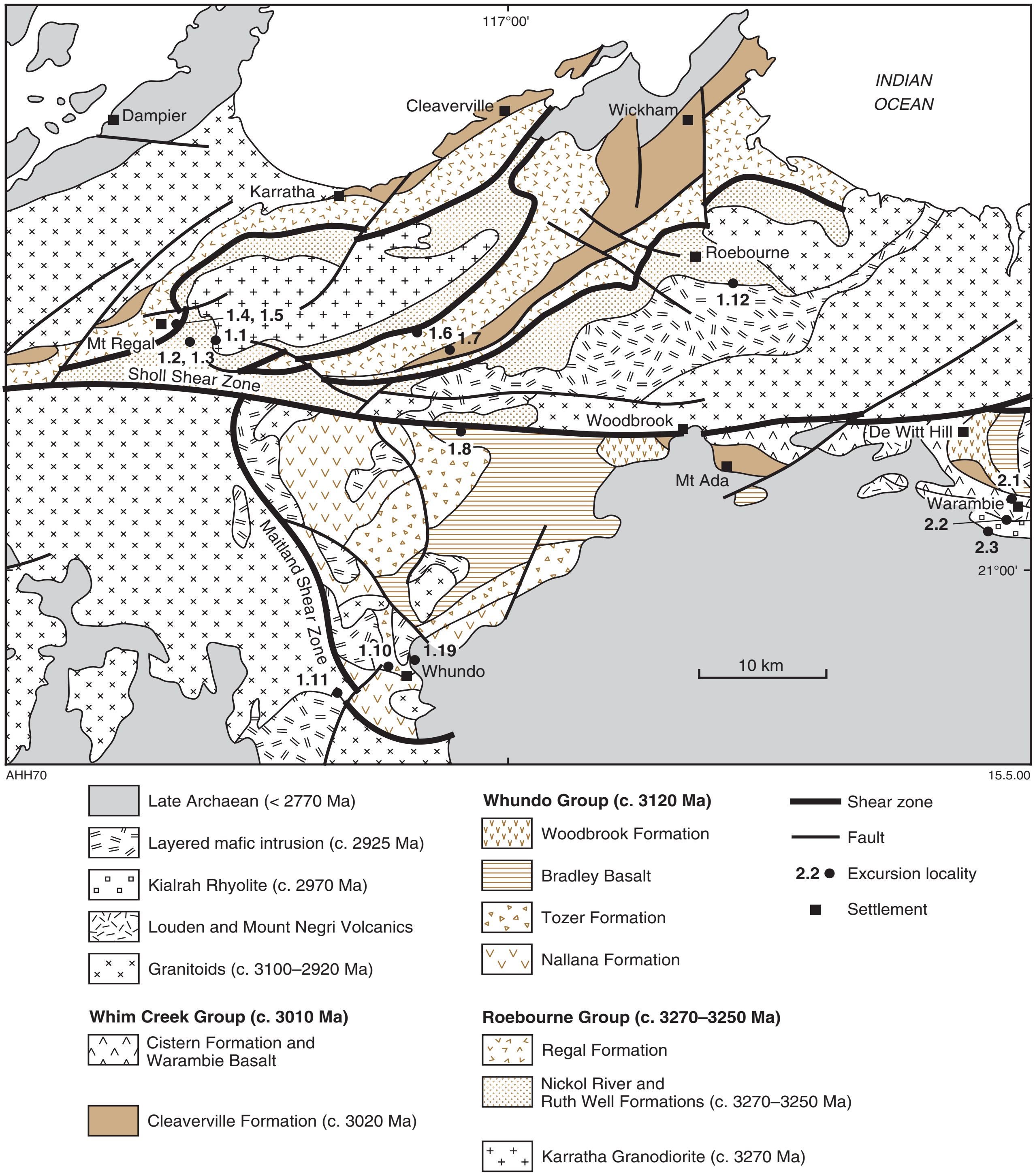


Figure 2. Revised stratigraphy and structure of the Roebourne–Whundo area, west Pilbara, showing localities referred to in the text

Cleaverville Formation

Hickman (1983) assigned all major iron-formations in the granite–greenstone terrain of the north Pilbara to the Cleaverville Formation. Clearly, this correlation, if correct, provides an extremely important stratigraphic reference level for almost all the Pilbara greenstone belts. In the west Pilbara, at least, all new geochronology supports a correlation between the iron-formations, indicating a common depositional age of 3020–3015 Ma; insufficient data exist to test correlations to the east Pilbara where the ages of the iron-formations in different belts are still very poorly constrained.

A fine-grained granophyric unit (probably a sill) from the Cleaverville Formation east of Woodbrook has a crystallization age of 3014 ± 6 Ma (Nelson, 1997), and clastic zircons within a volcanogenic sandstone within banded iron-formation in the same area have an age of 3018 ± 3 Ma (Nelson, in prep.). This geochronology, and that on the Cleaverville Formation north of the Sholl Shear Zone at Cleaverville and Wickham, has supported a previous stratigraphic correlation of the banded iron-formations in these two areas (Hickman, 1983).This precludes the Sholl Shear Zone being a suture younger than 3020 Ma. The contact between the Cleaverville Formation of the Woodbrook area and the overlying Warambie Basalt of the Whim Creek Group is marked by an angular unconformity. This has important regional significance and is discussed later.

Whim Creek Group

Only two formations of the Whim Creek Group are preserved in the area discussed in this paper (Fig. 2). The Warambie Basalt and Cistern Formation (Table 2) extend about 10 to 15 km west of Warambie (Fig. 2), but other formations of the group that occur in the Whim Creek area (Fig. 1), namely the Mons Cupri Volcanics and the Rushall Slate, are either absent or not exposed. Near De Witt Hill (Fig. 2), the Warambie Basalt is composed of vesicular basalt, basaltic tuff, and hyalo-clastites. Above these rocks there is a 15 m-thick unit of volcanogenic siltstone and pale green mudstone overlain by carbonated pillow basalt. It is probable that this unit represents the lower part of the Cistern Formation. About 2 km west of De Witt Hill the Warambie Basalt is overlain by poorly exposed greywacke and pelitic schist which could be part of the Rushall Slate.

The stratigraphic relationship between the Whim Creek Group of this area and underlying greenstones is seen approximately 3 km south of De Witt Hill. Here, the basal unit of the Warambie Basalt is a polymictic conglomerate, which is 10 m thick and contains clasts of chert, basalt, and rhyolite. This conglomerate unconformably overlies banded iron-formation similar to that of the Cleaverville Formation. At another locality, about 10 km east of Woodbrook, the Cleaverville Formation is unconformably overlain by sandstone and conglomerate at the base of a thick succession of pyroclastic, vesicular, amygdaloidal and pillow basalt of the Warambie Basalt.

The top of the Whim Creek Group is locally (Fig. 2) represented by the contact between the Cistern Formation and the overlying Louden Volcanics. In the Warambie area the Cistern Formation is laterally discontinuous between the Warambie Basalt and the Louden Volcanics, and the base of the Louden Volcanics appears to transgress the succession of the Cistern Formation, indicating a low-angle unconformity.

Smithies (1997) and Smithies et al. (in prep.) provide stratigraphic and geochronological data which indicate that the age of the Whim Creek Group is c. 3010 Ma (included is an age of 3009 ± 4 Ma on the Cistern Formation at a locality about 10 km east of Warambie), and that the De Grey Group (Fig. 1) is younger than 3000 Ma (clastic zircons), and overlies the Whim Creek Group.

Regional implications

The new data have established that previous stratigraphic interpret-ations for the area were variously incorrect. Hickman's (1983) lithostratigraphic correlation of rocks now assigned to the Whundo Group with the Warrawoona Group of the east Pilbara is precluded by the new geochronology, and his Roebourne Group – Warrawoona Group correlation was at least partly incorrect (only the maximum age of the Ruth Well Formation remains in doubt). The recognition of a major angular unconformity between the Cleaverville Formation and the Whim Creek Group invalidates Horwitz's (1990) proposal to include greenstones now assigned to the Whundo Group within the Whim Creek Group. This unconformity is exposed at three localities (Mount Ada, De Witt Hill, and Webster Well) over a strike length of 30 km, and testifies to regional deformation and erosion between deposition of the Whundo Group – Cleaverville Formation succession and the Whim Creek Group. There are also errors in the sequence stratigraphy advocated by Krapez (1993) because the ages of his 'Sholl Supersequence' (Whundo Group) and his 'Regal Supersequence' (Roebourne Group) are now shown to be quite different. Furthermore, the apparent regional nature of the Cleaverville Formation – Whim Creek Group unconformity questions the validity of the 'Roebourne Megasequence' (a unit which it is now known would span a time interval of at least 300 Ma).

Summary

Data recently obtained from detailed geological mapping and follow-up precise geochronology have resulted in a major revision of the greenstone stratigraphy of the west Pilbara between Roebourne and Whundo. Volcanic and sedimentary rocks north and south of the Sholl Shear Zone have different stratigraphic successions, and only one formation (Cleaverville Formation) occurs in both areas. Most of the greenstones north of the Sholl Shear Zone are now assigned to the Roebourne Group, and the age of this ranges from about 3270 to 3050 Ma. In contrast, the maximum age of the greenstones south of the Sholl Shear Zone is 3125 Ma. Stratigraphic relationships between the units south of the Sholl Shear Zone have been clarified, demonstrating that most of this succession unconformably underlies the Whim Creek Group.

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The Mallina Formation, Constantine Sandstone and Whim Creek Group: a new stratigraphic and tectonic interpretation for part of the western Pilbara Craton

by R. H. Smithies

Abstract

Detailed regional mapping of MOUNT WOHLER and SHERLOCK, and recent SHRIMP U–Pb zircon dates, permit a re-interpretation of the depositional and tectonic environment under which the sedimentary and volcanic rock successions of the Mallina Synclinorium and the Whim Creek Group accumulated in the western part of the Pilbara granite–greenstone terrain. Variations in the basal successions of the Constantine Sandstone, forming the lowest and oldest unit of the northeast-trending Mallina Synclinorium, reflect a rapidly subsiding depositional basin, with a hinterland to the southeast. Distal facies of the c. 3000 Ma Mallina Formation, which forms the upper unit of the synclinorium, onlap the c. 3010 Ma volcano-sedimentary rocks of the Whim Creek Group, which form the northwestern margin of the synclinorium. The Mallina Synclinorium is interpreted to represent a backarc basin that developed behind the magmatic arc represented by the Whim Creek Group.

KEYWORDS: Pilbara, granite–greenstone terrain, Constantine Sandstone, Mallina Synclinorium, Whim Creek Group

The geology of the MOUNT WOHLER – SHERLOCK* area (Fig. 1), in the western part of the Pilbara granite–greenstone terrain, is dominated by three rock units: the Constantine Sandstone, the Mallina Formation, and the Whim Creek Group. The first two are the result of deep-water deposition from turbidity currents (i.e. turbidites). The Whim Creek Group is a calc-alkaline volcano-sedimentary sequence deposited in subaerial and later, subaqueous environments. Kriewaldt and Ryan (1963) and Ryan and Kriewaldt (1964) interpreted the evolution of these sequences in terms of a subsiding trough (the Mallina Synclinorium) with a clastic sedimentary fill (Constantine Sandstone and overlying Mallina Formation) and contemporaneous volcanism along a stable northwest margin. This interpretation was embraced by Fitton et al. (1975) and Horwitz (1979, 1990), who placed all of the sequences into their ‘Whim Creek Group’. Hickman (1990), however, suggested that the Constantine Sandstone – Mallina Formation succession was distinct from, and older than, the volcano-sedimentary sequence and included this succession in the De Grey Group.

Horwitz (1979, 1990) described an unconformity at the base of the Constantine Sandstone and recent mapping of the MOUNT WOHLER sheet has uncovered further exposures of that unconformity. All of these studies identify regional lithological variations in the basal portion of the Constantine Sandstone and constrain evolutionary models for the Mallina Synclinorium. Additional constraints are gained from detailed mapping of the area and from geochronological data. This paper describes the nature and outcrop distribution of the Constantine Sandstone, and incorporates this into a preliminary tectonic model for the eastern part of the western Pilbara Craton.

Local geology

The Mallina Synclinorium is composed of the Constantine Sandstone and the conformably overlying Mallina Formation. These rocks have been intruded by granitoids and subjected to at least four phases of deformation (Smithies, in prep.). The northwest flank of the synclinorium is in faulted contact with the Whim Creek Belt, which hosts the Whim Creek Group. On the southeast flank, the Constantine Sandstone

* Capitalized names refer to standard map sheets

rests unconformably on a sequence of ferruginous chert and mafic to ultramafic volcanics, tentatively correlated with the Gorge Creek Group of the eastern Pilbara Craton. A layered mafic–ultramafic intrusion — the Millindinna Complex of Fitton et al. (1975) — was emplaced along much of the length of the unconformity.

The Constantine Sandstone and basal unconformity

Outcrops of the Constantine Sandstone are restricted to the southern parts of the synclinorium, with conglomerate-rich facies confined to the southeast margin. Throughout most of its exposure on Mount Wohler, the formation is dominated by medium- to coarse-grained feldspathic sandstone, grit and shale, which are either interbedded on a scale of 1 to 20 m, or individually form relatively homogeneous units from 300 to 1000 m thick. The coarser grained units contain rare and discontinuous pebble beds. No trough cross-bedding is observed, but poorly developed graded bedding is common. Eriksson (1982) interpreted these rocks as turbidites, representing various depositional environments on a submarine fan.

The basal unconformity to the Constantine Sandstone is exposed at four localities on Mount Wohler. In the core of the Croydon Anticline and in the eastern part of the Powereena Anticline the basal unit of the formation is medium- to coarse-grained feldspathic sandstone. However, in the western part of the Powereena Anticline and to the south at Nunyerry Gap the basal unit of the Constantine Sandstone ranges from medium-grained lithic sandstone to conglomerate. It unconformably overlies silicified shale and ferruginous chert of a succession which Hickman (1990) interpreted by to be part of the Gorge Creek Group. The conglomerate–lithic sandstone succession is only thinly developed in the western part of the Powereena Anticline, but is up to 1300 m thick at Nunyerry Gap.

The local geology of the Nunyerry Gap area is shown in Figure 2. Conglomerate containing randomly orientated (chaotic) angular blocks of chert, up to 2 m in size, supported in a matrix of medium- to coarse-grained, poorly sorted lithic sandstone, marks the unconformity with the chert. The succession above the unconformity fines upwards from conglomerate to interbedded medium-grained sandstone and shale, and is interpreted to represent a proximal submarine-fan succession.

The upward-fining submarine-fan succession at Nunyerry Gap is conformably overlain by the feldspathic sandstone, grit and shale succession that typifies the Constantine Sandstone elsewhere on Mount Wohler, and which Eriksson (1982) interprets as lobe and basin-plain deposits. The overall succession of the Constantine Sandstone thus represents an upward transition from deposition in a proximal submarine fan to a distal deeper water environment, namely a subsiding sedimentary basin. Furthermore, the thinning of the basal conglomerate–sandstone succession from Nunyerry Gap to the western part of the Powereena Anticline, and the absence of that succession from all exposures of the unconformity farther to the north, establishes a northerly trend from proximal to distal depositional environments. These lateral facies changes occur over a short distance and indicate a steep palaeoslope, away from a hinterland to the south or southeast. Fitton et al. (1975) describe conglomerate at the base of the Constantine Sandstone near the Teichmans gold mine, about 40 km to the northeast of Nunyerry Gap. It is possible that similar submarine-fan deposits characterize, and are restricted to, the southeastern margin of the Mallina Synclinorium.

Constraints on a model for the Mount Wohler–Sherlock area

Geochronology and detailed mapping of Mount Wohler and Sherlock have identified the following constraints on the geological evolution of the area.

- Smithies (in prep.) presents evidence that the Mallina Formation shows a general decrease in average grain size from the southern parts of Mount Wohler towards the Whim Creek Belt, indicating a northwest trend to more distal depositional facies.

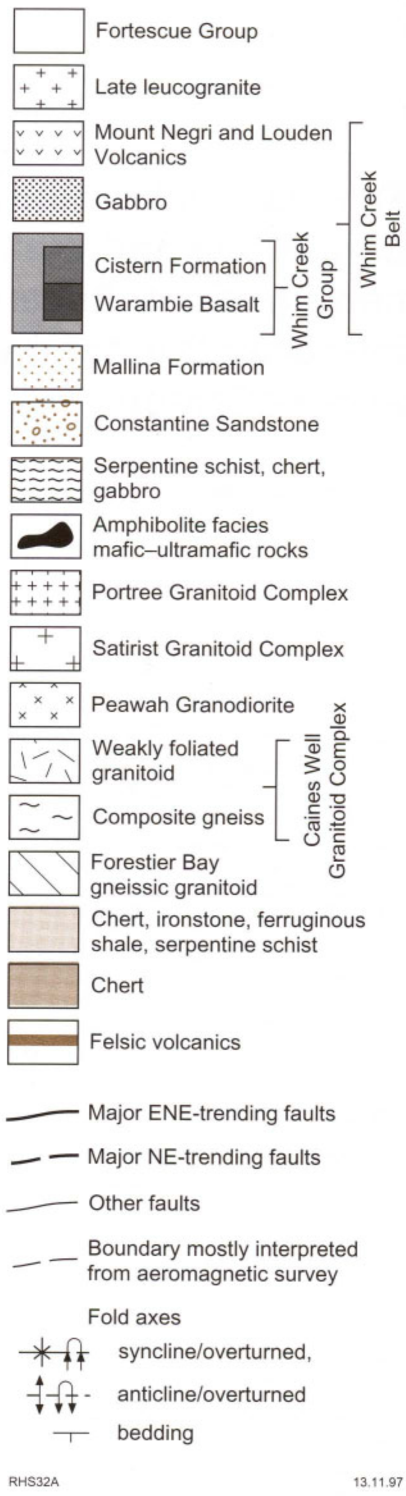
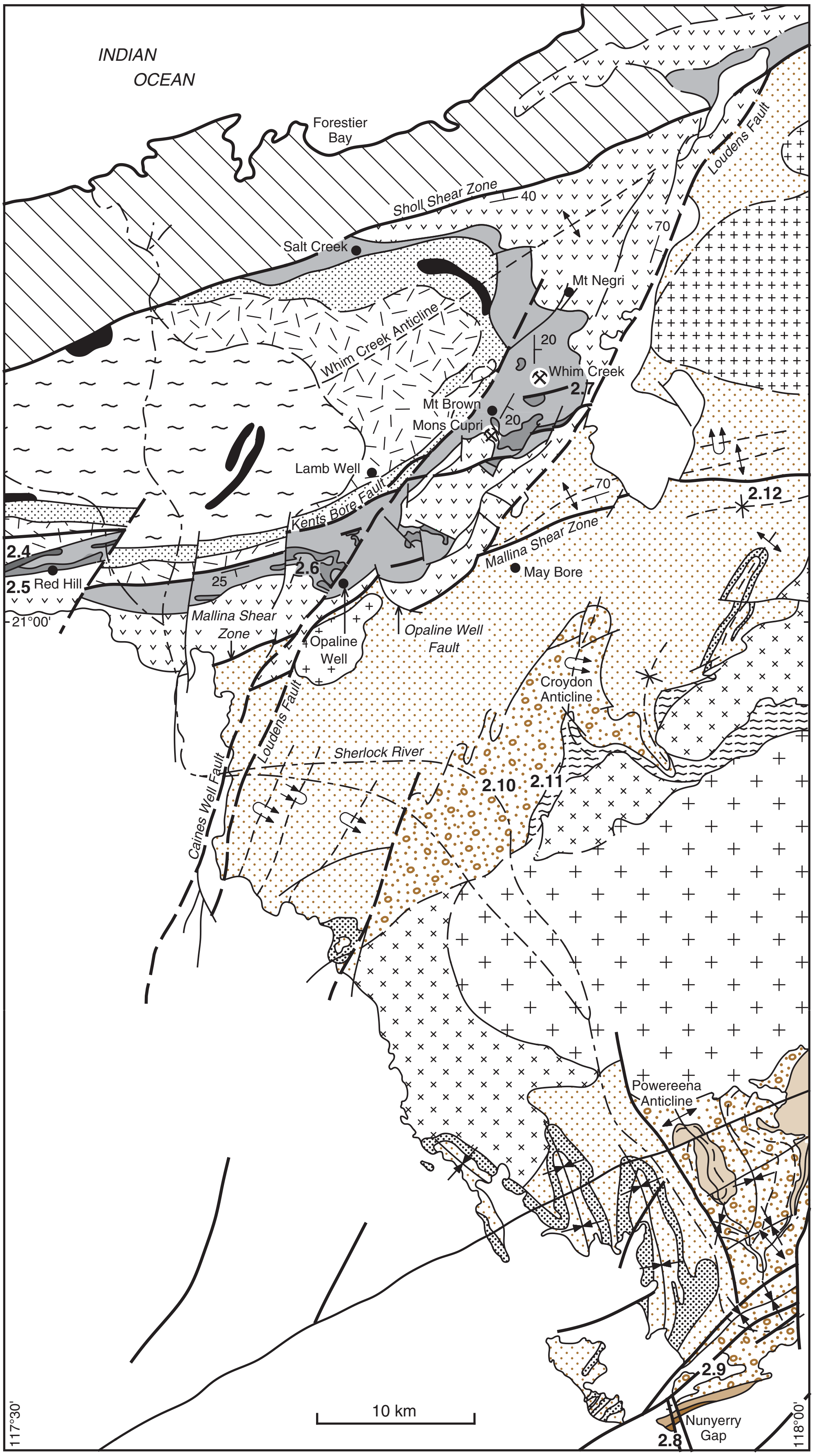


Figure 1. Geology of the central Western Pilbara granite–greenstone terrain

- Nelson (1997) has dated detrital zircons from the Mallina Formation to indicate a maximum age of deposition of 2997 ± 20 Ma. Few, if any,


INDIAN
OCEAN
Forestier
Bay
Sholl Shear Zone
40
70
Salt Creek
Mt Negri
Whim Creek Anticline
20
Whim Creek
2.7
Mt Brown
Mons Cupri
20
Lamb Well
Kents Bore Fault
70
2.12
Mallina Shear Zone
May Bore
2.4
2.5
Red Hill
2.6
25
21°00'
Mallina Shear
Zone
Opaline
Well
Opaline Well
Fault
Croydon
Anticline
Loudens Fault
Sherlock River
2.10
2.11
Caines Well Fault
Powereena
Anticline
2.9
10 km
Nunyerry
Gap
2.8
117°30'
118°00'

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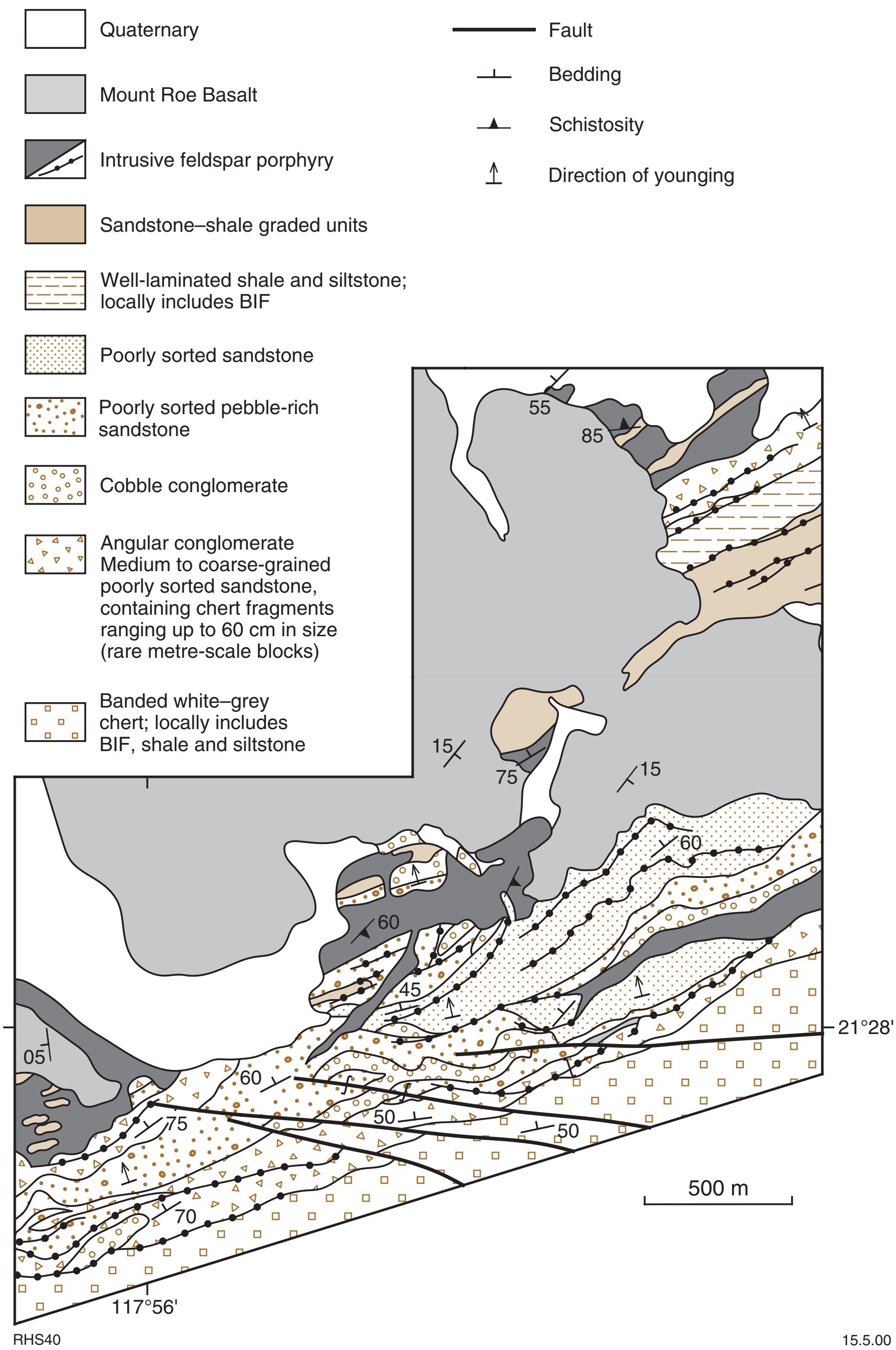

Figure 2. Local geology of the Nunyerry Gap area

zircons could have been derived from sources to the northwest of the Mallina Synclinorium; in particular, from the c. 3010 m.y. Whim Creek Group. Most of the detrital zircons were between 200 and 500 m.y. older than the maximum age of the Mallina Formation, with ages similar to many rocks found to the southeast.

- Smithies et al. (in prep.) interpret the Whim Creek Belt not as a small ensialic pull-apart basin that marks the original depositional extent of the Whim Creek Group (cf. Barley, 1987), but rather as the down-faulted remnants of an originally more extensive calc-alkaline volcano-sedimentary succession. In this interpretation, the Whim Creek Group formed in an extensional

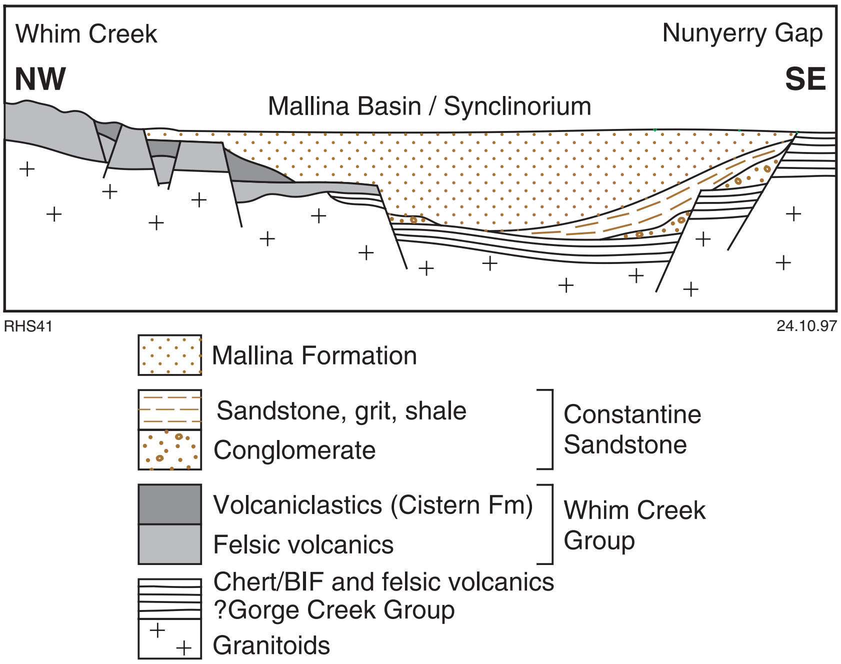

Figure 3. Schematic cross section of the Mallina Synclinorium

tectonic setting; deposition was predominantly subaerial, but in the later stages was clearly subaqueous.

- Smithies et al. (in prep.) dated dacitic tuff of the Cistern Formation, in the middle to upper part of the Whim Creek Group (of Hickman, 1990), at 3009 ± 4 Ma indicating that the group is older than the Mallina Formation, and possibly also older than the Constantine Sandstone.
- Krapez and Barley (1987) suggest that the faulted contact between the rocks of the Mallina Synclinorium and the Whim Creek Group represents a tectonostratigraphic domain boundary. However, Fitton et al. (1975), Horwitz (1979, 1990) and Smithies et al. (in prep.) find no evidence for significant strike-slip movement along that fault. Rather it represents a major basin margin.

Preliminary thoughts on a model

Figure 3 is a schematic cross section providing an interpretation of the depositional environment of the Constantine Sandstone and Mallina Formation. The section depicts a basement composed of chert (?Gorge Creek Group) and gneiss overlain to the north by the calc-alkaline volcanic rocks (lower half of the Whim Creek Group), and faulted to the southeast to produce the scarp that marked the edge of the Mallina Basin (Synclinorium). Development of the basin was asymmetric, with the northwestern edge subsiding less than the southeastern edge. During faulting along the northwestern edge, the Cistern Formation accumulated from a combination of detritus derived from erosion of the calc-alkaline volcanics and renewed andesitic to dacitic volcanism. An extensive series of submarine fans was developed along the southeastern edge of the basin at this time. The fans extended northwards to deposit progressively more distal sedimentary facies within the Constantine Sandstone. The southeastern hinterland included continental material some 200 to 500 m.y. older than the sandstone. As the basin subsided further, the Whim Creek Belt was submerged and the Mallina Formation was deposited. Fine-grained turbiditic sedimentary rocks (Rushall Slate — Hickman, 1990) overlying the Cistern Formation of the Whim Creek Group probably represent a distal onlapping facies of the Mallina Formation.

The geological evolution, as described here, is consistent with formation of a continental magmatic arc (Whim Creek Group) and partial destruction and burial of that arc during the development of a backarc basin (Mallina Basin/ Synclinorium).

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The Tabletop Terrane of the Proterozoic Rudall Complex: preliminary notes on the geology, granitoid geochemistry and tectonic implications

by R. H. Smithies and L. Bagas

Abstract

The Palaeoproterozoic Rudall Complex of northwestern Australia is divided into three terranes. The western two terranes were deformed by Palaeoproterozoic collisional orogeny and high-pressure metamorphism. The Palaeoproterozoic history of the eastern Tabletop Terrane is unclear but apparently did not involve high-pressure metamorphism. This terrane was, however, intruded by voluminous Mesoproterozoic (1300–1500 Ma) tonalite and leucogranite that is not found in the terranes to the west. These rocks are divided geochemically and petrographically into two groups of tonalite and a group of late leucogranites. The tonalites show close compositional similarities to modern subduction-(arc-)related granitoid rocks. It is speculated that the tonalites relate to a Mesoproterozoic subduction event.

KEYWORDS: Rudall Complex, Tabletop Terrane, Proterozoic, tonalite, leucogranite, subduction

Remapping of the RUDALL* 1:250 000 sheet has resulted in the compilation of a series of 1:100 000 map sheets covering the bulk of the exposed Proterozoic Rudall Complex. Mapping was extended to the southwest corner of the TABLETOP 1:250 000 sheet (the BLANCHE 1:100 000 sheet) to incorporate the poorly exposed eastern part of that complex. This revealed several geological features that distinguished the region from the main body of the Rudall Complex, which is characterized by strong deformation and medium- to high-grade metamorphism at high pressure (Smithies and Bagas, 1997). In particular, voluminous granitoid rocks on BLANCHE are not metamorphosed above greenschist facies. The only strongly foliated granitoid rocks occur near the major northwest trending Camel–Tabletop Fault Zone (Bagas and Smithies, in prep.), which corresponds to a geophysical anomaly that Fraser (1976) called the Anketell Regional Gravity Ridge. Also, tonalite dominates on BLANCHE whereas monzogranite dominates elsewhere in the Rudall Complex. The available geochronology (Nelson, 1995) suggests that granitoid rocks on BLANCHE were intruded at c. 1500–1300 Ma. A contemporaneous igneous event is unknown in the western part of the Rudall Complex. This paper presents a brief description of the geology of BLANCHE, with an emphasis on the petrology and geochemistry of the granitoid rocks.

* Capitalized names refer to standard map sheets

Geological setting

The Rudall Complex forms the Palaeoproterozoic to Mesoproterozoic core of the Proterozoic Paterson Orogen (Williams and Myers, 1990; Bagas et al., 1995). The complex consists of sedimentary and igneous rocks that were metamorphosed to granulite facies, at pressures up to 1200 MPa, during a Palaeoproterozoic (c. 1780 Ma) collisional event known as the Yapungku Orogeny (Smithies and Bagas, 1997; Bagas and Smithies, 1997).

Three tectonostratigraphic terranes are recognized in the Rudall Complex (Bagas and Smithies, 1997, fig. 2). The Talbot Terrane, in the west of the complex, comprises an older sequence of banded ortho- and paragneiss and a younger sequence of metasedimentary rocks. The Connaughton Terrane, in the centre of the complex, comprises a succession of mafic schist and gneiss and associated metamorphosed chemical and clastic sedimentary rocks. Augen orthogneiss forms a large portion of both of these terranes and is derived from a monzogranite that was intruded before and during the Palaeoproterozoic collision that juxtaposed the two terranes (Smithies and Bagas, 1997). The poorly exposed Tabletop Terrane forms the eastern portion of the complex.

The Tabletop Terrane

The Tabletop Terrane comprises a sequence of mafic schist, amphibolite and metasedimentary rocks that closely resembles the sequence found in the Connaughton Terrane. However, augen gneiss is not present in the Tabletop Terrane, and there is no evidence that the peak metamorphic grade exceeded the lower amphibolite facies or that it was accompanied by high pressure. Instead, the terrane is characterized by weakly metamorphosed tonalite and leucogranite that range from massive to strongly foliated with increasing proximity to the Camel–Tabletop Fault Zone, which marks the boundary with the Connaughton Terrane (Bagas and Smithies, 1997, fig. 2). The relationship between the Tabletop Terrane and the western two terranes is unclear, and it is possible that the Tabletop Terrane is exotic to the other terrane.

The exposed Tabletop Terrane can be subdivided into two assemblages that are poorly outcropping (Fig. 1). The western assemblage is dominated by medium-grained amphibolite, and includes metamorphosed leucogabbro–anorthosite–dunite bodies that range in length up to 6 km. Tonalite and leucogranite intrude the amphibolite and contain abundant mafic xenoliths and rafts. A complex interleaved, folded and deformed sequence of mafic to quartzo-feldspathic schist, chert and minor banded iron-formation was mapped as 'mixed gneiss' in the southeast of the western assemblage. Much of the mafic and quartzo-feldspathic schist is derived from amphibolite and tonalite respectively, but deformation masks the origin of some schist. Late, northerly trending dolerite dykes, generally less than 20 m thick, are common. Some areas of outcrop include up to 50% mafic dyke material and the intervening 'mixed gneiss' has been partially melted.

The eastern section of the Tabletop Terrane is dominated by tonalite and leucogranite, and quartzo-feldspathic schist of unknown origin. Amphibolite occurs as xenoliths within tonalite and leucogranite and possibly as layers in the schist. Some schist may be derived from tonalite and leucogranite within zones of strong deformation that parallel the Camel–Tabletop Fault Zone. However, local contact metamorphism requires that the schist pre-dates intrusion of the latest, if not all, of the granitoid rocks. A volcanic origin can not be ruled out for some of the schist, in which subhedral to euhedral plagioclase grains lie in a fine-grained quartzo-feldspathic groundmass.

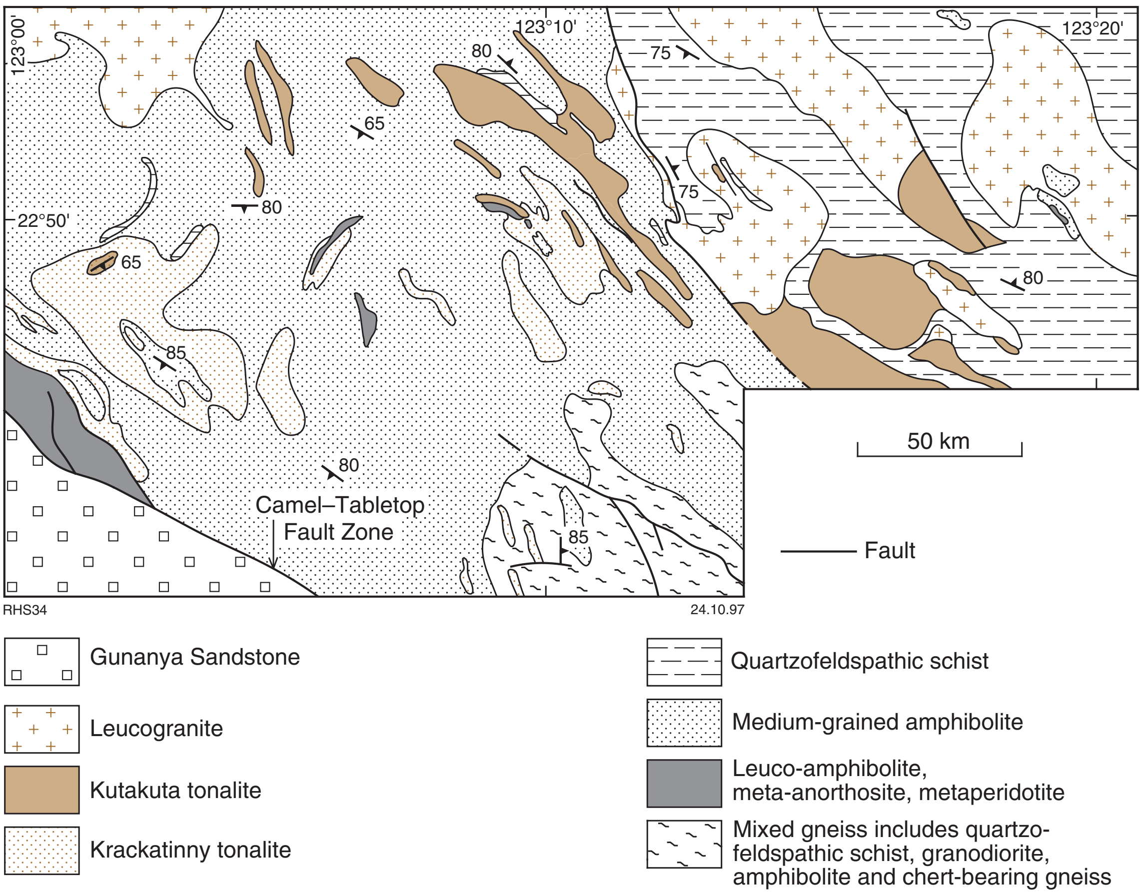

Figure 1. Local geology of the Tabletop Terrane

Tonalites and leucogranite of the Tabletop Terrane

Three groups of granitoid rocks have been tentatively identified. The groups outcrop subparallel to the Camel–Tabletop Fault Zone (Fig. 1); biotite tonalite (Krackatinny tonalite), biotite–(hornblende) tonalite (Kutakuta tonalite) and, leucogranite (syenogranite) occur at progressively greater distances from that zone. The Kutakuta tonalite forms inclusions within the other two granitoid rocks, and is the oldest intrusive phase.

The Kutakuta tonalite is generally composed of abundant euhedral to subhedral phenocrysts of plagioclase (≤ 7mm long) in a medium-grained groundmass of quartz, plagioclase, and mafic minerals. Biotite is the main mafic mineral and constitutes up to 15% of the rock. Hornblende, present in most rocks, never exceeds 8%, and is generally rimmed and partially replaced by biotite. Accessory phases include titanite, apatite, opaques, and zircon.

The Krackatinny tonalite is medium grained and equigranular to slightly porphyritic. Microcline crystallized late and constitutes less than 5% of the rock. Biotite is the main, or sole, mafic silicate and forms up to 10% of the rock. Hornblende occurs in some samples, where it is usually rimmed by biotite. Accessory phases include titanite, apatite, opaques and zircon.

The leucogranite is medium grained and generally equigranular, but some rocks contain K-feldspar (microcline microperthite) phenocrysts up to 1 cm in size. K-feldspar is always more abundant than plagioclase. Biotite forms up to 10% of the rock and is generally the sole mafic silicate. Accessory phases include apatite, opaques, zircon, allanite, and titanite.

Age of the tonalites and leucogranite

A leucogranite, immediately east of BLANCHE, was dated (SHRIMP U–Pb zircon) at 1310 ± 4 Ma and contained c. 1490 Ma inherited zircon xenocrysts (Nelson 1995). Granodiorite, sampled on CRONIN (1:100 000 sheet) from the southeasterly extension of the Krackatinny and Kutakuta tonalites, also gave an age (SHRIMP U–Pb zircon) of c. 1490 Ma (Power and Nuclear Corporation of Japan, 1995, pers. comm.). Hence, the age of granitoid magmatism within the Tabletop Terrane can be tentatively constrained to between c. 1490 Ma (tonalite) and c. 1310 Ma (leucogranite).

Geochemistry of the tonalites and leucogranite

Seventeen samples of fresh granitoid rock were analysed for major and trace elements (Table 1). The two tonalites and the leucogranite individually define very narrow silica ranges (Fig. 2). All three groups define typical calc-alkaline trends on an AFM diagram (not shown). The tonalites are generally metaluminous and show typical I-type compositions. All but one of the leucogranites are mildly peraluminous.

Figure 2 shows major- and trace-element variations. Because of the narrow range in silica, compositional trends are not well defined. The tonalites have high Al_2O_3 contents (16–17 wt%). The Kutakuta tonalite has slightly lower Na_2O and higher K_2O than the Krackatinny tonalite but both suites show trends to higher Na_2O/K_2O. The Kutakuta tonalite also shows higher concentrations of Rb, Th, and U than the Krackatinny tonalite, although flat trends for these elements, and for Rb/Sr, are characteristic of both tonalites.

Compared with the tonalites, the leucogranites are rich in K_2O, Rb, Th and LREE, and poor in Al_2O_3 and CaO (Fig. 2). With increasing silica the leucogranites show distinct trends to higher K_2O, Rb, (?Th) and U and lower Sr and Na_2O/K_2O. Consistent with the limited geochronological data, these trends negate any direct relationship between the tonalites and the leucogranite.

Comparison with other Proterozoic granitoid rocks and with subduction-related granitoids rocks

A feature of many Australian Proterozoic granitoid rocks is that the least fractionated samples show Sr-depleted and Y-undepleted patterns on Primordial Mantle-normalized diagrams and have high concentrations of K, Th and U (Wyborn et al., 1992). The augen orthogneiss of the Connaughton and Talbot Terranes is presented in Figure 3 as a typical example of such rocks. In contrast, most Archaean and many Late Cretaceous and Tertiary orogenic granitoid rocks show Sr-undepleted and Y-depleted patterns (Wyborn et al., 1992).

Figure 3 shows Primordial Mantle-normalized spidergrams for tonalites and leucogranite of the Tabletop Terrane. The tonalites contrast significantly with many Australian Proterozoic granitoid rocks in that they show Sr-undepleted (to slightly Sr-depleted) and Y-depleted patterns. The pattern is best developed in the Krackatinny tonalite, which also has generally lower concentrations of K, Th and U, and higher Na, than does the Kutakuta tonalite. The tonalites in general, and the Krackatinny tonalite in particular, show close compositional similarities both to Late Cretaceous and Tertiary subduction-related granitoid rocks and to Archaean granitoid rocks (Fig. 3), and are most like the former in terms of Na/K ratios and their narrow and low silica ranges.

Discussion

Available geochemical and geochronological data tentatively provide evidence for two temporally and compositionally distinct events of granitoid magmatism; early (c. 1490 Ma) tonalitic magmatism, and later (c. 1310 Ma) leucogranite magmatism. Magmatism at c. 1310 Ma is contemporaneous with the early stages of a major regional tectonic event that culminated, at c. 1100 Ma, with the assembly of Proterozoic Australia as an early component of the Rodinian supercontinent (Myers et al., 1996). The relationship between magmatism and tectonism at c. 1490 Ma is more enigmatic.

The Sr-depleted, Y-undepleted patterns that are common to many Proterozoic granitoid rocks of Australia are thought to relate to low-pressure melting during ensialic orogeny, which Etheridge et al. (1987) claimed to be characteristic of the Australian Proterozoic, to the exclusion of collisional plate-tectonic processes. Although rarely seen in

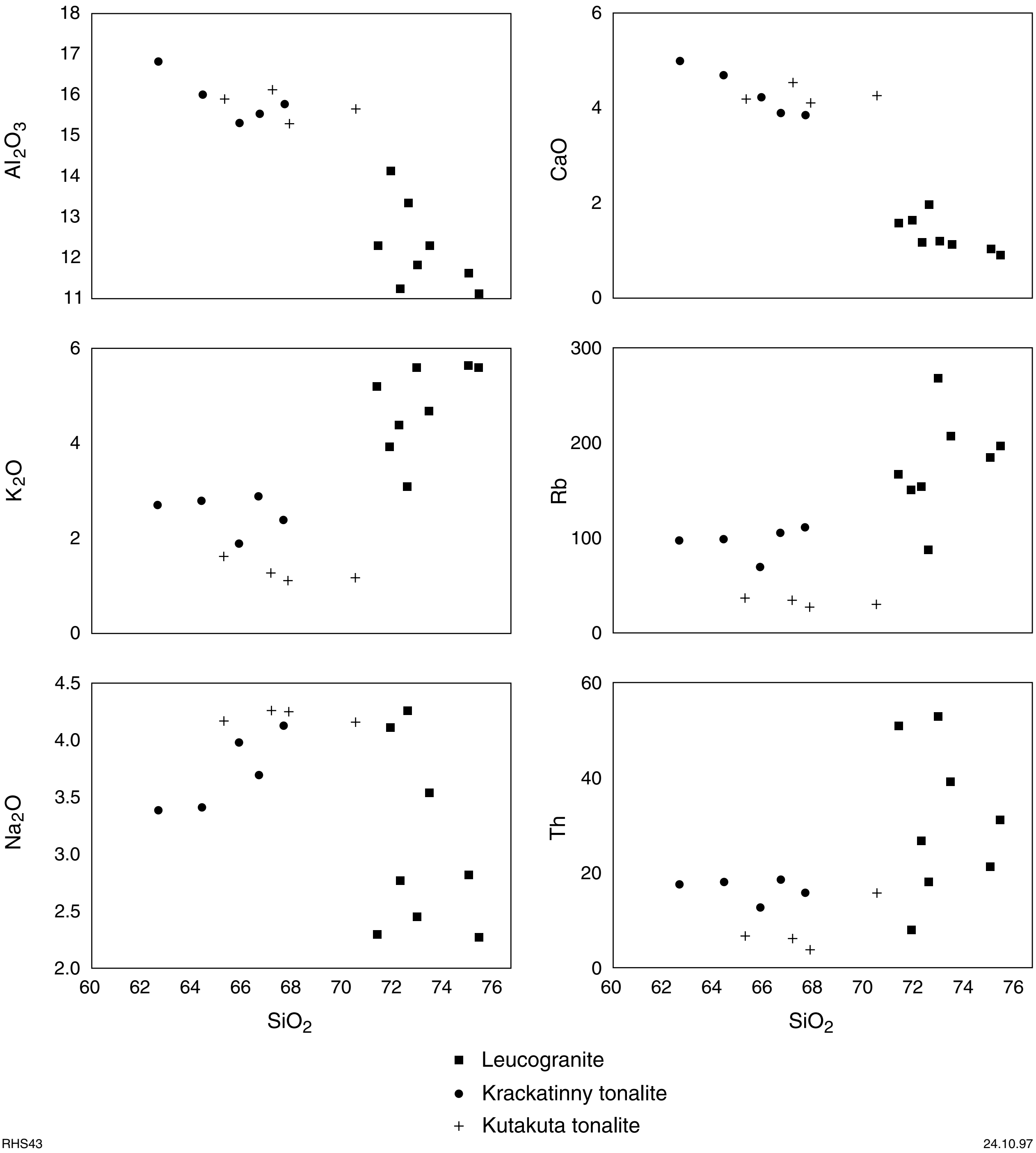

Figure 2. Harker diagrams showing the three groups of granitoid rocks from the Tabletop Terrane

Australia, Proterozoic granitoid rocks with Sr-undepleted, Y-depleted compositions similar to those of the Krackatinny tonalite of the Tabletop Terrane were found in the Arunta Inlier by Foden et al. (1988) and in the Halls Creek Orogen by Sheppard et al. (1995). In Late Cretaceous and Tertiary granitoid rocks, such patterns are indicative of subduction-related tectonic settings. Wyborn et al. (1992), however, warn that such patterns could also be 'inherited' from a source of appropriate composition during a melting event unrelated to subduction or plate collision, although a requirement here is probably that the source itself be arc-related. For example, although Cretaceous magmatism in central Queensland relates to a divergent (rift) tectonic setting, it shows typically arc-related calc-

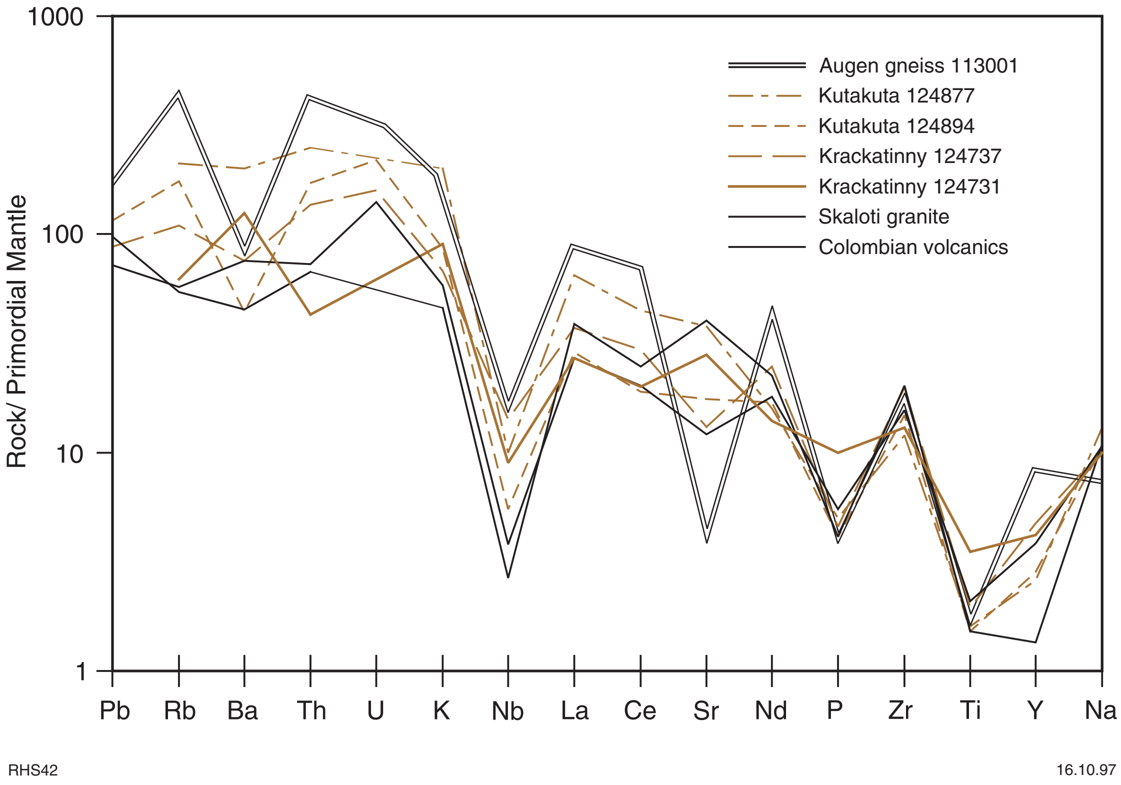

Figure 3. Primordial Mantle-normalized multi-element variation diagram comparing the tonalites from the Tabletop Terrane with an augen gneiss from the western part of the Rudall Complex (typical pattern of Proterozoic granitoid rocks) and Tertiary–Recent orogenic felsic rocks (Skaloti granite from Greece, and Colombian Volcanics — data from Tarney and Jones, 1994)

alkaline compositions as a result of partial melting of a Late Palaeozoic arc-derived source (Ewart et al., 1992).

There is clear evidence that some Australian Palaeoproterozoic orogens evolved through plate-tectonic processes. For example, high-pressure metamorphism in the Rudall Complex requires thickening of the crust by over 40 km (Smithies and Bagas, 1997), a feature most consistent with collisional orogeny. Furthermore, within the Halls Creek Orogen, the 1835–1800 Ma Sally Downs Supersuite shows an arc-related geochemistry which is consistent with many other geological attributes of that orogen (Sheppard et al., 1995).

Conclusions

Current knowledge is insufficient to construct any tectonic model of the post-Palaeoproterozoic geological evolution of the Paterson Orogen. However, if compositional similarities between the tonalites of the Tabletop Terrane and Late Cretaceous and Tertiary subduction-related tonalites reflect similar tectonic settings, then the former tonalites are either a direct result of subduction, or a remelt of subduction-related crust. The identification of an earlier Palaeoproterozoic collisional orogeny in the Rudall Complex (Smithies and Bagas, 1997) means that the tonalites in the Tabletop Terrane could have inherited an arc-like composition from a source generated during that orogeny. However, no rocks of appropriate composition have so far been identified in the Rudall Complex, and we therefore favour the alternative hypothesis that the c. 1490 Ma tonalites are directly arc-related.

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Prediction of sandstone porosity and permeability — an example from the Southern Carnarvon Basin

by P. J. Havord

Abstract

Successful petroleum exploration relies on accurate pre-drilling prediction of reservoir porosity and permeability. Recent recognition of a number of fundamental geological controls on sandstone reservoir quality, based on published studies of sandstone parameter datasets from around the world, facilitates more accurate estimation of porosity and permeability prior to drilling. For porosity these controls are sandstone composition, sorting, and thermal maturity. For permeability the same controls plus grain size apply.

Poor understanding of the controls on porosity and permeability, and concerns about reservoir quality at depth, have deterred petroleum exploration of the Early Permian Moogooloo Sandstone in the Southern Carnarvon Basin. Multivariate regression analysis of a calibration dataset for the Moogooloo Sandstone reveals mean formation porosity can be predicted to within ± 2% as a power function of mean thermal maturity. Regional mapping of the thermal maturity–porosity relationship shows that the Moogooloo Sandstone lies generally within the oil preservation window, with mean formation porosity ranging from 21% near outcrop to 12% in basinal areas. Likewise, permeability can be predicted to requisite accuracy as a function of porosity, thermal maturity, grain size and clay volume.

KEYWORDS: Petroleum exploration, sandstone, reservoir, porosity, permeability, multivariate regression, Moogooloo Sandstone

Background

With millions of dollars at stake on the outcome of pre-drill predictions of reservoir quality in petroleum exploration, estimates of porosity and permeability are needed to calculate the potential volume and production rate of petroleum from an undrilled prospect. The accuracy of these estimates is crucial to reliable economic evaluation, ranking and selection of prospects for drilling, and ultimately to the commercial success or failure of those actually drilled.

Once a discovery is made, measurements of reservoir porosity and permeability are used to assess commercial viability by calculation of hydrocarbon pore volume, potential recoverable reserves, future production rates, and required well spacing. The need for accurate estimates of rock properties extends to the whole life cycle of a petroleum reservoir including exploration, discovery, appraisal, development, and management.

Approximately half of the world's conventional petroleum reserves, and almost all of those in Australia, are found in sandstone reservoirs. Accordingly, this paper summarizes the common approaches to predicting porosity and permeability in sandstones, profiles several overseas examples, and presents a case study of an Early Permian sandstone unit that is the focus of renewed petroleum-exploration interest in the Southern Carnarvon Basin.

Approaches to reservoir quality prediction

Current efforts to predict porosity and permeability in sandstones prior to drilling are focused on empirical and process-oriented models[1].

Process-oriented techniques focus on modelling diagenetic processes and their effects on the evolution of reservoir quality. Among these techniques, chemical and mathematical models are useful in simulating diagenetic sequences but are not yet capable of quantifying changes in porosity and permeability. The main limitations of such models are the unavailability of many thermodynamic and kinetic data and their inability to quantify mass-

[1] Some recent success in predicting porosity prior to drilling has been achieved through analysis of seismic data.

transfer processes and their effect on reservoir quality (Bloch, 1991).

In its simplest form the empirical approach to reservoir-quality prediction is based on the observation that porosity and permeability of sedimentary rocks generally decrease with increasing burial depth. Predictions using the porosity–depth relationship assume that the mean porosity of the interval of interest is within some specified range of the mean of the trend established for wells drilled previously in the area. However, in most cases, plots of present-day burial depth against porosity display such a wide scatter of data points for any given depth that little statistical confidence can be placed in subsequent predrill predictions. Such inaccuracy can be attributed to several factors including different mechanical strengths and textures, as well as dissimilar temperature and pressure histories of sandstones occurring at similar present-day burial depths.

Present-day porosity and permeability of sandstones are the result of a sequence of depositional and post-depositional processes that have affected the original sediments. Depositional controls on sandstone reservoir quality are mainly lithological and textural, whereas post-depositional processes that affect porosity and permeability through chemical and physical effects, such as compaction, are functions of temperature, pressure, and time. The porosity–depth relationship is therefore best applied as an initial, ‘quick-look’ technique to set broad ranges on the porosity of target sandstones not affected by differential subsidence, uplift, and erosion.

The accuracy of the empirical approach to prediction of sandstone reservoir quality has been improved by mathematically linking porosity and permeability to predictable depositional and post-depositional controls. For porosity these are sandstone composition, sorting, and thermal maturity. For permeability the same controls plus grain size apply (Bloch, 1991). Quantification of the relationships between porosity, permeability and these variables can be readily achieved by applying multivariate linear regression (MLR) to calibration datasets that incorporate a representative range of values for each variable. The resultant empirical equations, particularly when used in conjunction with depositional and thermal maturity models, can frequently predict sandstone reservoir quality to requisite levels of accuracy[2] prior to exploration drilling.

Previous studies

The controls on reservoir quality in sand and sandstone have been studied throughout most of this century (see Scherer, 1987, table 1). In modern times, MLR has been used increasingly to generate empirical equations to predict porosity and permeability as functions of the primary controls on sandstone reservoir quality at field, play, basin and multi-basin scales.

Shell multibasin study

Drawing upon Shell’s international petrophysical database, Scherer (1987) established a calibration dataset comprising 428 cases and found strong correlation between sandstone porosity, **Ø** (% bulk volume), and four variables: **q**, detrital quartz content (% solid volume); **s**, sorting (Trask sorting coefficient); **d**, maximum depth of burial (metres); and **a**, age (years $\times 10^6$).

Using these data, Scherer (1987) developed a MLR equation that he tested on 37 cases not included in the original sample population and found a correlation coefficient of 0.98 between predicted and measured core porosities:

$$\mathbf{Ø} = 18.60 + (4.73 \ln \mathbf{q}) + (17.37/\mathbf{s}) - (0.0038\ \mathbf{d}) - (4.65 \ln \mathbf{a})$$

US multibasin study

Bloch and Helmold (1995) cited development of unspecified MLR equations described by Byrnes and Wilson (1994) for predicting porosity in quartz sandstones in several basins in the United States. These equations take into account burial history, detrital clay content, abundance of carbonate cement, and the effects of chlorite rims. Such rims, where complete, can preserve as much as 10% porosity by preventing authigenic quartz precipitation on detrital grains. As the completeness of such rims cannot be estimated prior to drilling, the equations of Byrnes and Wilson (1994) allow consideration of hypothetical scenarios, including the most optimistic case of complete coating of quartz grains by chlorite rims.

[2] For exploration purposes, predictions of the average porosity and permeability of target sandstones are arbitrarily defined by Bloch (1991) as accurate if they fall within ± 2% of the mean measured porosity and within the the same order of magnitude as the mean measured permeability.

Yacheng Field study

Using only 54 core samples and an existing depositional model of the Yacheng Field in the South China Sea, Bloch (1991) established a petrophysical calibration dataset representative of major facies to identify the main field-wide geological controls on reservoir quality. MLR was then applied to derive equations to predict porosity, **Ø** (% bulk volume), and permeability, **k** (md), in terms of: **s,** sorting (Trask sorting coefficient); **r,** rigid grain content (% solid volume/ 100); and **g,** grain size (mm).

Thus:

$$\mathbf{Ø} = 9.8/\mathbf{s} + 0.17\ \mathbf{r} - 6.1$$

$$\mathbf{k} = 10^{(1.34\ \mathbf{g} + 4.08/\mathbf{s} + 3.42\ \mathbf{r}/100 - 4.67)}$$

Bloch (1991) found that the regression coefficients and the entire model were statistically significant. The coefficient of determination for the porosity equation ($R^2 = 0.75$) indicates that 75% of the variance in porosity is accounted for by sorting and rigid grain content, whereas the coefficient of determination for the permeability equation ($R^2 = 0.86$) indicates that 86% of the variance in permeability is accounted for by grain size, sorting, and rigid grain content.

Case study — The Lower Permian Moogooloo Sandstone, Southern Carnarvon Basin

The Lower Permian Moogooloo Sandstone lies within the Wooramel Group in the Merlinleigh Sub-basin in the onshore portion of the Southern Carnarvon Basin (Fig. 1). It

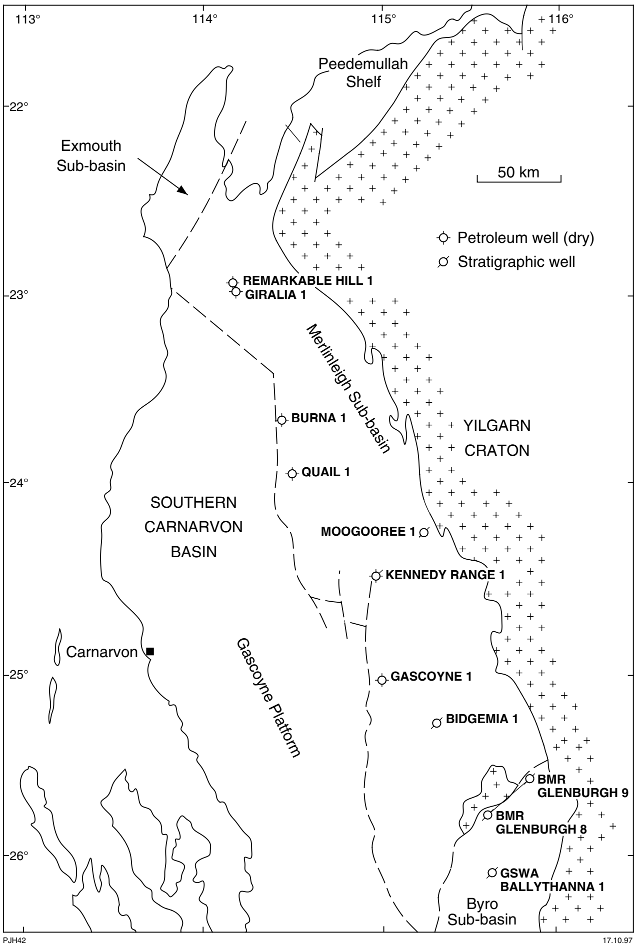

Figure 1. Structural subdivisions of the Southern Carnarvon Basin showing drillholes that intersected the Moogooloo Sandstone

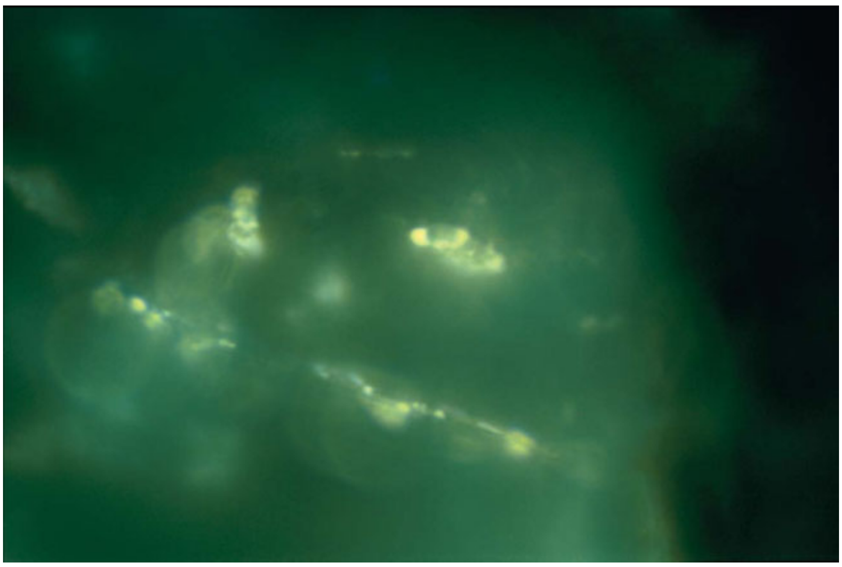

Figure 2. Photomicrograph of oil inclusions, fluorescing under UV light, decorating the trace of healed fractures in a detrital quartz grain in the Moogooloo Sandstone, Quail 1

is a dominantly sandy unit, with local minor conglomerate and siltstone, deposited as a north-westerly prograding wedge in braided, fluvial, and lower delta-plain environments. The Moogooloo Sandstone outcrops extensively and has been intersected by several wells in places where its thickness exceeds 100 m.

Demonstrated source rock-potential in adjacent units (Ghori, 1995), and recent identification of oil-bearing fluid inclusions in quartz rich, fluvial facies have refocused petroleum-exploration interest on the Moogooloo Sandstone (Fig. 2). Although only minor gas shows have been reported in previous drilling of the unit, few, if any, valid exploration prospects have been drilled.

Amongst the main deterrents to petroleum exploration of the Moogooloo Sandstone have, however, been poor understanding of the controls on porosity and permeability and reservations about reservoir quality at depth (Percival and Cooney, 1985).

Results of study by Geological Survey of Western Australia

Calibration dataset

Analysis of limited, pre-existing core porosity, permeability, and petrological data for the Moogooloo Sandstone indicated possible influence of thermal maturity and textural parameters on reservoir quality. To quantify such relationships, an integrated petrophysical calibration dataset was established through acquisition of new core porosity, permeability, petrology and vitrinite reflectance data for 80 samples selected from several wells and representative of the range of thermal maturity, textural and lithological characteristics present in the core. In addition, log analysis was used to generate porosity profiles and compute mean and maximum porosity values for the Moogooloo Sandstone in each well. The calibration dataset was subsequently analysed using curve fitting and MLR functions to generate porosity and permeability equations for statistically significant geological variables.

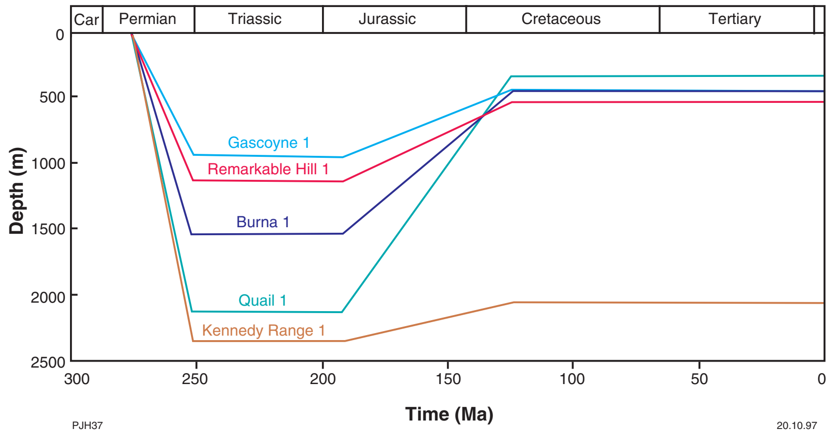

Figure 3. Differential subsidence, uplift, and erosion of the Moogooloo Sandstone (adapted from Ghori, 1995)

than relationships based on present or maximum depth of burial[3] (Fig. 4). Power-function relationships between porosity and thermal maturity, of a form similar to the above equation but with different rates of porosity loss, have been reported for sandstones in several basins around the world (Schmoker and Gautier, 1988).

Based on seismic, outcrop, and thermal-profile data from boreholes, a map of mean vitrinite reflectance for the Moogooloo Sandstone was created and the equation used to transform this into a mean-porosity map (Fig. 5). These maps show that the Moogooloo sandstone generally lies within the oil-preservation window (< 1.2%R_o) with mean formation porosity ranging from 21% near outcrop to 12% in basinal areas.

In Kennedy Range 1, however, thermal-history modelling (Ghori, 1995), and a coincident aeromagnetic anomaly, suggest unpenetrated intrusives as the cause of anomalously high thermal maturity in the Moogooloo Sandstone where mean porosity is reduced to 9% and mean permeability is negligible. Similar aeromagnetic anomalies in the region, though small, may pose similar local risks for reservoir quality.

Petrology results

The Moogooloo Sandstone is typically quartzarenite in composition and is predominantly cemented by quartz overgrowths, the abundance of which increases with increasing thermal maturity (Baker and Martin, 1996). Quartz overgrowth cement varies from less than 1% rock volume, where burial temperature never exceeded 58°C, to greater than 10% where maximum burial temperatures were around 100°C or higher.

In Giralia 1, pervasive authigenic chlorite occurs as early diagenetic grain rims that have preserved anomalously high visible porosity by inhibiting the development of quartz overgrowths. In a similar way, chlorite rims have preserved anomalously high porosity in deeply buried Middle Jurassic sandstones in the Norwegian continental shelf, where their presence indicates possible marine influence (Ehrenberg, 1993). In Australia, chlorite rims have also been recognized preserving porosity in sandstones in Permian gas-bearing reservoirs in the Tern and Petrel fields in the offshore Bonaparte Basin (Bhatia, 1984), and in the Upper Permian Wagina Sandstone in the onshore Perth Basin (Tupper et al., 1994).

Porosity modelling

The effect of increasing thermal maturity on porosity loss in the Moogooloo Sandstone was quantified in terms of mean formation vitrinite reflectance, **V** (%R_o), and mean wireline-log porosity, $Ø_L$ (%). Trial curve fitting of these data, using several function types, resulted in the following power function providing the best correlation (R^2 = 0.98) and attaining requisite ± 2% predictive accuracy:

$$Ø_L = 12.4\ \mathbf{V}^{-0.4540}$$

Significant differential subsidence, uplift and erosion of the Moogooloo Sandstone have resulted in variable heating unrelated to present depth of burial (Fig. 3). Local heating events, unrelated to maximum depth of burial, have also been identified (Ghori, 1995). Present-day mean porosity in the Moogooloo Sandstone is therefore more accurately predicted in terms of time–temperature exposure (thermal maturity), using the above equation,

[3] No wireline porosity logs were available for the Moogooloo Sandstone in Giralia 1, thus porosity preserved by chlorite rims could not be quantified.

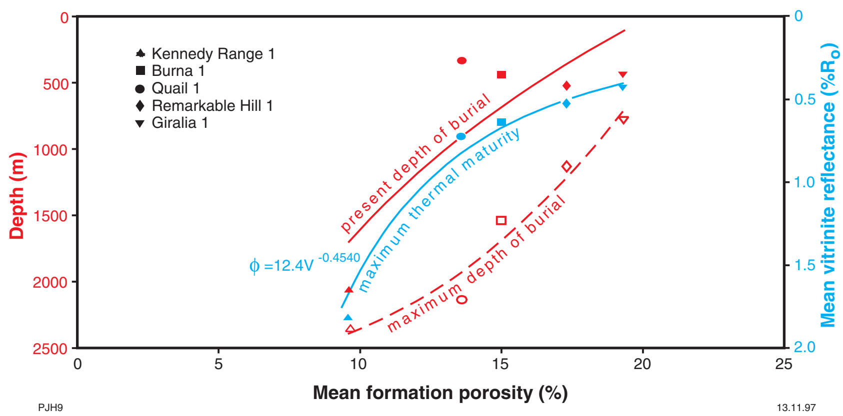

Figure 4. Best-fit relationships between mean porosity and present depth of burial, maximum depth of burial, and maximum thermal maturity in the Moogooloo Sandstone

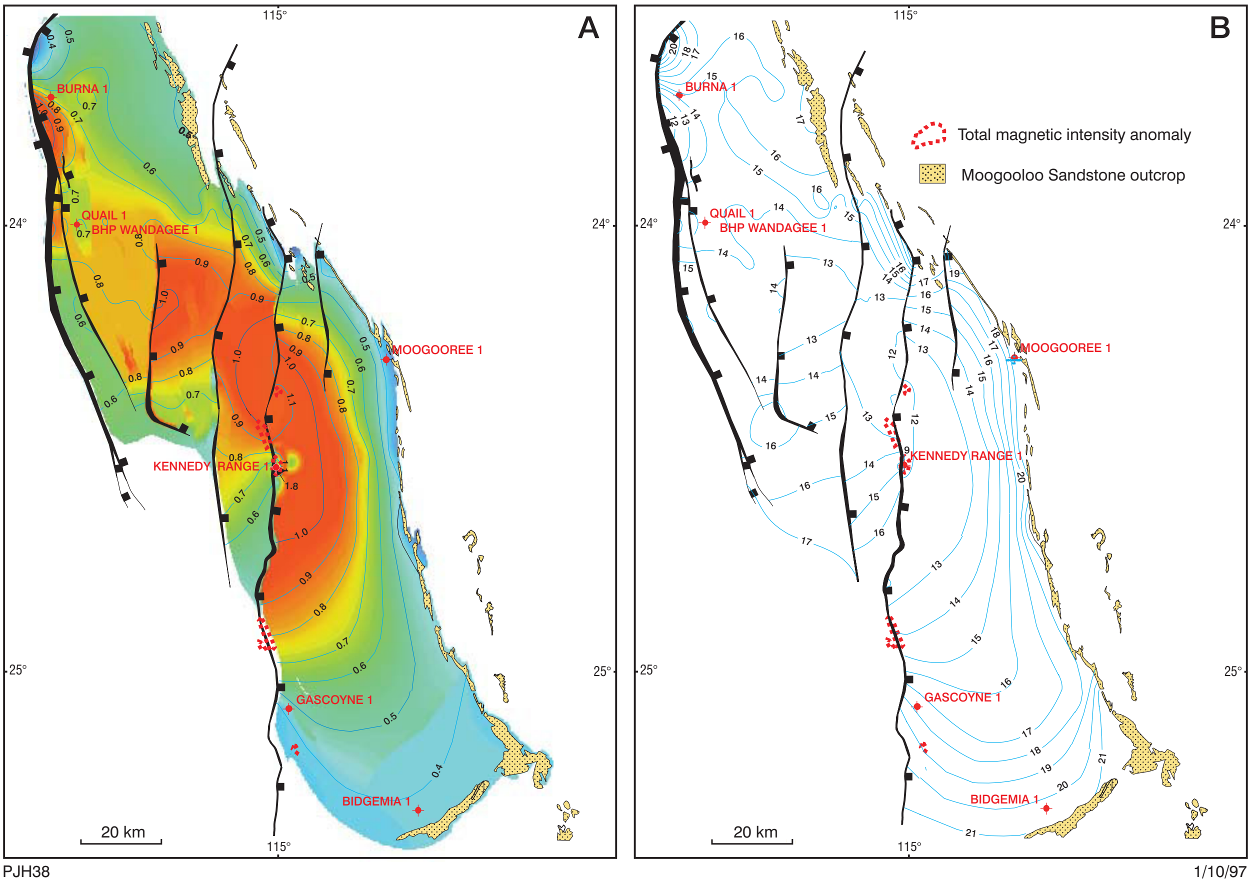

Figure 5. A: Mean vitrinite reflectance, R_o (%) of the base of the Moogooloo Sandstone; B: Mean formation porosity, Ø (%) of the Moogooloo Sandstone, where: $Ø = 12.4\ R_o^{-0.4540}$

Permeability modelling

Significance t-testing of regression coefficients for geological variables in the calibration dataset results in correlation of permeability, **k** (md), with: **V,** vitrinite reflectance (%R_o); **M,** mean grain size (phi units); **C,** clay volume (%); and $\mathbf{Ø_C}$ porosity (%).

The best-fit MLR equation linking these variables for the Moogooloo Sandstone calibration dataset is:

$$\mathbf{k} = 10^{\,0.137\,Ø_c\ -\ 0.821\,\mathbf{M}\ -\ 0.0476\,\mathbf{C}\ -\ 1.81\,\mathbf{V}\ +\ 2.18}$$

The value of the coefficient of determination ($R^2 = 0.87$) in equation 2 indicates that 87% of the variation in permeability can be attributed to porosity, grain size, clay volume, and vitrinite reflectance. In almost all cases, equation 2 attains requisite order of magnitude predictive accuracy of permeability for the entire range of pore-filling cement.

No palaeogeographic facies models are yet available to predict grain size and clay volume in the Moogooloo Sandstone. Consequently, the utility of the above equation currently lies in post-drill calculation of permeability in uncored intervals.

Conclusions

Process-oriented approaches to sandstone porosity and permeability prediction that attempt to model the effect of diagenesis on reservoir quality are currently hampered by inadequate quantitative understanding of the processes that preserve permeability and primary porosity and generate secondary porosity.

Predictions of sandstone reservoir quality, based on traditional empirical techniques of porosity–depth and porosity–permeability crossplots, are usually too inaccurate as they fail to distinguish the effects of different physical and chemical effects caused by differential subsidence, uplift and erosion.

The application of multivariate methods to identify, integrate, and quantify mappable geological controls on reservoir quality often provides requisite levels of predictive accuracy for sandstone porosity and permeability prior to drilling.

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The Earth's pre-4000 Ma history: evidence from trace element and microstructural investigation of 4000 to 4190 Ma zircons from granitic gneisses, northwest Yilgarn Craton

by D. R. Nelson, B. W. Robinson[1], and J. S. Myers

Xenocrystic zircons that crystallized more than 4000 m.y. ago have been found in two samples of late Archaean gneissose granite from the northwest part of the Yilgarn Craton (Nelson, 1996). Zircons older than 4000 Ma have been previously identified only as detrital grains within c. 3000 Ma metasedimentary rocks within the Narryer terrane (Froude et al., 1983; Compston and Pidgeon, 1986). Those zircons older than 4000 Ma are from localities within the Narryer Terrane and adjacent Murchison Terrane.

Detailed chemical and microstructural investigations of the older zircons (> 4000 Ma) using a newly developed cathodoluminescence (CL) technique, back-scattered electron (BE) imaging, and trace-element determinations using CSIRO-Trace, have revealed a complex history of crystallization, metamorphism and isotopic disturbance. SHRIMP U–Pb analyses of a zircon from a leucocratic granitic gneiss from near Churla Well (grain 11, from GSWA sample 105007) indicate a complex age pattern. Three core analyses have radiogenic $^{207}Pb/^{206}Pb$ ratios corresponding to an age of 4183 ± 6 Ma (95% confidence), one core analysis indicates an age of 4158 ± 4 Ma, and two additional analyses indicate a pooled mean age of 4140 ± 3 Ma (Fig. 1).

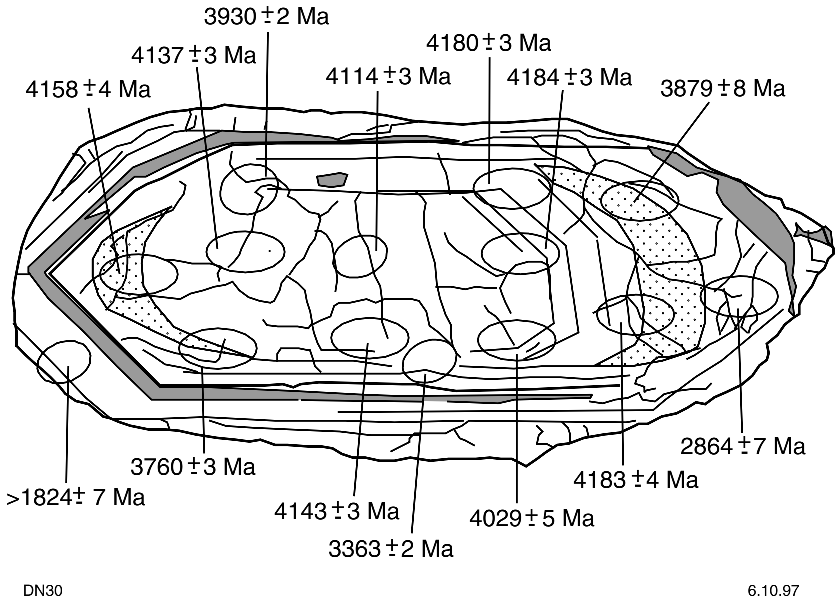

Figure 1. Schematic diagram showing SHRIMP analysis sites and U–Pb dates obtained on grain 11 from GSWA sample 105007, from a leucocratic granitic gneiss near Churla Well

Back-scattered electron imaging of grain 11 (sample 105007) has revealed numerous microfractures traversing the old core (Fig. 2). These microfractures are not visible in transmitted or reflected light. They probably developed by expansion of the crystal during early metamictization, and have been infilled by metamorphic zircon with higher concentrations of Fe and Al. The diverse younger SHRIMP ages from this core appear to reflect the presence of various proportions of younger metamorphic infill and older igneous zircon at these analysis sites. The microfractures probably formed before the growth of the outer-rim zircon. Further studies to determine the timing of the metamorphic event are in progress.

Cathodoluminescence imaging has revealed at least three zones within grain 11. An inner core containing

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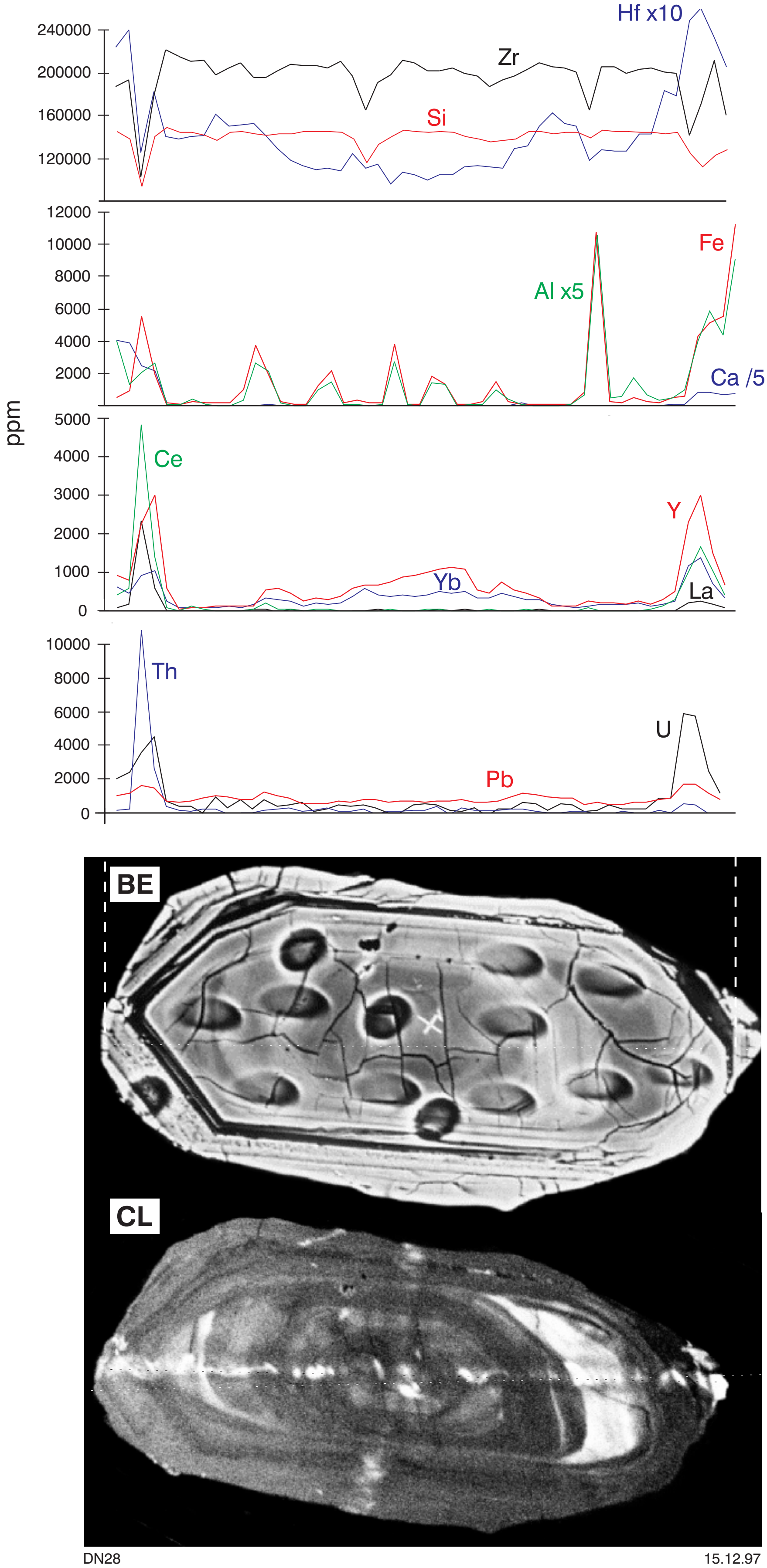

Figure 2. Back-scattered electron (BE), cathodoluminescence (CL), and trace-element abundance patterns determined using CSIRO-Trace along a traverse (shown as dotted line) of grain 11. Microfractures that have been infilled with zircon, and SHRIMP analysis sites, are visible in the BE image. The CL image reveals complex zoning pattern within the zircon

high abundances of heavy rare-earth elements is enclosed by a comparatively highly cathodoluminescent zone, characterized by lower abundances of those rare-earth elements. This is enclosed by an outer rim of low cathodoluminescence, rich in light rare-earth elements, Fe, U, and Th. At least part of the outer rim probably formed during crystallization of the host granites at about 2650 Ma, following partial melting of source rocks containing igneous components older than 4000 Ma.

This old zircon records a complex history within a single grain. Further detailed investigations of the internal chemistry and microstructures of similar old zircons may provide the only direct means currently available of investigating conditions and events on the Earth prior to 4000 Ma.

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Provenance studies in the Yerrida Basin: initial report

by N. G. Adamides

Abstract

The Yerrida Basin is one of several Palaeoproterozoic ensialic sedimentary basins that resulted from the collision of the Yilgarn and Pilbara Cratons around 2.0–1.8 Ga. Within this basin, the Doolgunna and Thaduna Formations represent turbidite facies that are probably temporally and stratigraphically related. The Doolgunna Formation is a kaolinitic wacke of granitic derivation. It is characterized by a clastic assemblage of quartz and feldspar and a heavy-mineral suite of zircon, schorlite, corundum, apatite, topaz, cassiterite, and fluorite. On the QFL diagram, samples from this unit occupy the field of continental block provenance. The Thaduna Formation is characterized by a varied assemblage of clasts and minerals of mafic igneous derivation, intermixed with sedimentary components. The heavy-mineral fraction is dominated by epidote, subordinate clinopyroxene, and detrital opaque minerals of the titanomagnetite group. These show a variety of textures (sandwich-type, trellis) suggesting similarly varied source rocks. Samples from this formation occupy the field of magmatic arc provenance. Interaction between the sedimentary environments of the Doolgunna and Thaduna Formations is inferred from field relationships as well as from mixed heavy-mineral assemblages.

KEYWORDS: Yerrida Basin, turbidites, heavy minerals, discriminant diagrams, petrography

The Yerrida Basin (Fig. 1), together with the adjacent Bryah Basin and a number of other depocentres (Earaheedy Basin, Ashburton Basin), formed approximately 2.0–1.8 billion years ago as a result of the collision of the Yilgarn and Pilbara Cratons (Myers, 1993; Tyler and Thorne, 1990). This collision, which resulted in the formation of the Capricorn Orogen (Gee, 1979), is thought to have been initiated with the southeastern part of the Pilbara Craton impacting into the middle of the northern margin of the Yilgarn Craton (Tyler and Thorne, 1990). The original extent and relationships of the resultant sedimentary basins are not known, as much of the ground is either obscured by the younger Bangemall Basin to the north, or eroded.

Early ideas (Horwitz and Smith, 1978) envisaged sedimentation in a single major basin. These are in contrast to more recent views (Pirajno et al., 1995) which suggest that sedimentation took place in a number of spatially restricted basins associated with pull-apart openings created by transpressional strike-slip movements. Provenance studies are useful for the evaluation of these two alternatives, by placing constraints on palaeogeographic reconstructions and providing information on the nature of the source rocks. Such studies may be multidisciplinary, incorporating petrography, geochemistry and the study of heavy-mineral populations, supplemented by analytical data.

In the following paragraphs, some preliminary data are presented from work currently in progress on the Yerrida Basin.

Geological framework

The Yerrida Basin (Fig. 1) is in tectonic contact with the Bryah Basin to the northwest and is probably ensialic, resting unconformably on Archaean granite of the Yilgarn Craton. An inlier of Archaean granite — the Goodin Inlier — lies close to the northwest margin of the basin. Flat-lying shales of the Maraloou Formation and mafic volcanics of the Killara Formation cover the southeastern parts.

Current ideas on the formation of the Yerrida Basin envisage initial peneplanation of a granite–greenstone basement with deposition of a basal quartz arenite (Juderina Formation) and associated quartz siltstones and evaporite units. Argillaceous siltstone and shale with minor dolomite (Johnson Cairn Formation) and lithic wacke follow the basal sequence. This package is interpreted as a sag-basin phase in the evolution of the basin, with the argillaceous lithologies signifying deepening of the basin and the onset of turbidite activity (Pirajno et al., 1995).

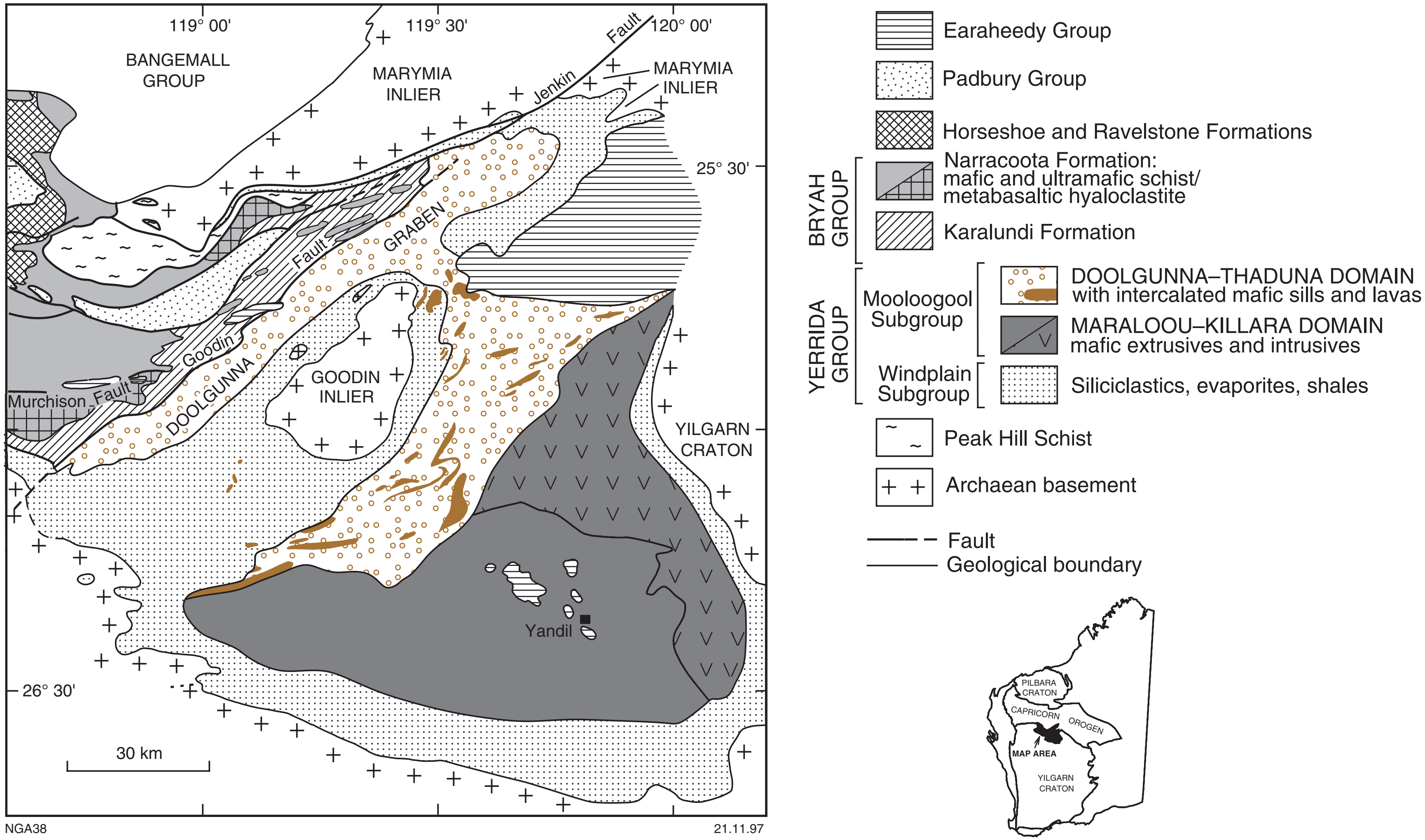

Figure 1. The general geology of the Yerrida and Bryah Basins

Rocks of turbidite facies, which form the theme of this study, are represented by the Doolgunna and Thaduna formations and are particularly developed through the basin in a northeasterly trending belt. Interfingering relationships and thinning of the two formations have been documented in the area east of the Goodin Inlier by Pirajno and Adamides (1997).

Features of the turbidite assemblages

Petrography

The petrographic features of turbidite assemblages provide significant guides as to the likely source rocks. The Doolgunna Formation is typically a kaolinitic quartz wacke consisting of quartz and feldspar in a clay matrix. The feldspar comprises roughly equal amounts of plagioclase and potassium feldspar, including microcline. Quartz is present as subrounded clasts, commonly monocrystalline with undulose extinction; however, polycrystalline grains are also abundant. Sand-size polycrystalline grains are mostly composed of fewer than five subequant, commonly undulose crystals, implying a plutonic provenance. Polycrystalline quartz grains of gneissic origin (Blatt et al., 1972) are not present. Chert, quartzite and rare rounded, recycled quartz are also present in small amounts, as is white mica and biotite. These assemblages strongly suggest a granitic source with a very subordinate sedimentary component.

The Thaduna turbidites, by contrast, display a complex mineralogy, with a wide variety of clast types in a chloritic matrix. The reactive nature of the dominantly mafic assemblages resulted in widespread metamorphic overprinting with minerals characteristic of lower greenschist facies (epidote, pumpelllyite, chlorite, and calcite). The main phases identified petrographically include plagioclase, rarer amphibole and clinopyroxene, and micrographic intergrowths of quartz and feldsdpar. Minerals of the epidote group are widespread and, although a metamorphic origin is envisaged in some cases by the replacement of the matrix and siltstone clasts, most of the epidote is clearly detrital. Some plagioclase displays zoning and probably retains its original volcanic chemistry (Trevena and Nash, 1981). Laminated siltstone and grains of rounded quartz and carbonate are present in subordinate amounts. Volcanic clasts in the Thaduna Formation typically consist of an assemblage of albite and chlorite showing a variety of textures including intersertal, feathery, and spherulitic.

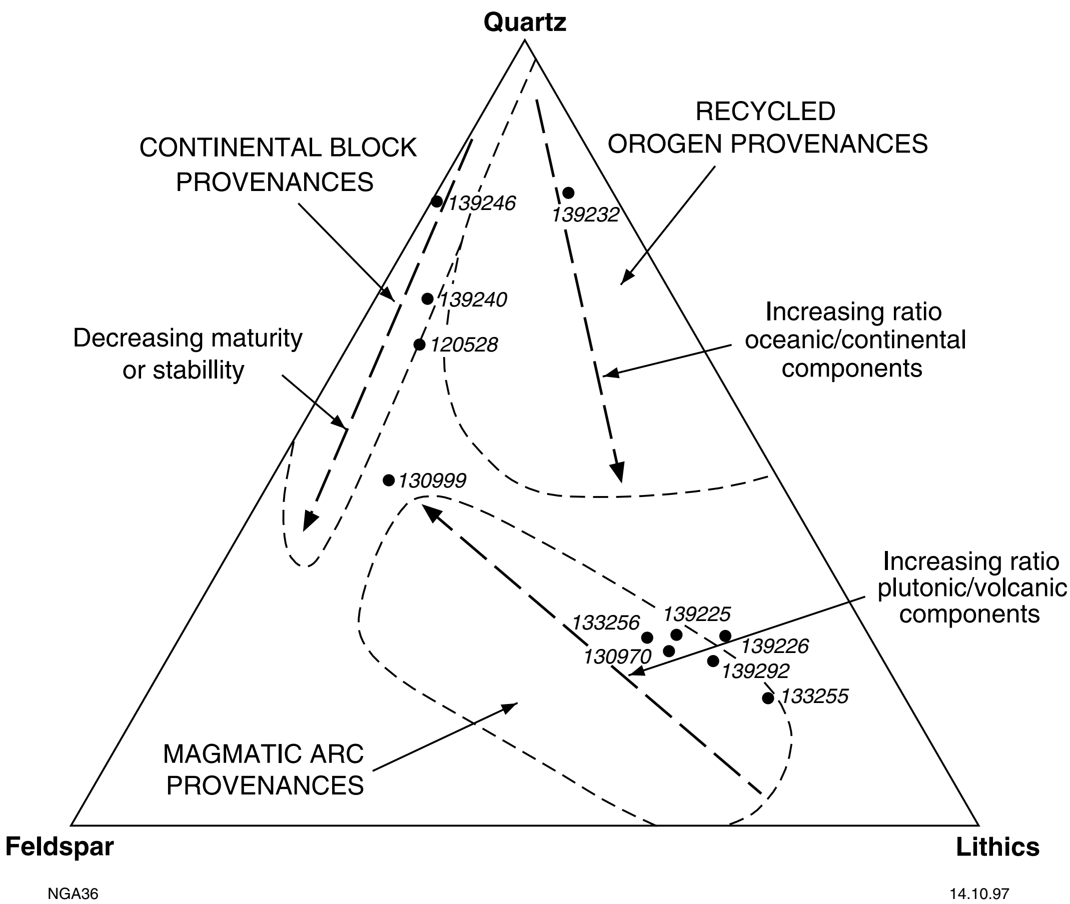

Figure 2. Ternary diagram showing the proportions of quartz, feldspar and lithic fragments highlights the lithological differences between Doolgunna and Thaduna Formations. After Dickinson and Suczek (1979)

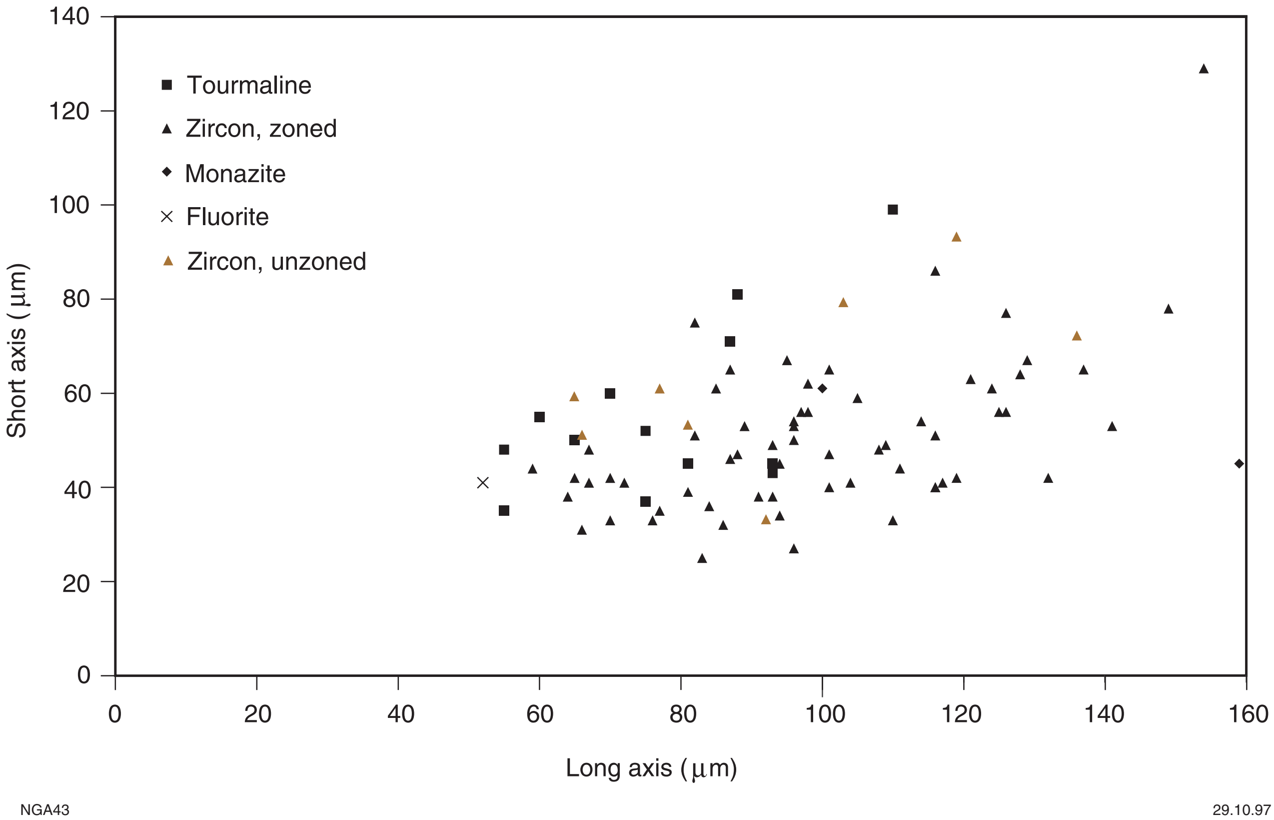

Figure 3. Plot of non-magnetic heavy-mineral separates from the Doolgunna Formation

A significant feature of the Thaduna Formation is the increased abundance of granite-derived and sedimentary detritus in areas away from its type locality at Thaduna mine. This is in keeping with previous conclusions (Gee, 1987) which suggest that deposition of the more mafic parts of the formation occurred in a spatially restricted trough.

Provenance diagrams

The lithological differences between the Doolgunna and Thaduna Formations, highlighted from petrography, are further emphasized by the use of ternary diagrams. Such diagrams utilize the proportions of quartz, feldspar and lithic fragments in sandstones to determine their plate-tectonic setting, and are used extensively in the discrimination of provenance of turbidite assemblages (Dickinson and Suczec, 1979; Korsch, 1984).

Grain counting of a small number of samples from the Doolgunna and Thaduna Formations was performed using a Swift grain counter. Grains were separated into quartz (dominantly monocrystalline), feldspar of all types, rock fragments and matrix. An average of 300 grains was counted from each section. A plot of the results on the discriminant diagram of Dickinson and Suczek (1979) is shown on Figure 2. The quartzofeldspathic assemblages of the Doolgunna Formation occupy the field of continental-block provenances. Samples from the quartz-poor, lithic-dominated turbidites of the Thaduna Formation occupy the field of magmatic-arc provenance. The distinct compositional differences between the two formations, apparent from the diagrams, support major differences in source regions.

Heavy-mineral assemblages

Typical heavy-mineral separates from the Doolgunna Formation (Fig. 3) are characterized by abundance of well-formed, commonly euhedral and zoned zircons of variable morphology, including strongly elongated and lath-like (Fig. 4A), as well as more equant types. Partial or complete overgrowths have been rarely observed. Schorlite occurs either as subhedral crystal fragments or, more rarely, as rounded grains suggesting a recycled origin. Apatite is present as rare small, clear prismatic crystals. Corundum, in the form of transparent rhombohedral fragments, is locally abundant and topaz occurs in transparent crystals with prismatic outline. Fluorite is a trace component.

The opaque fraction in the Doolgunna Formation commonly shows a distinctive sugary aspect of anatase (Fig. 4B) most probably derived from the alteration of ilmenite. This origin is supported by microscopic examination of a heavy-mineral separate from the granite of the Goodin Inlier that displays ilmenite as a major phase, with subordinate magnetite. The magnetite shows marginal thin exsolution lamellae of ilmenite with spacings between lamellae in the 8–10 microns range. Associated zircons extracted from the granite are morphologically similar to those from the Doolgunna Formation.

The heavy-mineral fraction of the Thaduna assemblages is dominated by minerals of the epidote group in association with abundant opaque minerals. Sparse rounded zircon suggests a recycled sedimentary component. The detrital opaque fraction consists mostly of titanomagnetite and subordinate ilmenite. These minerals display a variety of textures which include oriented (trellis-type) ilmenite lamellae (Fig. 4C) of varying width implying variable cooling histories for the source rocks (Buddington and Lindsley, 1964; Haggerty, 1981). Locally, thick sandwich-type lamellae have also been identified (Fig. 4D). Most of these opaque minerals are partially or totally oxidized, resulting in a skeleton of ilmenite with interstitial iron hydroxides. However, in some cases, well-preserved isomorphically martitized magnetite with fine ilmenite lamellae along crystallographic directions is observed.

The interfingering relationships between the turbidites of the Doolgunna and Thaduna Formations are also reflected in the heavy-mineral assemblages. Samples collected from the area east of the Goodin Inlier display a mixed assemblage of mafic volcanic fragments, abundant detrital opaque minerals and epidote. These are intermixed with minerals of granitic derivation, particularly zircon and tourmaline, with scarce drusy cassiterite. This is interpreted as evidence both of coevality between the Doolgunna and Thaduna Formations as well as of interaction between volcanic and granitic source regions during sedimentation.

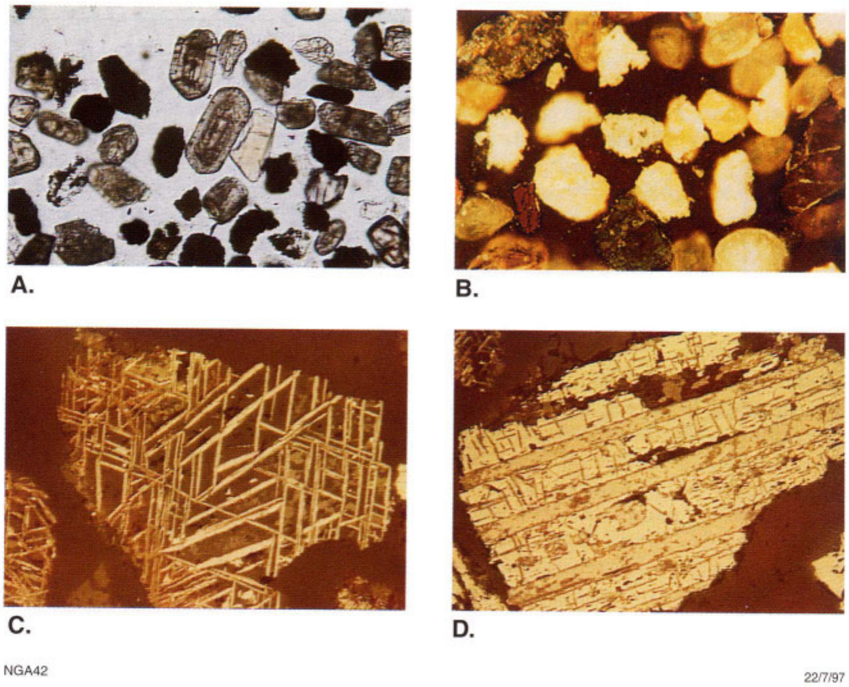

Figure 4. A. Euhedral and zoned zircons
B. Distinctive sugary aspect of anatase
C. Oriented (trellis-type) ilmenite lamellae
D. Thick sandwich-type lamellae in ilmenite

Conclusions

This work has shown that the Doolgunna and Thaduna Formations of the Yerrida Basin are derived from different source regions. Minerals of granitic derivation (zircon, schorlite, apatite, topaz, corundum, cassiterite) dominate the Doolgunna Formation with a subordinate recycled component indicated by rounded grains of tourmaline. The Thaduna Formation, on the other hand, displays a large variety of detrital opaque phases, associated with abundant epidote and clinopyroxene. Mafic rock is recognized in lithic fragments. Intermixed with these purely igneous assemblages are sedimentary components. However, coevality between the two formations, and possible interaction between source regions, is suggested both by field relationships and by the presence of mixed heavy-mineral assemblages with characteristics of both regions.

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Palaeoproterozoic tectonic evolution of the Rudall Complex, and comparison with the Arunta Inlier and Capricorn Orogen

by L. Bagas and R. H. Smithies

Abstract

The Palaeoproterozoic rocks of the Rudall Complex can be divided into three terranes. The western two terranes were affected by the Yapungku Orogeny between c. 2.00 and 1.76 Ga, and included progressive thrust stacking from the east to the west. The orogeny records the collision between the Pilbara Craton and a continent to the northeast. The Palaeoproterozoic deformation and metamorphic history of the Rudall Complex is broadly synchronous with that of the Arunta Inlier in central Australia, and possibly also of the Capricorn Orogen in central Western Australia.

KEYWORDS: Palaeoproterozoic, Rudall Complex, Arunta Inlier, Capricorn Orogen, Yapungku Orogeny, tectonic evolution, metamorphism, plate tectonics

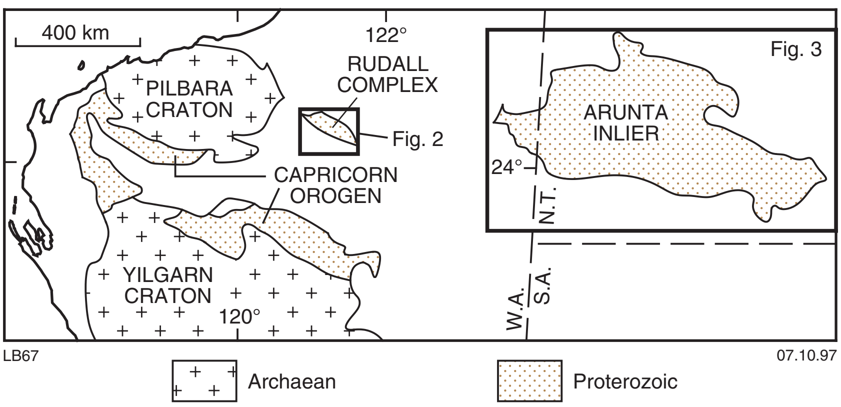

Figure 1. Location of the Pilbara and Yilgarn Cratons, Capricorn Orogen, Rudall Complex and Arunta Inlier

The Proterozoic Rudall Complex is situated along the southeastern margin of the Archaean Pilbara Craton, and between the Proterozoic Capricorn Orogen and Arunta Inlier (Fig. 1). The contact between the complex and the Pilbara Craton is obscured by unconformably overlying Meso- to Neoproterozoic cover rocks. The Rudall Complex and the deformed cover rocks together form part of the Paterson Orogen (Fig. 2).

The Rudall Complex was subjected to a Palaeoproterozoic orogeny (D_{1-2}) and Meso- to Neoproterozoic orogeny (D_{3-4}), which have recently been referred to as the Yapungku and Miles Orogenies respectively (Bagas and Smithies, in press). A fifth deformation event (D_5) is locally preserved in cover rocks (Hickman and Clarke, 1994). All components have been deformed by the late Neoproterozoic Paterson Orogeny (D_6). This paper principally discusses the Yapungku Orogeny; the other orogenies have been discussed elsewhere (Bagas et al., 1995; Bagas and Smithies, in press).

The Yapungku Orogeny shows similarities in terms of styles and timing of deformation and metamorphism, to other central and northwestern Australian Palaeoproterozoic orogenies, even though they are hundreds of kilometres apart (such as the Stafford tectonic event and the Strangways Orogeny of the Arunta Inlier in central Australia (Collins

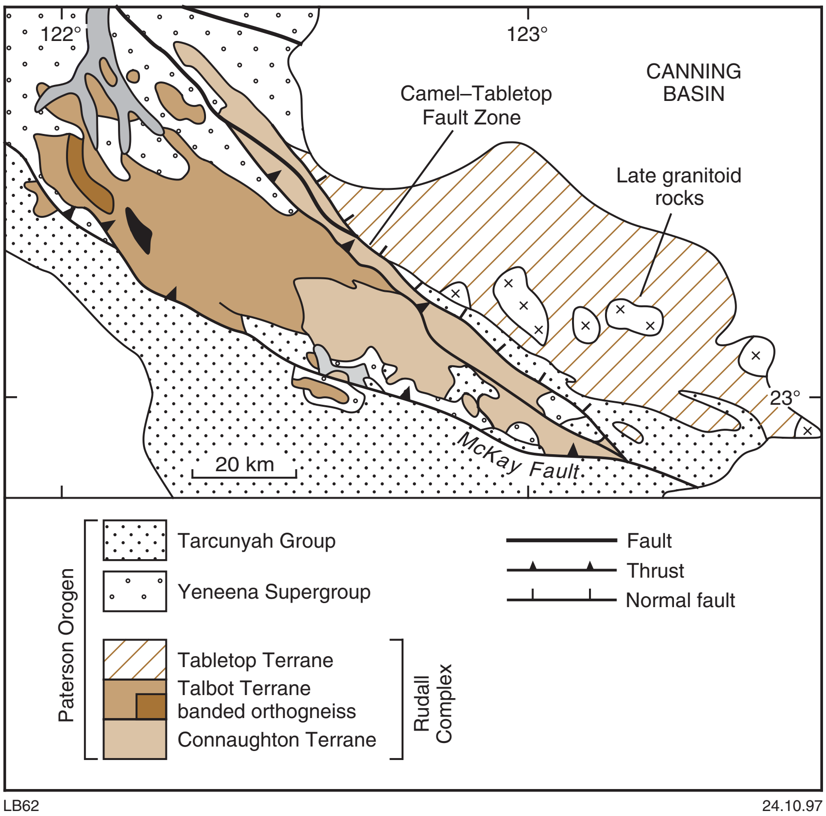

Figure 2. Simplified geological map of the Rudall Complex, illustrating regional setting and the distribution of tectonic elements

and Shaw, 1995), and the Capricorn Orogeny in Western Australia (Myers, 1993)).

Geology of the Rudall Complex

The Palaeoproterozoic Rudall Complex is divided into the Connaughton Terrane in the central and southeastern parts, and the Talbot Terrane in the northwestern part (Fig. 2). A third, and poorly exposed, Tabletop Terrane is situated to the northeast of a major regional shear zone called the Camel–Tabletop Fault Zone (Smithies and Bagas, 1997a).

The first recognizable event in the evolution of the Connaughton Terrane was the deposition of continental tholeiitic basalt, and chemical and clastic sediments. The succession indicates extensive exhalative activity associated with mafic (high-Fe tholeiitic) volcanism in a shallow-water, restricted continental basin, or in a deep-water outer continental-shelf environment characterized by near saturation in iron, silica, and carbonate (Bagas and Smithies, in press). This early Rudall basin was possibly elongate to the north or northwest (Bagas and Smithies, in press) and may have developed as a rift on the eastern margin of the Pilbara Craton during late Archaean to early Palaeoproterozoic fragmentation of the Archaean continents (Myers et al., 1996).

A thick siliciclastic succession forms the base of the Talbot Terrane and can be subdivided into an older assemblage and a younger assemblage. The older assemblage appears to have been deposited in a deep-water environment, and includes turbiditic units (the Larry and Butler Creek Formations) and units deposited in a low-energy environment during periods of low clastic supply (the Yandagooge Formation). Facies changes suggest basin elongation to the north or northwest, with relatively deep-water muds and turbidites thickening eastwards across the terrane (Hickman and Bagas, 1995). The assemblage may have been deposited in a subsiding rift basin along the eastern margin of the Pilbara Craton, analogous to the Yerrida Basin on the southern margin of the Capricorn Orogen (Pirajno et al., 1996). The younger assemblage includes relatively shallow-water ?fluviatile quartzitic units such as the Fingoon Quartzite and Poynton Formation. The youngest detrital zircons in the Fingoon Quartzite have an age of c. 1.79 Ga (Nelson, 1995), and this unit is complexly interleaved with the other formations.

The older assemblage of metasedimentary rocks of the Talbot Terrane was intruded by granitic rocks (now banded orthogneiss) with zircons dated at 2.0–1.8 Ga (Nelson, 1995). Both assemblages of metasedimentary rocks were extensively intruded by porphyritic granite (now augen gneiss). The igneous ages of zircons in this augen gneiss range from 1.79 to 1.765 Ga (Nelson, 1995), indicating that the younger assemblage of metasedimentary rocks was deposited between 1.80 and 1.79 Ga.

The Tabletop and Connaughton Terranes are lithologically similar, comprising amphibolite, ultramafic rocks, calc-silicate rocks, banded iron-formation and quartzite, but are separated by the Camel–Tabletop Fault Zone (Fig. 2), a major tectonic boundary. The relationship between the two terranes is uncertain, but the Tabletop Terrane is intruded by voluminous post-D_2 granitic rocks and dolerite dykes that are not found in the Connaughton Terrane. U–Pb SHRIMP zircon ages of these granitic intrusions range from 1.475 to 1.3 Ga (Smithies and Bagas, 1997a).

Yapungku Orogeny

The earliest orogenic event recognized in the Rudall Complex is the Yapungku Orogeny, which includes two deformation events (D_1 and D_2). The age of the orogeny, which represents a cycle of crustal thickening characteristic of a major continental collision, is poorly constrained between c. 2.00 and 1.76 Ga.

Evidence for the earliest deformation event (D_1) is recognized only as bedding-parallel fabrics in the Talbot Terrane. However, major isoclinal (possibly recumbent) folds and subhorizontal thrusts described locally from this terrane by Clarke (1991) may also be D_1 structures. Associated metamorphic features are likewise poorly preserved, but indicate low-pressure metamorphism at amphibolite facies. The rocks in the Connaughton Terrane have been extensively recrystallized during amphibolite–granulite facies metamorphism associated with M_2. Evidence of D_1 and M_1 in this terrane is preserved only as deformed inclusion trails in the cores of garnet porphyroblasts (Smithies and Bagas, 1997b).

Banded orthogneiss in the western part of the Talbot Terrane contains two fabrics, S_1 and S_2, and is intruded by the relatively homogeneous K-feldspar augen gneiss dated between 1.79 and 1.765 Ga. The augen gneiss contains only S_2, indicating that D_1 occurred before 1.79 Ga.

The second deformation (D_2) is characterized by north–south isoclinal folding, faulting, and crustal thickening in the Connaughton Terrane, and by the emplacement of the granitic protolith of the augen gneiss, together with ultramafic (peridotite–dunite) and mafic (gabbro) rocks, in the Talbot Terrane. Dates from pre- and post-D_2 granites constrain the D_2 event to between 1.79 and 1.76 Ga (Nelson, 1995).

D_2 thrusting in the Talbot Terrane is progressively younger towards the east (Hickman and Bagas, 1995), with peak regional M_2 metamorphism being syn-D_2 in the Connaughton Terrane, but post-D_2 in the Talbot Terrane. Mineral assemblages produced during M_2 include prograde kyanite- and garnet–staurolite-bearing amphibolite facies assemblages in pelitic schist of the Talbot Terrane. The amphibolites and mafic granulites in the Connaughton Terrane were metamorphosed at high pressures (≤ 1200 MPa) to the amphibolite–granulite facies transition, indicating that the present erosion surfaces expose rocks deformed and recrystallized at crustal depths of up to 35 km (Smithies and Bagas, 1997b). These conditions also indicate that the progressive deformation and metamorphism assigned to D_2/M_2 was in response to major crustal thickening, consistent with a continent–continent collisional orogeny in which the Connaughton Terrane was thrust westwards over the Talbot Terrane. It appears that the D_2 structures were produced during 1.79–1.76 Ga by a plate advancing from the east during late stages of the Yapungku Orogeny. The Tabletop Terrane could represent the eastern plate, which may continue eastward beneath the Canning Basin.

Comparison with the Arunta Inlier and Capricorn Orogen

Deformation and metamorphism in the Rudall Complex, Capricorn Orogen (Tyler and Thorne, 1990), and in the Arunta Inlier (Collins and Shaw, 1995) have similar age ranges. Below, we briefly describe the Arunta Inlier and the Capricorn Orogen, highlighting features comparable with those of the terranes of the Rudall Complex.

Arunta Inlier

The Arunta Inlier is a major mobile belt of some 200 000 km^2 in central Australia (Fig. 3). The belt is characterized by mafic and felsic meta-igneous rocks, and abundant silicic aluminous and carbonate metasedimentary rocks (Shaw et al., 1984; Collins and Shaw, 1995). The inlier comprises three distinct east–west orientated tectonic provinces (Northern, Central, and Southern of Shaw et al., 1984). Most exposed province boundaries are either faulted, sheared, and metamorphosed and/or intruded by granite.

The Northern Tectonic Province is the most extensive and comprises a turbidite succession that was intruded by granite, prior to deformation and metamorphism (Stewart et al., 1984). In the Central Tectonic Province an assemblage of mafic and felsic meta-igneous rocks are interlayered with, and are locally overlain by, metamorphosed subordinate aluminous and calcareous sedimentary rocks. Similar rocks also form a minor component of the Northern Tectonic Province (Collins and Shaw, 1995). The Southern Tectonic Province is characterized by a platform succession, comprising quartzite, shale and carbonate (Stewart et al., 1984).

The Northern and Central provinces underwent localized tectonism, low-P and high-T metamorphism, and magmatism at ~1.88 Ga during the Yuendumu tectonic event, and at 1.86–1.82 Ga during the Stafford tectonic event (Collins and Shaw,

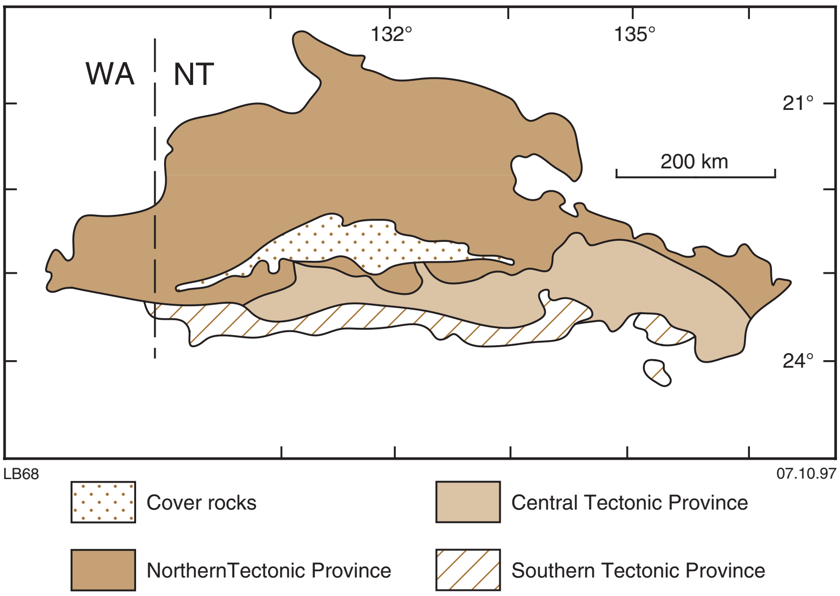

Figure 3. Simplified map of the Arunta Inlier, showing the Northern, Central, and Southern Tectonic Provinces (after Shaw et al., 1984)

1995). These events may overlap the D_1 event in the Rudall Complex.

The Northern Tectonic Province was metamorphosed up to the lower amphibolite facies, and locally to the granulite facies, during the Weldon tectonic phase of the Strangways Orogeny between 1.78 and 1.77 Ga (Collins and Shaw, 1995; Myers et al., 1996). This province appears to be similar to the Talbot Terrane of the Rudall Complex in terms of lithological association, and style and time of deformation and metamorphism.

The Central Tectonic Province developed at a greater crustal depth than the Northern Tectonic Province. Here, widespread deformation was followed by metamorphism at the amphibolite–granulite facies with pressures of 700–900 MPa, during the Strangways Orogeny (Shaw et al., 1984; Shaw and Black, 1991; Collins and Shaw, 1995). These metamorphic conditions imply a depth of burial to 30 km. The Central Tectonic Province has similarities with the Connaughton Terrane of the Rudall Complex in terms of lithological association, and style and timing of deformation and metamorphism.

The Strangways Orogeny was most intense in the Central Tectonic Province, and was accompanied by the intrusion of extensive granites between 1.78 and 1.745 Ga (Shaw et al., 1984; Collins and Williams, 1995). This orogeny was possibly related to plate convergence (Myers et al., 1996), as is proposed for the D_2 event included in the Yapungku Orogeny of the Rudall Complex.

The Southern Tectonic Province is mostly younger than the other provinces. It is characterized by amphibolite-facies quartzo-feldspathic gneiss unconformably overlain by siliceous and aluminous metasedimentary rocks, and is extensively intruded by granites and widespread dolerite dykes (Shaw et al., 1984; Black and Shaw, 1995). Most of the province appears to be younger than about 1.68 Ga, was not affected by the Strangways Orogeny, and was an exotic terrane prior to 1.5–1.4 Ga (Black and Shaw, 1995). The evolution of this province appears to be synchronous with that of the Tabletop Terrane of the Rudall Complex (Smithies and Bagas, 1997a).

Table 1. Age constraints of Palaeoproterozoic tectonic events in the Rudall Complex, Capricorn Orogen, and Arunta Inlier

Capricorn Orogen	*Rudall Complex*	*Arunta Inlier*
1.95–1.80 Ga granite intrusion [a]	2.00–1.80 Ga granitic magmatism (now banded orthogneiss) [b]	~1.88 Ga Yuendumu tectonic event, granitic magmatism [d]
		1.86–1.82 Ga Stafford tectonic event, granitic magmatism [d]
early deformation associated with the Capricorn Orogeny	1.80 Ga minimum age for D_1	
1.80 Ga post collisional granitic magmatism [b]	1.80–1.79 Ga deposition of younger assemblage in the Talbot Terrane	
	1.79 Ga maximum age for D_2	
		1.78 Ga maximum age for the Strangways Orogeny [d][e]
	1.79–1.765 Ga granitic magmatism (now augen gneiss) in the Connaughton and Talbot Terranes [b]	1.78–1.745 Ga granitic magmatism [f][g]
	1.76 Ga minimum age for D_2	
		1.745 Ga minimum age for the Strangways Orogeny [d]
~1.72 Ga late deformation in the Capricorn Orogen [c]		
		1.68 Ga maximum age for the Southern Tectonic Province [h]
	1.475–1.3 Ga granitic magmatism in the Tabletop Terrane [i]	

Notes: (a) Tyler et al. (in press); (b) Nelson (1995); (c) McMillan et al., (1995); (d) Collins and Shaw (1995); (e) Myers et al. (1996); (f) Shaw et al. (1984); (g) Collins and Williams (1995); (h) Black and Shaw (1995); (i)Bagas and Smithies (in press)

Capricorn Orogen

The Capricorn Orogen is situated west of the Rudall Complex (Fig. 1) and is a zone of deformation, metamorphism, and igneous activity that formed between the Archaean Pilbara and Yilgarn Cratons during 2.0–1.6 Ga. The orogen consists of several tectonic units, namely the high-grade (up to granulite facies) Gascoyne Complex, incorporating voluminous 1.95 and 1.8 Ga granites that are similar in age to the banded orthogneiss in the Rudall Complex (Tyler et al., in press), and basins, such as the Padbury and Yerrida Basins, which mainly contain low-grade sedimentary rocks, including turbidites, and volcanic sequences (Pirajno et al., 1996).

Myers et al. (1996) interpreted the tectonic development of the Capricorn Orogen in terms of a convergent plate-tectonic model involving oblique collision of the two Archaean cratons at about 2.0–1.8 Ga. Post-collisional granitic magmatism, at about 1.8 Ga (Nelson, 1995), was synchronous with early granitic magmatism within the Rudall Complex (banded orthogneiss). Continued deformation in the Capricorn Orogen involved thrusting accompanied by greenschist facies metamorphism that culminated by about 1.72 Ga (McMillan et al., 1995). This event is broadly synchronous with the D_2 event included in the Yapungku Orogeny of the Rudall Complex.

Discussion

The Palaeoproterozoic tectonic events of the Rudall Complex, Capricorn Orogen, and Arunta Inlier are outlined in Table 1.

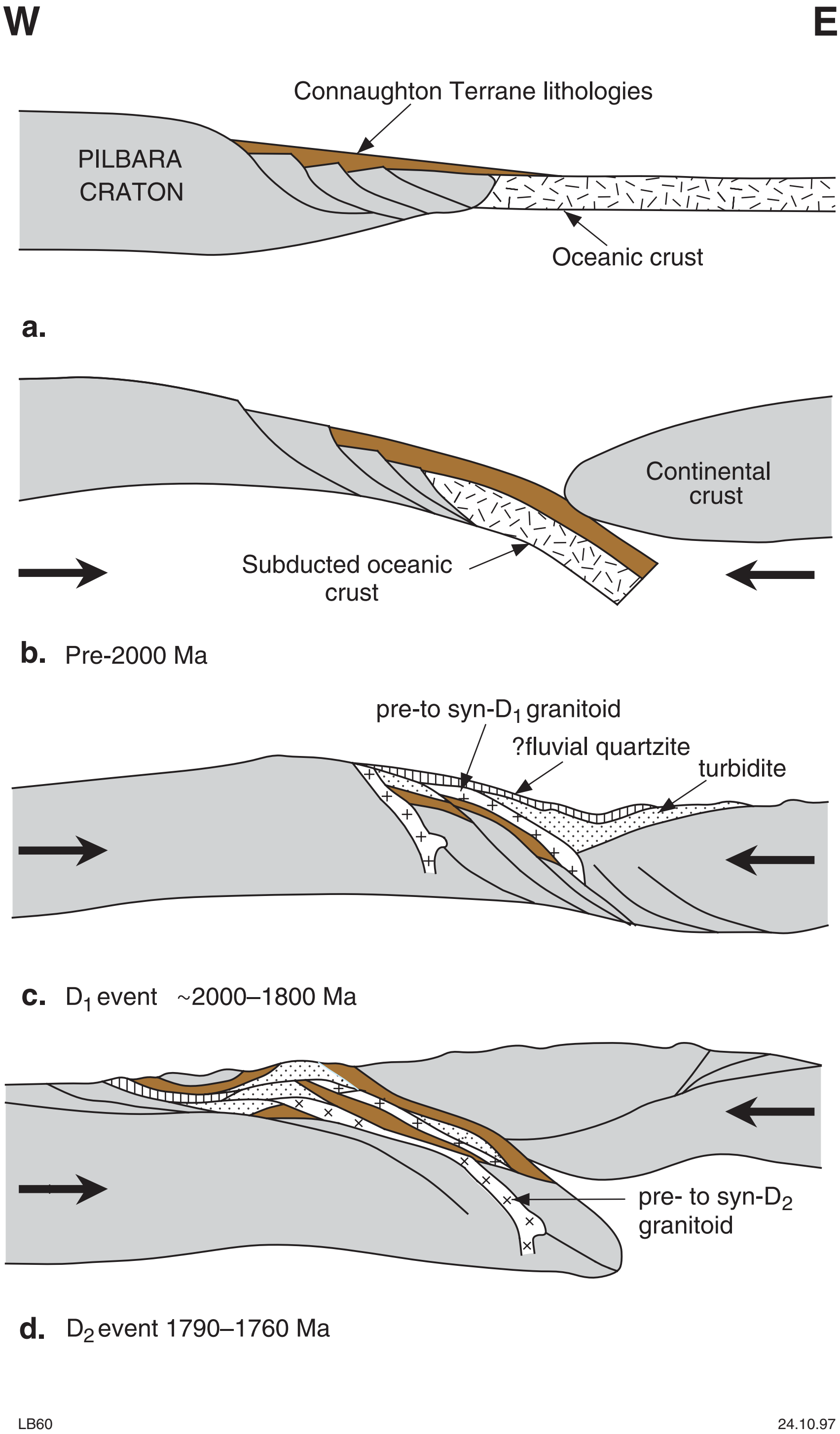

Figure 4. Tectonic model showing the evolution of the Rudall Complex during the Yapungku Orogeny: (a) deposition of rocks along the eastern 'passive margin' of the Pilbara Craton; (b) active-margin stage, with a possible magmatic arc to the east; (c) collision with inferred continental crust to the east, deposition of turbidites and shale in the Talbot Terrane, intrusion and tectonism of pre- to syn-D_1 granite (now banded orthogneiss), and deposition of post-D_1 sedimentary rocks; (d) folding and thrusting accompanied by high-pressure and high-temperature metamorphism (doubly thickened crust) during D_2, reactivation of D_1 thrusts, intrusion and tectonism of pre- to syn-D_2 granite (now augen gneiss)

The Yapungku Orogeny (D_1 and D_2) deformed and metamorphosed rocks of the Talbot and Connaughton Terranes between 2.0 and 1.76 Ga (Fig. 4). D_1 took place between 2.0 and 1.8 Ga (Fig. 4c). This age range for D_1 is synchronous with the initial stages of the Capricorn Orogeny, which took place between 1.95 and 1.83 Ga and established the West Australian Craton by continental collision of the Archaean Pilbara and Yilgarn Cratons (Myers et al., 1996). Both regions were intruded by granites at c. 1.8 Ga (Nelson, 1995; Myers et al., 1996).

The D_2 event of the Yapungku Orogeny continued during 1.79–1.76 Ga, synchronous with the Strangways Orogeny, and broadly synchronous with late deformation in the Capricorn Orogen. During this period, distinct crustal terranes were constructed within each orogen, as contrasting lithological assemblages were juxtaposed, deformed, and metamorphosed. The Talbot and Connaughton Terranes have very close analogues in the Northern and Central tectonic provinces of the Arunta Inlier respectively, both in terms of lithological assemblages and style, and in timing of deformation and metamorphism. The Connaughton Terrane and Central Tectonic Province, in particular, show evidence for contemporaneous high-pressure metamorphism and collisional tectonics during the Yapungku and Strangways Orogenies.

The Yapungku and Capricorn Orogenies may record a period of crustal assembly where the Pilbara Craton was joined to the North Australian Craton (Myers et al., 1996) along the Rudall Complex, and to the Yilgarn Craton along the Capricorn Orogen. The Strangways Orogeny also records a synchronous crustal assembly in central Australia, and may be related to the collision between the Pilbara Craton and the North Australian Craton. The exact spatial and temporal relationships between the Rudall Complex and Arunta Inlier during the Palaeoproterozoic cannot be determined because of plate readjustment during later collisional events. An example of such an event is recorded in the Tabletop Terrane (as described by Smithies and Bagas, 1997a).

It is apparent that plate-tectonic processes cannot be ignored in terms of the geological evolution of Palaeoproterozoic Australia. It appears that several Australian cratonic elements were involved in regional collision events at about 1.78 Ga.

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A Palaeoproterozoic hot spring environment for the Bartle Member cherts of the Yerrida Basin, Western Australia

by F. Pirajno and K. Grey

Abstract

Bartle Member cherts (Yerrida Group) contain textures indicative of evaporite, pyroclastic and hot spring environments. The latter have anomalous gold abundances and also contain spheroids (about 10–12 mm in diameter) that resemble micro-organisms. Present-day analogues of the Bartle Member could be those of the Afar region and Lake Magadi in the East African Rift System.

KEYWORDS: microdubiofossils, hot springs, evaporites, gold mineralization

Volcano-sedimentary basins developed between the Pilbara and Yilgarn Cratons in Western Australia, during the Proterozoic (Myers et al., 1996). One of these is the Yerrida Basin (Fig. 1), previously part of the Glengarry Basin of Gee and Grey (1993), which was formed as a pull-apart opening resulting from strike-slip movements during the oblique collision between the Pilbara and Yilgarn Cratons (Pirajno et al., 1995).

Rocks of the Yerrida Basin have been assigned to the Yerrida Group (Pirajno et al., 1996; Occhipinti et al., 1997). The age of the Yerrida Group is constrained between 2.2 and 1.8 Ga by a Pb–Pb isochron of 2173 ± 64 Ma obtained from stromatolitic carbonate rocks, and a 1785 ± 11 Ma U–Pb zircon date from the overlying Earaheedy Group (Woodhead and Hergt, 1997; Nelson, 1997; Occhipinti et al., 1997). The Yerrida Group is subdivided into the Windplain and Mooloogool Subgroups. The Windplain Subgroup consists of shallow-water siliciclastic, evaporitic and stromatolitic carbonate rocks overlain by a succession of siltstone and shale units. The Mooloogool Subgroup contains clastic sedimentary rocks (Doolgunna and Thaduna Formations) and a volcano-sedimentary succession, the Killara and Maraloou Formations (Fig. 1). The Killara Formation includes low-K tholeiitic lavas, with dolerite sills and dykes, and some minor gabbro and pyroxenite. These rocks are characterized by low REE abundances with positive Eu anomalies and a trace-element chemistry suggestive of an intra-continental tectonic setting (Pirajno et al., 1995). The Killara Formation is overlain by carbonaceous shale and siltstone of the Maraloou Formation.

In this paper we describe the possible depositional environment of the Bartle Member, a recently defined sedimentary unit within the Killara Formation (Occhipinti et al., 1997). The member overlies, and is locally intercalated with, the volcanic rocks of the Killara Formation, and is overlain by argillaceous sedimentary rocks of the Maraloou Formation.

Rocks of the Bartle Member are pervasively chertified and display a variety of sedimentary structures and relict textures suggestive of pyroclastic and evaporitic rocks, or hot springs chemical precipitates. Some of the chert rocks contain abundant spheroids, which display a range of diameters and internal morphologies, some of which are probably of inorganic origin (e.g. flocculates from colloids). Others, however, ranging in diameter from 10 to 14 μm and occurring in aggregates or clusters, may have a biogenic origin, and are tentatively classified as microdubiofossils.

Field geological, geochemical and petrographic data suggest that precursor rocks to the Bartle Member were formed in a rift setting towards the end of a mafic volcanic cycle, in a depositional environment like that of present day Lake Magadi or the Afar region in the East African Rift System. The presence of anomalous Au abundances in a number of samples has implications for possible hot spring-related mineralization.

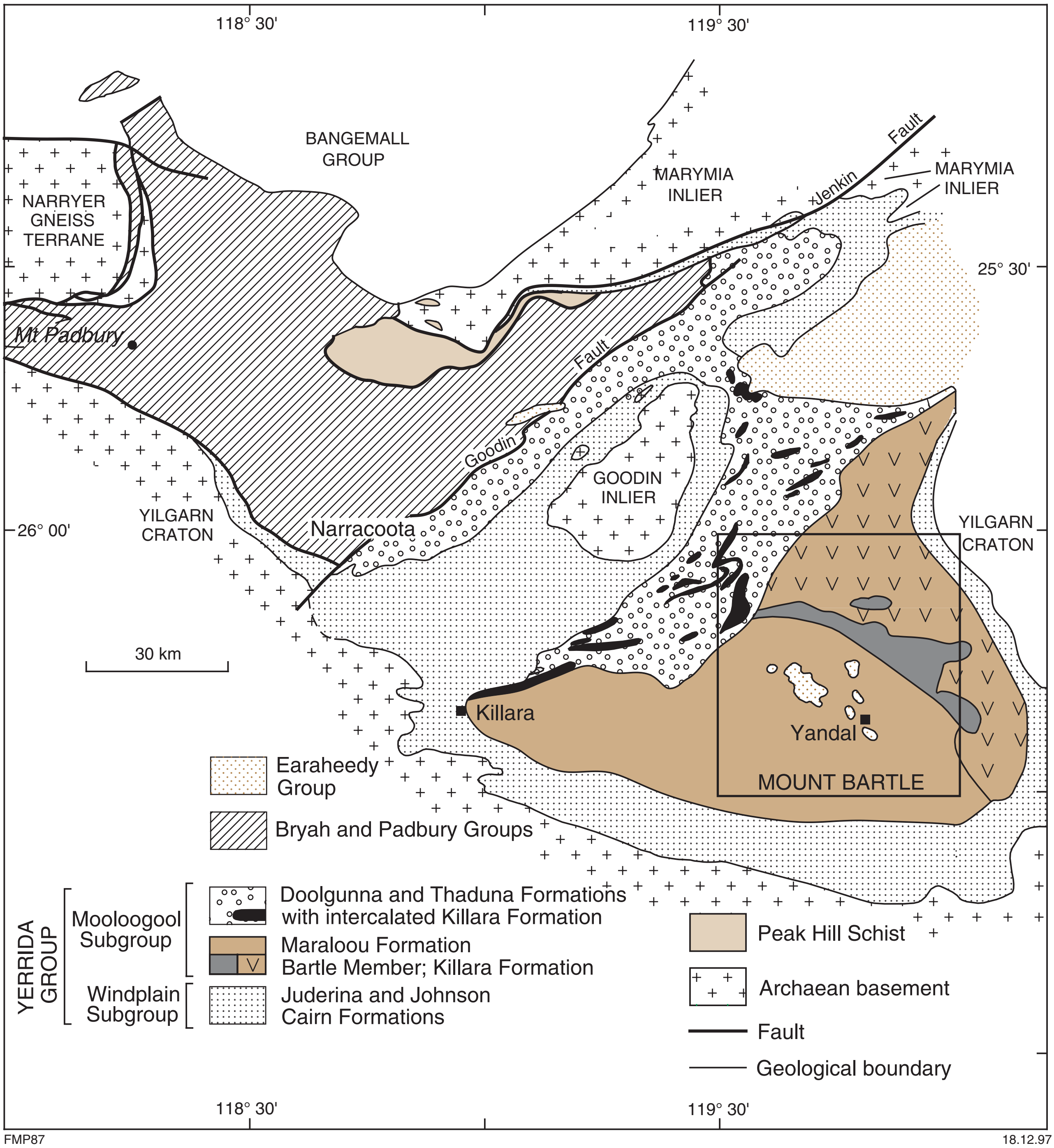

Figure 1. Simplified geology of the Yerrida Basin and distribution of the Bartle Member

Bartle Member

Distribution and geology

The Bartle Member of the Killara Formation outcrops in a north-westerly trending zone in the southeast of the Yerrida Basin, mainly in the MOUNT BARTLE* 1:100 000 map sheet area (Fig. 1). Its thickness is uncertain, but varies between a few metres and 30 m thick. Exposures are generally poor and rubbly.

The Bartle Member consists exclusively of pervasively chertified rocks, comprising black to multicoloured, massive to laminated cherts, and chert breccia. The cherts are made up of crypto- and microcrystalline quartz, chalcedonic quartz, iron oxides, kaolinite, and minor carbonaceous matter. In places these chert rocks may contain chert clasts (rounded to angular, 0.2–1 mm across) or garnet crystals (≤ 1 mm across). Petrological studies have revealed a

* Capitalized names refer to standard map sheets

variety of textures that suggest fine-grained welded pyroclastic material (e.g. subeutaxitic textures, cuspate glass shards, and flattened ash particles; Fig. 2A), carbonate allochems, kaolinized (SEM analysis), bladed, rosette-like or stellate aggregates of crystal pseudomorphs (probably after sulfate such as gypsum or anhydrite; Fig. 2B) in chert laminites, and silica-pseudomorphed nodules. Laminated chert commonly contains nodular concretions up to 5 mm in diameter. These nodules are chertified, and have septarian cracks infilled with chalcedonic quartz. Relict inclusions of low-birefringence minerals suggest that these bodies may have been gypsum or anhydrite nodules. Another important feature of the chert is the almost ubiquitous presence of a late-phase chalcedonic quartz. The chalcedony occurs mainly as a cement between angular chert clasts (brecciated chert), is locally overprinted by euhedral (oxidized) pyrite crystals, and is cut by fine quartz veinlets.

Outcrops of the Bartle Member commonly display platy quartz with abundant superficial moulds, possibly after calcite crystals, ranging in size from millimetre-scale to 5 cm long, together with nail-hole-like structures. Nail-shaped crystals are characteristic of the mineral shortite and may be indicative of a saline lake environment (Southgate et al., 1989). The plate-like quartz morphology occurs across a very wide area of poor outcrop near the base of the member, in irregular, bedding-parallel bands and lenses up to 20 cm thick. They may represent either siliceous replacement of evaporitic minerals or chemical precipitates.

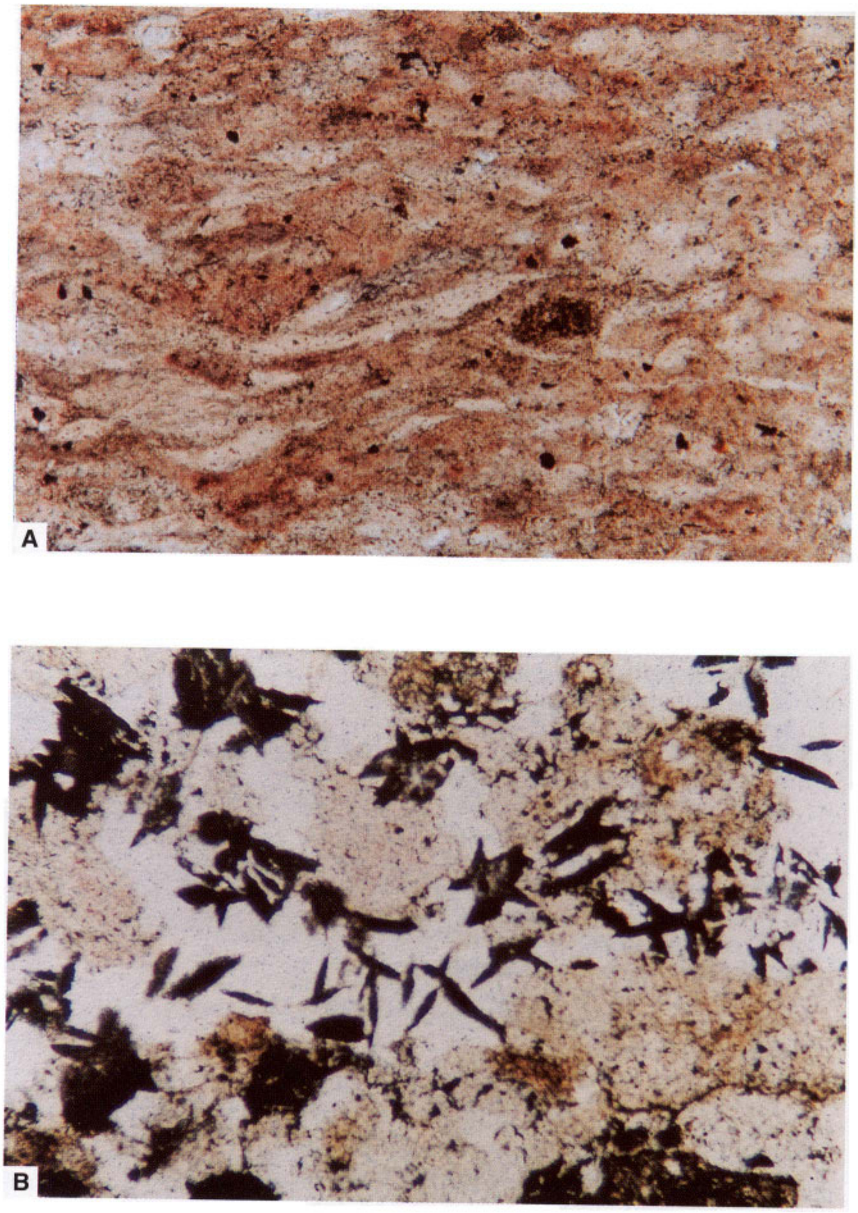

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Figure 2. (A) GSWA 120420: subeutaxitic texture in chert rock, possible shards and flattened pumice fragments. Plane-polarized light, horizontal field of view is 2.8 mm. (B) GSWA 127618: Fe oxide pseudomorphs after an evaporite mineral phase, probably anhydrite or gypsum. Plane-polarized light, horizontal field of view is 1.08 mm

Geochemistry

A plot of chondrite-normalized REE abundances for rocks of the Bartle Member is shown in Figure 3. The Bartle Member has very low REE abundances, pronounced positive Eu anomalies (Eu/Eu*1.47–20.76), and a slight enrichment in LREE (La/Yb_{CN} 1.27–6.57). The overall REE pattern matches that of the mafic rocks, except for the much less pronounced Eu in the latter. REE patterns of the Bartle Member are similar to oceanic hydrothermal waters (Fig. 3) and the chert layers of banded iron-formations (BIF) from the Archaean Dharwar Craton in India (Khan et al, 1996; Fig. 3). Khan et al. (1996) concluded that the silica and the iron of the BIF in the Dharwar Craton were derived from hydrothermal solutions. The pronounced positive Eu anomaly is attributed to acidic, high-temperature hydrothermal fluids and/or to changing oxidation–reduction state.

Trace-element analyses of Bartle Member rocks (Table 1) are notable for anomalous abundances in Au (up to 12 times average crustal value of 4 ppb) and Ba (≤ 4055 ppm).

Microdubiofossils or possible microfossils?

The Bartle Member cherts contain a number of structures, some of which

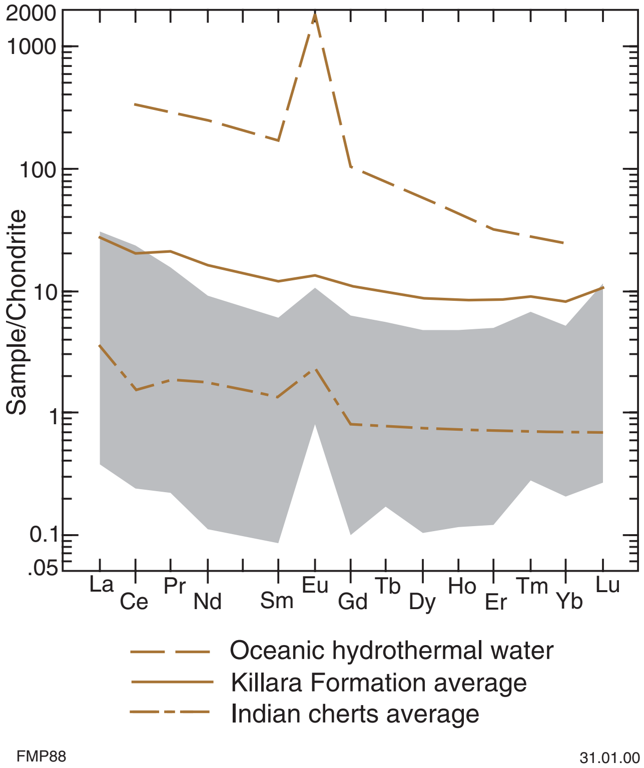

Figure 3. Chondrite-normalized rare-earth abundances in Bartle Member cherts (shaded area), oceanic hydrothermal water and average of chondrite-normalized rare earth abundances in chert layers of Indian banded iron-formations, after Khan et al. (1996). Normalization factors after Taylor and McLennan (1985); oceanic-water data after McLennan (1989)

may be of biogenic origin. The true nature of many of these structures cannot be determined without more-detailed study based on selective sampling. However, preliminary investigations suggest that at least some satisfy criteria for biogenicity (Walsh, 1992; Walter, 1983). Until biogenicity can be demonstrated unequivocally, these structures must be regarded as *microdubiofossils* or as *abiogenic structures* in the sense of Hofmann (1987).

Preservation of the structures is variable, but because of taphonomic degradation, few structures are well preserved. The best preserved structures occur in a microcrystalline, laminated chert that is characterized by finely disseminated, abundant, amorphous, dark brown organic matter. The probable organic nature of this material is suggested by the fact that it is readily extracted by maceration in hydrofluoric acid. Preservation of presumed organic material appears to have resulted from permineralization by silica-rich, hydrothermal fluids. Few of the larger structures survive maceration, but some have been observed in palynological preparations. The following structures have been recorded in thin sections:

- Amorphous organic fragments; black, cloudy-looking material as thin sheets, most likely formed from degraded mats produced by benthic microbial communities.

- Polygons bounded by disseminated organic matter (Fig. 4A); mosaic patterns occur in much of the chert and consist of polygonal quartz crystals bounded by finely disseminated kerogen. The finely disseminated organic matter was probably pushed outwards by crystal growth.

- Pigmented zones in spheroidal quartz; zoned spheroidal quartz grains ranging in diameter from 20 to 100 µm, commonly have a pigmented core, and contain concentric zones of dark, finely disseminated organic matter. The origin of the structures is enigmatic, but individual quartz crystals may have nucleated around a grain of organic material, and organic particles were pushed outwards as the crystal grew. In some specimens the core appears to be a pyrite framboid that may have replaced or coated an organic particle. In some respects these structures seem analogous to ambient pyrite trails (Knoll and Barghoorn, 1974) but are spheroidal instead of linear. Knoll and Barghoorn (1974) suggested that the trails formed when grains were propelled through a gel by gases emitted by decomposing organic matter surrounding the grain.

- Parallel traces of carbonaceous matter; finely disseminated carbonaceous matter occurs in parallel lines that resemble filament traces. Such structures may represent an original biogenic carbonate fabric (Hesse, 1989).

None of the structures described above can be considered as fossils. Rather, they belong to the group of structures described as *palimpsest microstructures*, defined as ‘a microstructure in which the distribution of kerogen, iron oxide, pyrite or some other pigmenting material indicates the former distribution of microbial cells’ (Walter, 1983, p. 188).

Other structures that qualify readily as microdubiofossils or putative microfossils are:

- Iron-oxide spheroids, 12 to 14 µm in diameter;

- Spheroids coated with carbonate or silica with a diameter of 10 µm;

- Spheroids coated with iron oxides with a diameter of 10 µm. These structures occur either singly, or in linear arrangements, sometimes with distinct patterns (Fig. 4B).

Of these, the first two are microdubiofossils. They may well be

Table 1. Whole-rock trace-element analyses of Bartle Member cherts

Sample no.	*127522*	*127524*	*127526*	*127528*	*127545*
Easting	*779565*	*782289*	*782839*	*782839*	*782225*
Northing	*7097787*	*7101667*	*7095785*	*7095785*	*7103575*
Ag	0.1	0.8	0.1	0.1	0.5
As	0.5	3.4	2.8	2.3	0.5
Au ppb	37	48	56	66	35
Ba	105	46	392	4 055	97
Bi	0.8	1.3	1	0.7	1.3
Cr	36	51	29.3	32	49
Cu	15	11	10	14	22
Ga	1.4	7.3	1.4	5.2	5.1
Mo	0.8	1.3	2.1	0.4	0.1
Nb	0.5	4.6	1	3.4	2.7
Ni	11	27.5	6.3	10	67
Pb	6	13.6	17	11	10
Rb	1.3	2.8	0.6	6.3	14.2
Sc	23	17	28	15	21
Sr	9	9.5	49.4	56	11
Th	0.6	5	0.7	2.5	4.2
U	0.5	1.1	0.4	0.7	1
V	21	33	6.4	43	40
W	0.5	3.3	0.5	0.5	2
Y	0.5	4.4	0.5	2.9	16.5
Zn	1.7	50	9.5	5	34
Zr	18.6	36	12	27	61

Notes:
1. All values in ppm, unless stated otherwise
2. Analyses performed at the Chemistry Centre, Dept. Minerals and Energy, by ICP-MS following mixed acid dissolution

replacements of originally biogenic material. The third type is too poorly preserved for the single specimens to be classified as microfossils, but the arrangement into patterns, in particular the grouping of spheres into festoons, and even into a petal-like pattern, shows a degree of organization consistent with a biogenic origin. Interpretation of these structures is difficult, but they are reminiscent of some *Eoentophysalis* mats that show well preserved cellular structure at the surface, but show less internal organization towards the centre of the structure.

The origin of the spheroids (Fig. 4A,B) is uncertain. They may be the result of deposition from hydrothermal solutions, for example due to flocculation of colloids (Pirajno, 1992), or they may represent fossil micro-organisms. Similar spheroids have been reported from Archaean cherts in the Barberton greenstone belt by Walsh (1992), who compared them to modern bacterial and cyanobacterial cells; and in black cherts of the Proterozoic Bitter Springs Formation in the Amadeus Basin, central Australia, where they have been interpreted as having formed as microbial mats in non-marine saline lakes (Southgate, 1986).

Protoliths

From the evidence discussed above, the protoliths for cherts of the Bartle Member can be interpreted to be one or all of the following: carbonate rocks (allochems, dolomite), fine-grained pyroclastics (Fig. 2A), hot spring deposits, lake deposits, evaporites (Fig. 2B).

Sedimentary structures that allow the reconstruction of the general depositional environment include: bedding surfaces with polygonal diastasis cracks in laminated cherts that possibly indicate emergence and desiccation of ash-rich muds; millimetre-scale, silica-pseudomorphed gypsum concretions; nail-hole-shaped casts; and radial fibrous crystal growths of gypsum crystals. All of these features indicate evaporitic conditions. Locally, hot springs may have precipitated sinter-like deposits (now garnetiferous chalcedonic chert and which, in places, contain anomalous gold; see Table 1). The hot-spring environment may have provided ideal conditions for the growth of microbial communities. There are several modern analogues for this type of hydrothermal ecosystem (Walter, 1983). One of the better known and described examples of the association of hot-spring environments and biogenic activity is the Yellowstone National Park, U.S.A. (Brock, 1978).

Depositional environment of Bartle Member cherts and possible present-day analogues

Deposition of the Bartle Member took place towards the end of a phase of mafic volcanism (Killara Formation) and was followed by accumulation of deeper basinal carbonaceous argillites under anoxic conditions (Maraloou Formation). The association of features recognized in the Bartle Member cherts is typical of an environment of shallow-water playa–saltpan associated with alkaline hot springs. A feature characteristic of salt-lake environments is the spectrum and diversity of depositional facies in which only end-members can be readily recognized.

Taking into account that the volcanic rocks of the Killara Formation were erupted in a rift setting, the possible modern analogues of the Bartle Member depositional environment could be the Afar region in northeast Africa, or perhaps the East African Rift Valley alkaline lakes, such as Lake Magadi.

The Afar region is a depression at the triple junction defined by the Red Sea, the Gulf of Aden and the Ethiopian part of the East African rift system. Aspects of the geology, volcanology and tectonics of the Afar region can be found in the works of Barberi et al. (1975), and Barberi and Varet (1978). The Afar region is dominated by predominantly fissure-type mafic volcanism, explosion craters, volcaniclastic deposits, hot springs, below-sea-level salt and playa

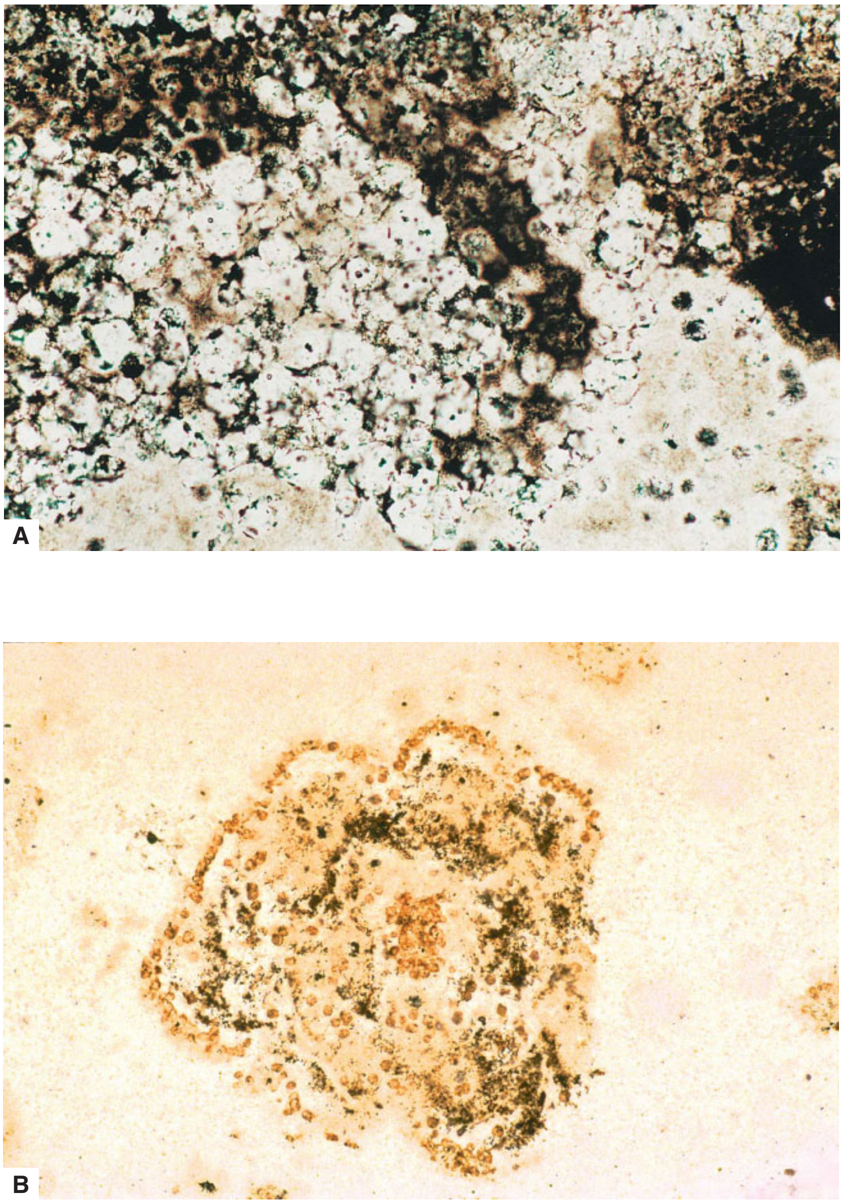

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Figure 4. *(A) GSWA 120464: polygonal quartz crystals bounded by finely disseminated kerogen. Plane-polarized light, horizontal field of view is 2.8 mm. (B) GSWA 119437: Petal-like pattern of spheroids in garnetiferous chert. Plane-polarized light, horizontal field of view is 1.08 mm*

lakes with thick sequences of evaporites, and abundant micro-organisms. In western Afar, against the Ethiopian escarpment, the Mio-Pliocene Hadar Formation was deposited in a fluvio-lacustrine environment and consists of sands, silts, laminated clays and tuffs (Tiercelin, 1986). The main points in common between deposits in the Afar region and the Bartle Member are rift-related mafic volcanic rocks, evaporitic, volcaniclastic and chemical sedimentary rocks, and carbonate rocks.

The laminated cherts of the Bartle Member resemble the bedded cherts of Lake Magadi. Lake Magadi is an ephemeral alkaline lake where hydrous Na silicates, such as trona and magadiite, are precipitated (Eugster, 1970, 1986). The mineral magadiite ($NaSi_7O_{13}(OH)_3.3H_2O$) is of special interest because it forms layers which grade along strike into bedded cherts. The replacement of the magadiite by microcrystalline silica is, in the view of Eugster (1970, 1986), related to dehydration and groundwater leaching of Na. Hot springs in Lake Magadi have temperatures of about 86°C, and are enriched in Na, HCO_8^-, Cl, K, SO_4^{2-}, F, SiO_2, P and B. The Magadi alkaline brines are, in places, enriched in silica (≤ 1900 ppm SiO_2). Total dissolved solids range from 10 000 to 35 000 ppm. Hot springs discharge into lagoons forming brine pools and precipitating silica gels.The brine pools also contain varicoloured bacteria and cyanobacteria which give rise to black organic muds (Baker, 1986).

Conclusions

Cherts of the Bartle Member, which contain anomalous abundances of Au and Ba, were probably formed in hot springs and playa lakes towards the end of mafic volcanism in a rift setting. Volcanism-related hot-spring deposits have potential for epithermal precious metal mineralization. The presence of spheroids, some of which may be classified as microdubiofossils, in garnetiferous chert, suggest a hot-spring environment containing microbial communities.

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Program review

Program 3
Subprogram 3102
MINERALS AND PETROLEUM RESOURCE STUDIES

Regional mineralization studies

Objective: *To undertake geoscientific studies of the State's principal mining districts to investigate the geological controls of mineralization, document resources, and propose new exploration strategies.*

Granitoid geology and geochemistry, Eastern Goldfields Province

A map showing the interpreted granitoid geology of the southwest Eastern Goldfields Province was published in November 1996. Report 49 that describes the geology and geochemistry of the granitoids was published in June 1997.

Ravensthorpe greenstone belt

The RAVENSTHORPE and COCANARUP 1:100 000 geological maps were published in September 1996 and explanatory notes were published in June 1997. A detailed account of the tectonic evolution and controls on mineralization of the Ravensthorpe greenstone belt will be published as Report 54 during 1997–98.

Kanowna–Kurnalpi–Pinjin regional gold documentation project

Systematic documentation of all gold deposits with more than 5 kg of production has been completed for the region covered by the Kurnalpi–Edjudina terranes map (GSWA Report 47, Plate 1). Gold deposits having a resource and listed in GSWA's MINEDEX database have also been documented. The ensuing report will have a similar format to GSWA Records 1993/13, 1993/14 and 1993/15 and will be accompanied by a 1:250 000-scale solid-geology map summarizing the geology, size, and location of each deposit described. The report will include AMG coordinates of all the described deposits (approximately 200) as well as geochemical data for some occurrences.

These data will help to constrain exploration models for gold deposits in the Yilgarn Craton. Significant results to emerge from this project include:

- Abundance of mineralized felsic rocks
- Recognition of possible epithermal and porphyry styles of gold mineralization
- Appreciation of potential for syenitic intrusions to host gold mineralization (syenitic intrusions not as late as previously thought)
- Recognition of calc-silicate alteration at several mining centres (previously unrecognized or under-appreciated)
- Widespread hematitization in gold deposits (see for example, Witt, *in* GSWA 1995–1996 Annual Review)
- Improved understanding of structural controls on gold mineralization

Volcanological facies mapping in the Gordons area

During 1996, detailed mapping and core logging was carried out in the region of the Gordons gold mining area. The study was to determine the distribution of primary depositional facies for felsic and mafic volcanic rocks, and the subsequent styles of alteration.

W. K. Witt

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; also to provide advice concerning industrial mineral resources to industry, government and the public.*

An important objective of the GSWA 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 1996–97 include the publication of two commodity Bulletins and a review of industrial minerals in Western Australia published in the magazine *Industrial Minerals*.

Commodity studies

Two commodity Bulletins were published: 'Talc, pyrophyllite and magnesite in Western Australia' (MRB16); and 'Barite and fluorite in Western Australia' (MRB17). Both Mineral Resources Bulletins contain comprehensive summaries of all known deposits and occurrences in the State, past production, and aspects of mineralization, and also chapters on the mode of occurrence, global production, prices, and specifications for various end-uses. Some highlights from these bulletins were published in the 1995–96 Annual Review of the Geological Survey.

Two commodity Records were compiled. One, entitled 'Industrial minerals in Western Australia — the situation in 1997', represents an expanded version of the paper published in the *Industrial Minerals* magazine, and will be published late in 1997.

The other Record, 'Armour stone investigation, north of King Bay – Burrup Peninsula, Western Australia' describes geotechnical drilling and rock mechanics studies 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 >0.3 m.

A Mineral Resources Bulletin entitled 'Limestone and limesand resources in Western Australia' has been compiled and will be published shortly (as MRB18), and another on kaolin resources in Western Australia is being compiled.

Large deposits of limestone and limesand occur along the coastal belt from Dampier in the north to Eucla Basin in the south. High-quality, metallurgical-grade limestone occurs at Cape Range and Loongana, and high-grade deposits of limestone and limesand suitable for the manufacture of cement and lime are known from many localities in the Perth Basin, Eucla Basin and on the Dampier Archipelago. Many of these deposits contain in excess of a few hundred million tonnes of high-grade limestone and limesand. The Bulletin will provide information on the quality of major limestone deposits in the State, their mode of occurrence and end-uses, and will also discuss the present status of the industry.

Review of industrial minerals in Western Australia

An article entitled 'Western Australia's industrial minerals, Quality is the key' was published in the March 1997 issue of the magazine *Industrial Minerals*.

In 1995–96 about 13% of WA's mineral production, valued at $1465 million, was derived from industrial minerals — mainly titanium minerals and diamonds. Recent developments such as the extension of natural gas pipelines to key mining centres, coupled with added-value processing by many advanced technology companies will place Western Australia in a favourable position to service the rapidly expanding South East Asian markets.

GSWA/DGMR 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 (DGMR) of the Zhejiang Province in the Peoples Republic of China. Part of the agreement was for the provision of experts in industrial minerals from DGMR to assist in a research project in Western Australia relating to a number of undeveloped industrial mineral deposits that indicate potential for development. The Report related to this project has now been compiled.

Australian Uniform Code of Nomenclature

The final report of the Australian Uniform Code of Nomenclature for reporting of industrial mineral production is now complete and has reached the implementation stage. Discussions are in progress with the Policy and Planning Division of this Department on the implementation of the code in Western Australia. The purpose of the code is to provide a framework, acceptable to all bodies, for reporting their individual production figures in a consistent way, based on the end-uses of the minerals.

Industrial minerals database

An industrial minerals module of the Division's WAROX geoscience database was developed during the year and data input has begun.

Other activities

A considerable amount of time was spent providing advice relating to industrial minerals resources and issues to industry, government and the public.

P. B. Abeysinghe

Archaean mineral prospectivity enhancement

Objectives: *To enhance perceived prospectivity in Archaean shield areas for precious metals, base metals, ferro-alloys, and diamonds; and to encourage exploration activity in areas of the State that are prospective, particularly areas that see little mineral industry activity, by undertaking studies that synthesize and integrate open-file statutory data with existing geological, mineral occurrence, geophysical, geochemical and remote sensing data.*

Considerable work during the year was directed toward the design of a mineral-occurrence database for WA that was compatible with AGSO's OZMIN database.

North Eastern Goldfields

By the end of 1996–97, the spatial index to mineral exploration data in statutory reports (see GSWA Annual Review 1994–95, pages 64–70 for description of spatial index) was completed. Spatial and textual attribute information on the locations of drilling, geochemical and geophysical surveys came from a total of 1300 statutory reports describing exploration on DUKETON*, SIR SAMUEL, and WILUNA. In addition, attributes of all mineral occurrences on these three 1:250 000 sheets have been entered into the GSWA WAROX database system and most non-confidential mineral occurrences on the DUKETON 1:100 000 sheet were field validated. It is anticipated that a report synthesizing information on the mineral prospectivity of the three 1:250 000 sheet areas will be released toward the end of 1997–98.

West Pilbara granite–greenstone terrane

Work has started on compiling the spatial index to mineral exploration in this area, as well as capturing open-file mineral occurrence data.

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

Comprehensive regional assessment of the SW forest area of WA

Assessments of forest regions (Comprehensive Regional Assessments — CRAs) are required before individual States and the Commonwealth can negotiate Regional Forest Agreements (RFAs) that embody agreed conditions for native forest resource development, including preservation of a fixed proportion of old-growth forests in reserves.

In conjunction with the Bureau of Resource Sciences (Commonwealth Department of Primary Industry and Energy), GSWA undertook a qualitative assessment of known and potential mineral, coal, and petroleum resources of the area shown in Figure 1.

Phase 1 of the project (September–December 1996) involved geoscience and resource information gathering by GSWA, whereas Phase 2 (January–June 1997) focused on a qualitative assessment by BRS and GSWA of the mineral, coal, and petroleum potential of the region. Critical input to the assessment was provided by industry and academia during a workshop in February 1997.

During Phase 1, GSWA compiled the following:

- spatial index to mineral exploration described in open-file statutory reports
- spatial index to anomalies identified in open-file statutory reports
- mineral occurrence database
- spatial index to aggregated estimates of known in-ground resources for different mineral deposit types
- digital 1:250 000 geological maps (regolith and solid geology)
- geophysical images
- spatial index of petroleum wells
- spatial index of regional-scale geophysical surveys flown for petroleum licensees
- spatial index of current exploration licenses, State agreement mining leases, and large mining leases.

All of these datasets were produced in ARC/INFO format with related textual databases.

It is expected that the report describing the qualitative assessment of mineral, coal, and petroleum resources compiled by GSWA and BRS will be released by the joint Commonwealth – WA Regional Forest Agreement Steering Committee during the latter part of 1997.

R. Rogerson

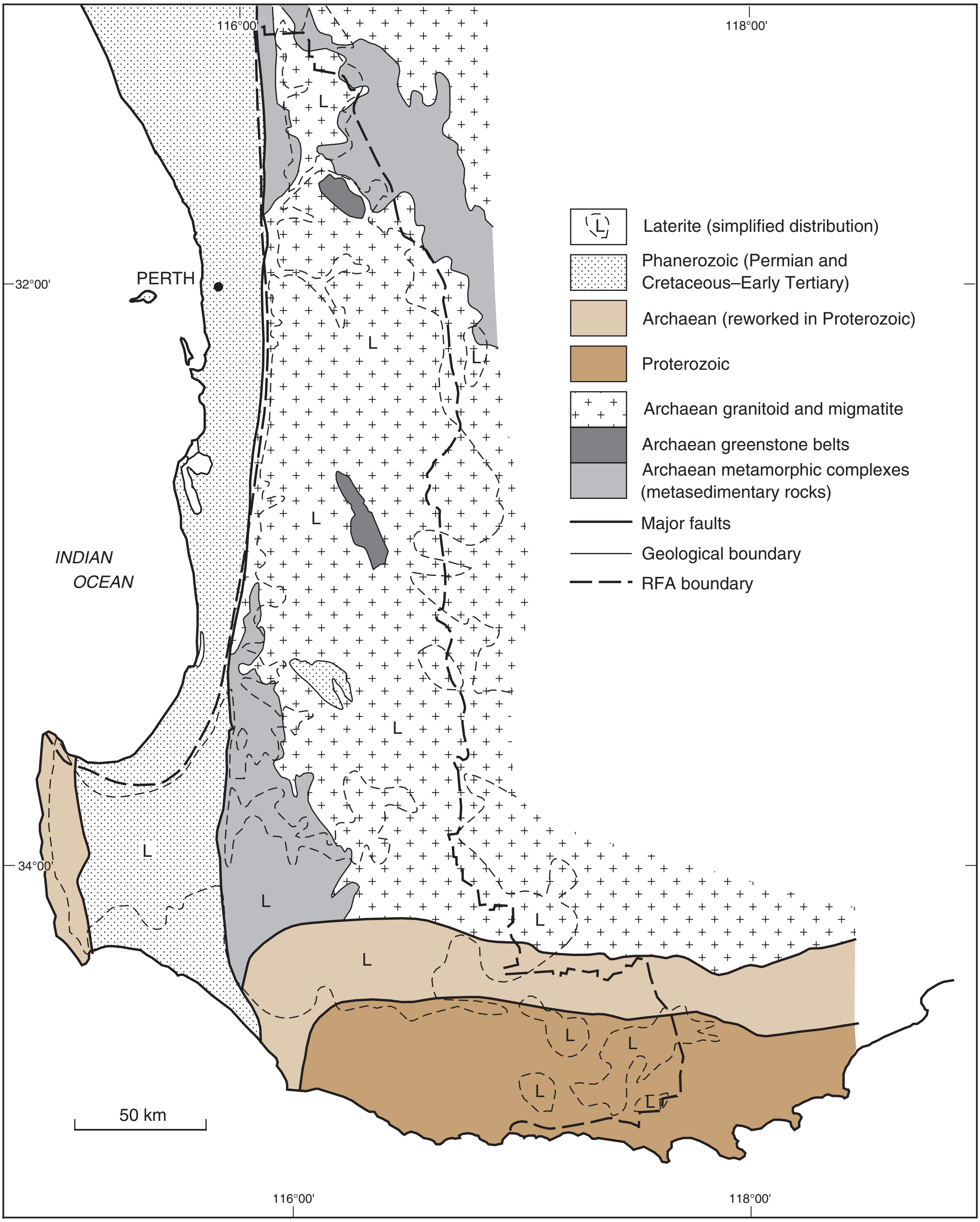


Figure 1. Boundary of Regional Forest Agreement (RFA) area assessed jointly by GSWA and Bureau of Resource Sciences during a Comprehensive Regional Assessment of known and potential mineral, coal, and petroleum resources

Proterozoic mineral prospectivity enhancement

Objectives: *This project will enhance and promote the mineral prospectivity of Proterozoic orogens and basins, particularly for base metals, ferro-alloys, gold, platinum-group metals, and diamonds. The hard copy and GIS-compatible database products being developed, compiled from mineral occurrence, geochemical anomaly and exploration activity data held in open-file statutory reports, will be integrated with geological, geophysical, and remote-sensing data in the final data package.*

The Proterozoic orogens and basins targeted in the first year of this project were the Bangemall Basin, the Halls Creek and King Leopold Orogens, and the Kimberley Basin. By the end of 1996–97 the database development for both the mineral occurrences and exploration-activity index was also completed.

Bangemall Basin

An unvalidated mineral occurrence database was completed for the Bangemall Basin in 1996–97, and by the end of the year much of the database had been upgraded and validated. Field checking of mineral occurrences in the west Bangemall Basin and adjacent areas of the Gascoyne was also completed. The activity index was completed for the western part of the Bangemall Basin, and the geochemical anomaly index was completed for EDMUND (1:250 000 sheet) and adjacent areas. The geology database was also compiled for much of the Bangemall Basin, and both geophysical and Landsat TM images were acquired for twelve 1:250 000 sheets covering the entire Bangemall project area.

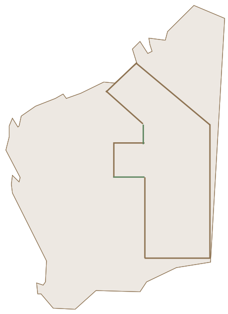
Kimberley region

More than half of a comprehensive study of mineralization in the Halls Creek Orogen was validated and transferred to the mineral occurrence database by the end of 1996–97. In addition, the activity index was completed for the King Leopold Orogen. The Geological Survey also contributed to the acquisition of data for a multi-client remote-sensing study of the Kimberley region.

R. L. Langford

Petroleum exploration initiative — Interior Basins

Objectives: *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 are considered by many geoscientists to be highly prospective for oil and gas, yet remain under-explored, whereas the Amadeus Basin in Western Australia remains unevaluated for hydrocarbon prospectivity.*



Highlights 1996–1997

- Apak, S. N., 'A compilation and review of data pertaining to the hydrocarbon prospectivity in the Canning Basin' was published as Record 1996/10.
- Havord, P., ' Permo-Carboniferous petroleum reservoir data, selected wells, Canning Basin, Western Australia, Edition 1' was published as Record 1996/11.
- Release of the Savory Basin Gravity Survey.
- Submission of the Officer Basin Scoping Study for publication.
- Submission of the Savory Sub-basin Scoping Study for publication.
- Submission of the Trainor 1 Well Completion Report for publication.
- Carlsen, G., 'Petroleum exploration in Proterozoic basins using potential fields data and stratigraphic coring' was presented to the 1997 Australian Society of Exploration Geophysicists conference.
- Perincek, D., 'The stratigraphic and structural development of the Officer Basin, Western Australia: a review' was published in the GSWA Annual Review 1995–96.
- Grey, K., ' Palynology in the search for Proterozoic hydro-

carbons' was published in the GSWA Annual Review 1995–96.

Nature of studies

The Petroleum Initiative studies provide basic data to the petroleum exploration industry, a historical perspective to exploration, new data and interpretations, and strategies for planning future activities in frontier basins of Western Australia. Our studies include revisions to correlations between stratigraphic tests and petroleum exploration bore holes through the application of biostratigraphy, sequence stratigraphic methods and seismic interpretation. We have demonstrated the value of Neoproterozoic palynomorphs for biostratigraphic and palaeoenvironmental interpretation, and for analysis of thermal maturity in the Officer and Amadeus Basins in Western Australia. We have compiled and analysed basic data pertaining to porosity and permeability for petroleum reservoirs and highlighted those targets with the greatest porosity and permeability. We have conducted detailed gravity surveys and high resolution aeromagnetic surveys in order to detail the structural elements and sedimentary thicknesses in frontier basins that do not have complete coverage by seismic data. Because of the interest of minerals explorers in the sedimentary sequences we are studying, we have also supplied element analysis and core description from a mineral exploration perspective on new stratigraphic cores acquired by this group.

Publications in preparation

- Crostella, A.,'A review of oil occurrences within the Lennard Shelf, Canning Basin, Western Australia' has been submitted for publication.
- Ghori, A.,' Petroleum source rock potential and thermal history, Officer Basin, Western Australia' has been submitted for publication.
- Stevens, M., 'Skates Hills Formation and Tarcunyah Group, Officer Basin — carbonate cycles, stratigraphic position and hydrocarbon prospectivity' appears in this volume.
- Grey, K., 'Neoproterozoic palynomorphs from the Savory Sub-basin and their relevance to petroleum and mineral exploration' appears in this volume.
- Shevchenko, S., 'A new procedure for calculating depth to basement from magnetic and gravity data with an example from the western Officer Basin in Western Australia,' appears in this volume.

During 1996–97 the Interior Basins team has identified and addressed the exploration challenges in the Canning and Officer Basins.

In the Canning Basin exploration in the Permo-Carboniferous has been hampered by a lack of comprehensive basinwide biostratigraphic correlations and a plethora of stratigraphic terminology, which varies across the basin. Current work emphasizes the re-evaluation of all available biostratigraphic data and the application of biostratigraphic zonation to seismic sequence stratigraphy in the Barbwire Terrace region. The Lennard Shelf paper provides an analysis of the elements of the petroleum system which have resulted in the accumulation of commercial reserves of oil. This paper provides paradigms for success elsewhere in the Canning Basin.

In the Officer Basin, previous petroleum exploration failed to define and locate source rocks. Current seismic mapping, stratigraphic coring, and geochemical analysis by the GSWA is working toward a definition and location of the source rocks of the Neoproterozoic sequences. Biostratigraphic correlation has been improved in the Canning and Officer Basins through the application of our in-house expertise in palaeontology and palynology. Such studies demonstrate that thin organic-rich sequences have been penetrated in the Officer Basin, and highlight the need to map organic facies in the basin through continued stratigraphic coring and basin analysis. Continued field work on the carbonate successions of the Officer Basin and their relation to the developing source-rock model for the basin will be necessary to complete maps of organic facies. Biostratigraphic correlation within the Officer Basin continues to improve as we gather and analyse additional samples from outcrop and core. A new map showing depth to magnetic basement for the Officer Basin has been constructed using methods developed by the Geological Survey of Western Australia. This map aids in the definition of depocentres, as well as structural elements that have influenced deposition in the sub-basins of the Officer Basin.

Intended publications

- The Permo-Carboniferous Grant Group in the Barbwire Terrace and Fitzroy Trough, and Gregory Sub-basin, Canning Basin.
- Gibson Sub-basin seismic interpretation report with recommendation for stratigraphic coring.
- Lennis Sub-basin seismic interpretation report with recommendation for stratigraphic coring.
- Yowalga Sub-basin seismic interpretation report.
- Empress 1 final well completion report.
- Gravity acquisition record and data set for the Waigen Sub-basin.
- Gravity interpretation report for the Waigen Sub-basin.
- Reservoir characterization in the Officer Basin — based upon petroleum exploration wells, mineral exploration wells and stratigraphic cores.

Notes on Canning Basin work program

Work in the Canning Basin has been suspended in light of the recent award of the Special Prospecting Licence 3/1995–96.

Notes on the Officer Basin work program

The Empress 1 stratigraphic well was spudded during June 1997: it is anticipated that this well will fully penetrate the Browne Beds in a more marginal setting than previous Yowalga Sub-basin tests. Geophysical modelling indicates a maximum thickness of 1200 m of sedimentary rocks to the base of the Brown Formation. Geological data indicate that an equivalent of the Townsend Quartzite should underlie the Brown Formation. Correlation with outcrop data along the western margin of the Yowalga Sub-basin indicates that the Earaheedy Basin should underlie the Officer Basin at this location. Empress 1 is anticipated to reach a total depth of not more than 2000 m in the Earaheedy Basin sequence.

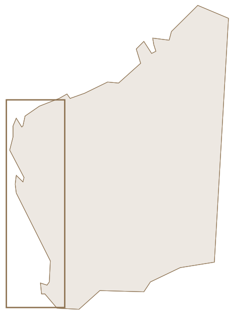
Analysis of cores, cuttings, and logs from Empress 1 will provide new data to the reservoir, source rock and biostratigraphic interpretation of the Officer Basin. These data will be used along with outcrop studies and correlations to previous wells drilled to build a depositional model for organic facies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

The Stage I interpretation of seismic data in the Officer Basin is nearing completion and will provide the basic interpretative structure and isopachs of the major depositional sequences of the basin.

The detailed survey of the Waigen Sub-basin will provide estimates of sedimentary thicknesses and the structural data necessary to select a stratigraphic drilling location in this unexplored area as no seismic or stratigraphic-test data currently exist for the sub-basin. Preliminary interpretation of the gravity and magnetic data on file 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 Formation (source) and Pindyin Sandstone (reservoir).

G. M. Carlsen

Petroleum exploration initiative — Western Margin



Objective: *To stimulate and encourage petroleum exploration of the onshore Carnarvon and Perth Basins by producing comprehensive basic data packages and high-quality geoscientific reports on the hydrocarbon potential of those areas by integrating newly acquired GSWA data and industry open-file data.*

Highlights and activities 1996–97

Two major data acquisition projects were planned for 1996–97. These were the continuation of the stratigraphic coring program in the onshore Carnarvon Basin, as indicated in the 1995–96 Annual Review, and the acquisition of a detailed gravity survey of approximately 1100 stations in the Coolcalalaya Sub-basin.

Results from the Coolcalalaya Gravity Survey will not be available until early 1998 as the survey commenced in mid-June 1997. These newly acquired data will be integrated into the recently completed regional gravity images of the onshore Southern Carnarvon Basin.

The GSWA-funded stratigraphic coring program was conducted during October and November 1996 with the drilling of Mooka 1 (TD 418 m) and Barrabiddy 1 (TD 783 m). These two boreholes were designed to follow-up on the encouraging petroleum geochemical results obtained from a thin Devonian shale interval in the 1995 GSWA Gneudna 1 corehole. The GSWA Barrabiddy 1 corehole, drilled on the western flank of the Merlinleigh Sub-basin, and located on a seismic line shot in 1990, confirmed it was further into the basin than Gneudna 1. Barrabiddy 1 penetrated a 35 m gross Devonian shale interval containing multiple zones with geochemical characteristics far superior to those encountered in Gneudna 1. The stratigraphic zone containing the rich source interval has a mappable seismic character thereby allowing the distribution of that sediment package to be determined spatially by future explorers. With the assistance of industry sponsors (WAPET, Woodside, and Ampol), the Cretaceous section in Barrabiddy 1 was also fully cored to provide additional biostratigraphic and sedimentological data. These core data will provide additional regional control on the facies behaviour of Cretaceous units that are petroleum reservoirs in the offshore areas of the Carnarvon Basin.

The objectives of the Mooka 1 stratigraphic corehole were also to evaluate the hydrocarbon source potential of the Devonian Gneudna Formation in a basinward position west of the Gneudna 1 borehole. In the absence of seismic control, shallow mineral-exploration boreholes in the vicinity of the Mooka location were used to site the bore. These bores indicated Devonian palynomorphs in units subcropping the Cretaceous unconformity. Mooka 1 failed to confirm this interpretation and penetrated the Kopke Sandstone and Faure Formation of the Silurian (?)Kalbarri Group. The corehole was terminated at 418 m. Geochemical analyses of samples from the Kalbarri Group were not encouraging.

The evaluation of the petroleum potential of the Gascoyne platform, the western area of the onshore Southern Carnarvon Basin, was unexpectedly accelerated through access to the Yaringa East 1 and Coburn 1 coreholes. These two coreholes were drilled by the operator of EPs 378 and 401, which lie immediately east and south respectively of Hamelin Pool, Shark Bay.

Yaringa East 1 was cored to a depth of 829 m and, below the Cretaceous unconformity, penetrated the Sweeney Mia Formation and the Kopke Sandstone, the uppermost units of the Kalbarri Group. Coburn 1 intersected the Kalbarri Group at the middle of the Kopke Sandstone and then cored the balance of the Kalbarri Group before reaching a total depth of 1093 m within the Tumblagooda Sandstone. The Tumblagooda Sandstone is well documented and understood from the excellent exposures in the Murchison River gorges at Kalbarri. Consequently, with the overlap of cored intervals between the Mooka 1, Yaringa East 1 and Coburn 1 wells, the first completely cored section of the Kalbarri Group sedimentary rocks is now available for biostratigraphic, geochemical, and sedimentological analysis. These analyses will be fundamental to the assessment of the petroleum potential of the Gascoyne platform area.

Reprocessing of 1960s Carnarvon Basin analog-recorded seismic data has proceeded, following the positive results of the pilot reprocessing program last year, which indicated substantial improvements to data quality could be obtained with the use of current processing techniques and algorithms. During 1996–97 approximately 300 km of data have been reprocessed, 245 km are currently being reprocessed, and an additional 550 km are scheduled to be reprocessed. In most cases these seismic data are the only subsurface data available and provide invaluable insights and links with neighbouring areas having more extensive seismic and borehole data. Integration of these reprocessed data with more recent seismic work will substantially assist in upgrading the understanding of the tectonic history of the onshore Southern Carnarvon Basin.

1996–97 publications and products

A number of significant products were released as publications during the year. Report 46 ‘Structure and stratigraphy of the northern Perth Basin’ is the most comprehensive regional summary of that Basin, providing a clear perspective of the current state of knowledge for the area.

Four Records: Two well completion reports for the Gneudna 1 and Ballythanna 1 coreholes; Northwest Cape petroleum exploration results; and gravity of the northern Perth Basin; were also published. Two papers: Structural interpretation of a sedimentary basin using high-resolution aeromagnetic and gravity data; and Integration of seismic, gravity and magnetic data in the structural evolution of the Merlinleigh Sub-basin, were presented respectively at the Australian Society of Exploration Geophysicists (ASEG) Conference in Sydney, and the Australian Petroleum Production and Exploration Association (APPEA) Conference in Melbourne.

Promotional booths, containing displays of major products from the Western Margin and Interior Basins Project Teams were prepared for the APPEA and ASEG conferences. A similar booth and display was presented at the American Association of Petroleum Geologists Conference in Dallas, Texas.

Future work

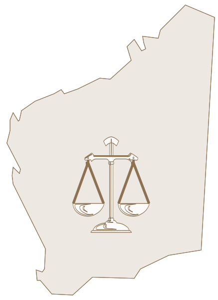
Acquisition of new data during 1997–98 will be limited to completing the Coolcalalaya gravity survey and reprocessing the outstanding designated regional seismic lines. The results of the Coolcalalaya gravity survey will assist in designing a shallow drilling program for 1998–99, aimed at understanding the nature of the 6000–8000 m of sedimentary rocks in the graben feature. Interpretation of the reprocessed seismic data will enable an integrated structural picture of the onshore Southern Carnarvon Basin to be presented in a forthcoming Bulletin.

A review of existing Drill Stem Test (DST) pressure charts from petroleum exploration wells in the Peedamullah Shelf will be carried out with a view to updating the hydrodynamic pressure regimes for major aquifers and checking on the validity of tests on ‘non-commercial’ hydrocarbon zones. This review will also provide a summary of DST data relative to results and stratigraphic intervals tested.

A complementary review of the petroleum exploration activities of the southern Perth Basin is nearing completion. This study aims to rationalize the stratigraphy of the southern areas with the more comprehensive studies completed in the north, and review the play concepts and subcommercial petroleum discoveries within that stratigraphic framework and a new seismic structure interpretation of the area.

A. Svalbe

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 for proposed changes to, the Mining Act and Offshore Minerals Act.*

Most mineral tenements are held for exploration or prospecting rather than productive mining. Advice on these exploration activities, as gauged from 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.

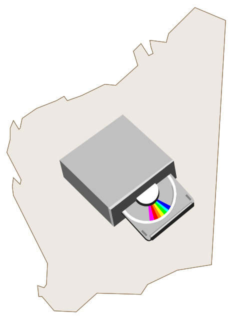
Exploration performance on more than 700 mineral tenements was reviewed during 1996–97 (3400 in 1995–96) as part of the assessment of applications for exemption from expenditure conditions, applications for extensions of term of exploration licences, and applications for Ministerial consent to dealings in exploration licences during the first year of tenure. Stricter guidelines were agreed with Mineral Titles Division so that only tenements definitely requiring geological input were referred to the Geological Survey for comment. This led to a drop in referrals, as shown in Table 1. Where approp- riate, in relation to expenditure exemptions, recommendations were made for conditions to be imposed on particular tenements to ensure that ground does not remain unworked for long periods.

Table 1. Tenement reviews

Geological advice	*Number of tenements 1995–96*	*1996–97*
Expenditure exemption 1 year	2 909	442
Expenditure exemption 2 or more years	95	16
Extension of term of exploration licences	353	186
Dealings in first-year exploration licences	36	58
Es iron ore authorization	n/a	6
Es iron-ore drop offs	n/a	13
Total	**3 393**	**721**

J. Pagel, I. R. Ruddock, and D. J. Flint

Resource studies and MINEDEX



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

In 1996–97, ongoing data capture formed a large part of the function, together with ongoing advice to a wide range of customers. A non-confidential digital dataset from MINEDEX, including information on mineral resource and mine locations, commodities, ownership, and development status, was released to the public as Record 1996/13. This supplements an 'Atlas of Western Australian mineral deposits and petroleum fields', showing resource localities superimposed on geological maps, which was released during 1995–96.

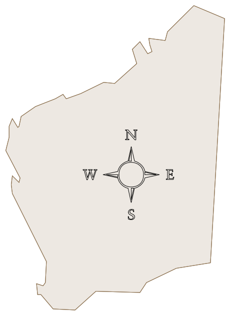
Development of the production statistics component of the MINEDEX database continued during the year. This will allow current resources and historical production to be linked to provide total in-ground resources for known individual deposits and for the whole State.

A quarterly update of mineral exploration activity was produced during the year. This revealed a continuing high level of mineral-exploration expenditure in Western Australia, predominantly led by the gold sector, but with increased exploration expenditure also recorded for base metals (including nickel and cobalt), iron ore, and diamonds. Western Australia is maintaining its dominant share (60%) of Australia-wide exploration expenditure (55% in 1995–96), but the proportion of overseas activities by Australian companies is increasing still.

D.B. Townsend, R. Cooper, and D.J. Flint

Subprogram 3103
REGIONAL GEOSCIENCE MAPPING

East Yilgarn Project



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

Summary of activities 1996–97

A first edition 1:100 000-scale map of MILLROSE* was released in mid-1997 and WILUNA was almost completed. Field mapping was completed on BANJAWARN, COSMO NEWBERY, DEPOT SPRINGS, CUNYU, and BOYCE. Geological compilations of new editions of EDJUDINA and DUKETON (1:250 000 sheets) have also been completed (Fig. 2).

A new geological mapping program in the Southern Cross Province began with the commencement of field mapping on JOHNSTON RANGE.

Field geological mapping is supported by petrographic studies and whole-rock geochemistry. Interpretations in areas of poor exposure are enhanced by using processed images of remotely sensed geophysical and Landsat TM data.

* Capitalized names refer to standard 1:100 000 map sheets

SHRIMP U–Pb zircon ages have been obtained for a variety of granitoid, gneissic, metasedimentary, and metamorphosed felsic volcanic rocks from SIR SAMUEL, WILUNA, and EDJUDINA (1:250 000 sheets) that were collected in 1996.

A geological data package in CD-ROM format covering SIR SAMUEL was released in October. The data package includes a spatial index to WAMEX open-file mineral exploration information, outcrop geology, interpreted solid geology, regolith geology, and regolith geochemistry. A regional geological interpretative map covering the rest of SIR SAMUEL, DUKETON, and WILUNA (1:250 000 sheets) has been compiled and geological data packages covering much of the northern part of the Eastern Goldfields Province will be released during 1997–98.

Explanatory notes have been prepared for KALGOORLIE (1:250 000 sheet), to be released in 1997–98. Notes are also being compiled for SIR SAMUEL, DARLOT, and DUKETON.

GSWA officers based in Kalgoorlie have been involved in regional mapping and gold mineralization studies and the office continues to provide geological information and advice to both the local community and visitors from outside the region.

The NGMA Eastern Goldfields Project continued, with an AGSO geologist carrying out field mapping on SIR SAMUEL (1:250 000 sheet). AGSO released preliminary editions of a number of 1:100 000 sheets generated during earlier phases of the mapping program. GSWA provided data and logistical support to AGSO geologists involved in the AMIRA Yilgarn granitoid study (AMIRA Project P482). GSWA and AGSO conducted a second Eastern Goldfields Mapping Expo at the WMC Conference Centre in Kalgoorlie in October. The display was subsequently mounted in the foyer of Mineral House in Perth.

S. Wyche

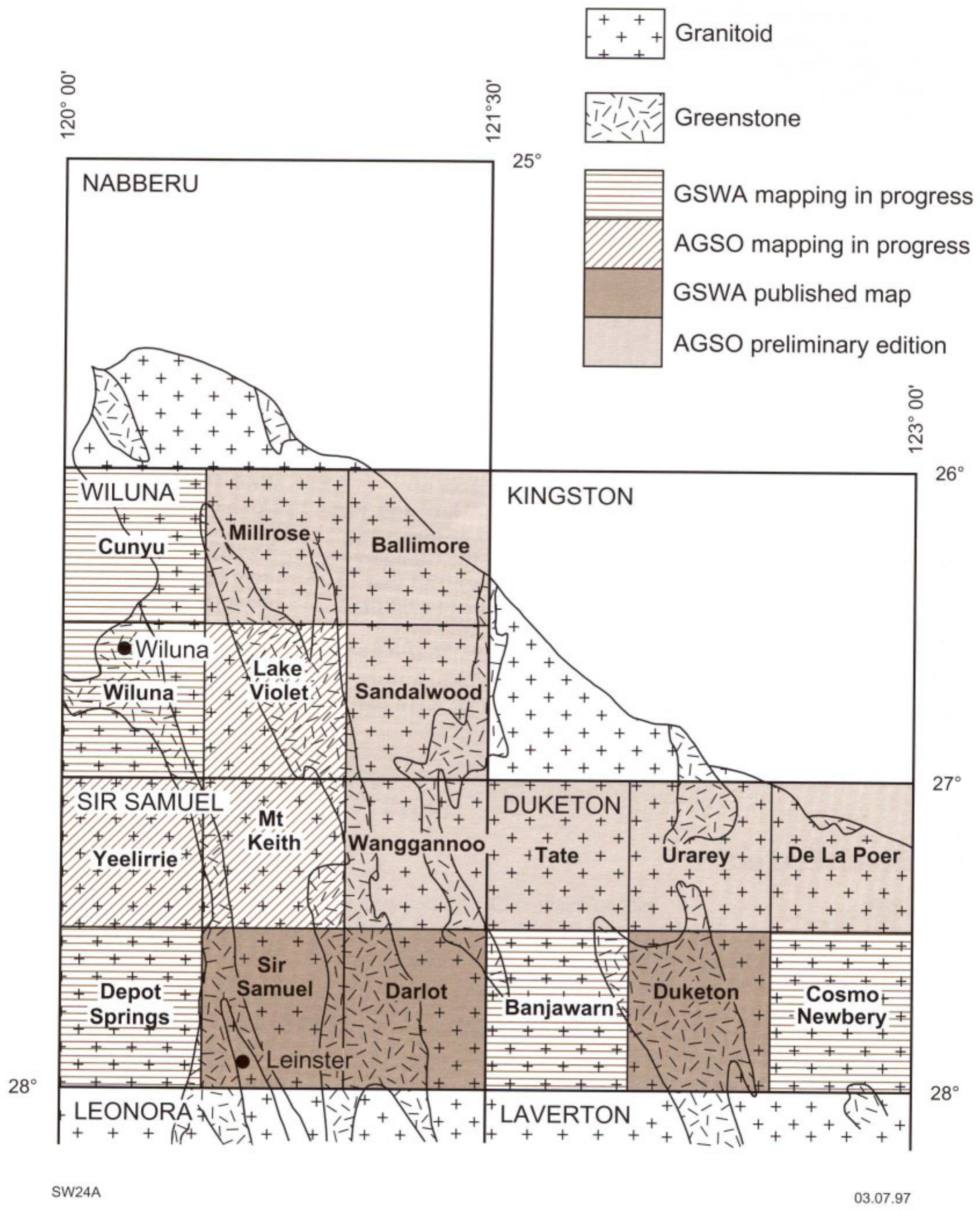
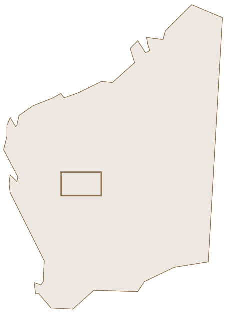


Figure 2. Simplified geological map of the northern part of the Eastern Goldfields showing the progress of the 1:100 000 mapping program

Glengarry Project (Bryah, Padbury and Yerrida Basins)



Objective: *To increase geoscientific knowledge of Early Proterozoic basins in the Glengarry area, 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, geophysics, remote sensing and metallogeny.*

Summary of activities 1996–97

Field work and photoscale compilations of Marymia and Cunyu were completed. Geological maps of Milgun, Padbury, Glengarry, Mount Bartle, Bryah, Thaduna, Doolgunna, and Mooloogool were published during the year, as shown on Figure 3.

Explanatory notes have been written for Padbury, Bryah, Mount Bartle, Doolgunna, and Glengarry. Explanatory notes for Thaduna, Mooloogool, Milgun, and Marymia are being prepared. A seamless map at a scale of 1:250 000 for the Bryah and Padbury Basins was compiled.

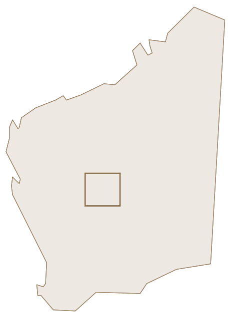
During the year, team members were invited to present papers at mineral industry-sponsored conferences on aspects of the geology and mineralization of the Glengarry area. One of the team members attended and presented a paper at the 30th International Geological Congress in Beijing.

The Bryah, Padbury and Yerrida Basins cover a total area of approximately 20 000 km^2 and were formerly considered as one geological entity — the Glengarry Basin. It is now recognized that these basins developed in rift and foreland settings related to the collision of the Yilgarn and Pilbara Cratons. Thus, the volcanic and sedimentary rocks that were part of the former Glengarry Group are now divided into the Bryah, Padbury and Yerrida Groups. The Bryah Group is especially important because it represents a short-lived proto-oceanic retro-arc basin. In addition, the economically important Peak Hill Metamorphic Suite, previously also considered to be part of the Glengarry Group, is recognized as a separate unit — the Peak Hill Schist – of possible Archaean age.

Two Geological Survey Reports are being compiled to describe the geology and mineralization of the Bryah, Padbury and Yerrida Basins.

F. Pirajno

Earaheedy Basin Project



Objective: *To increase geoscientific knowledge of the Proterozoic Earaheedy Basin 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.*

Aeromagnetic and Landsat TM images at a scale of 1:100 000 were prepared. Aerial photography has been obtained for Fairbairn, Methwin, Nabberu and Merrie, which are due to be mapped during the 1997–98 field season. A reconnaissance field trip to the area was made late in 1996.

F. Pirajno

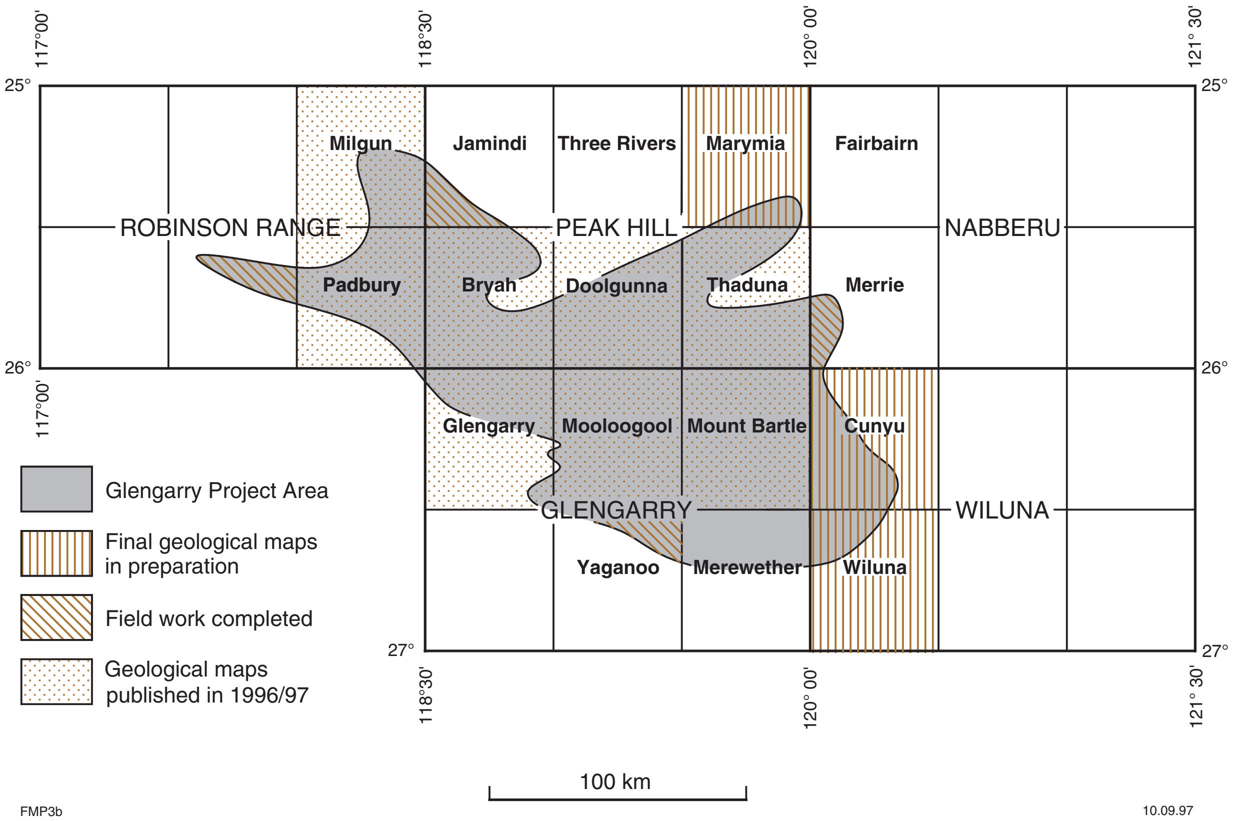
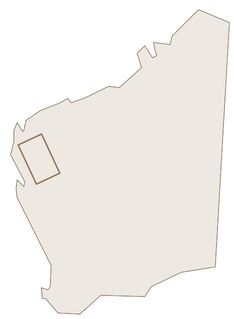


Figure 3. Progress of geological mapping in the Glengarry Project area

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.*



The Gascoyne Complex is the deformed, medium- to high-grade metamorphic core of the Capricorn Orogen. An understanding of it is essential to understanding the tectonic evolution of the Capricorn Orogen — which first developed during the Palaeoproterozoic — and also the formation of large-scale structures that have controlled gold, base metal, and iron mineralization along the northern margin of the Yilgarn Craton and the southern margin of the Pilbara Craton.

Reactivation of major structures within the orogen during the Meso- and Neoproterozoic have controlled the formation and deformation of the overlying Mesoproterozoic Bangemall Basin, and may have provided pathways for mineralizing fluids from the basement into its cover. They may have controlled also the location of diamondiferous intrusions. The complex contains sub-economic deposits of gold, lead, copper, barite, uranium, rare earths, muscovite, beryl, tantalum, tungsten, graphite and semi-precious gemstones.

Summary of progress

Remapping of the southern part of the Gascoyne Complex commenced during the 1996 field season. Initially fieldwork has been concentrated on ROBINSON RANGE (1:250 000 sheet), the eastern part of which has already been remapped as part of the Glengarry Basin

Project. Remapping and compilation of MARQUIS and MOORARIE and the northeastern part of GOULD has been completed. Geological mapping prior to the start of this project has been incorporated into the second edition of BYRO that was published in 1996–97.

Sampling for whole-rock geochemical analysis and geochronology was carried out during the 1996 field season. Zircons were separated from seven samples, and U–Pb isotopic ages have been obtained using the SHRIMP at Curtin University of Technology.

Summary of results

One of the aims of the Southern Gascoyne Complex Project is to determine the nature of the boundary between the Archaean Narryer Terrane of the Yilgarn Craton and the Gascoyne Complex to the northwest. The oldest rocks on MARQUIS and MOORARIE are complexly deformed and metamorphosed gneisses derived from early to late Archaean granitoids tectonically interleaved with metamorphosed sedimentary and mafic igneous rocks. These gneisses are a continuation of the Archaean Narryer Terrane, but are extensively intruded by veins and sheets of medium- to coarse-grained Palaeoproterozoic granitoid and pegmatite that have given SHRIMP U–Pb zircon ages of between c. 1813 and 1800 Ma.

Also present on MARQUIS is an extensive pluton of unrecrystallized porphyritic granitoid that gives a SHRIMP U–Pb zircon age of c. 1620 Ma. The presence of granitoids in the Gascoyne Complex that were intruded at about the same time as the adjacent c. 1640 Ma Bangemall Basin was forming has important implications for the development of tectonic and metallogenic models for the Capricorn Orogen.

Future work

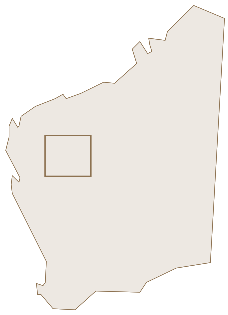
During the 1997 field season, remapping of the ROBINSON RANGE 1:250 000 sheet will be completed and work will begin on the eastern part of the GLENBURGH 1:250 000 sheet. This will involve mapping across the Errabiddy Fault, which previously has been considered to mark the boundary between the Archaean rocks of the Narryer Terrane and the Palaeoproterozoic rocks of the Gascoyne Complex.

Further geochemical and geochronological sampling will document the extent of the c. 1810 Ma and c. 1620 Ma magmatic events within the Gascoyne Complex and the northwestern part of the Narryer Terrane.

I. M. Tyler

Bangemall Basin Project

Objectives: *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 the Abra deposit, Western Australia's largest stratabound Pb–Cu–Ag–Ba deposit. This, combined with the age and geological setting of the basin, make 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.

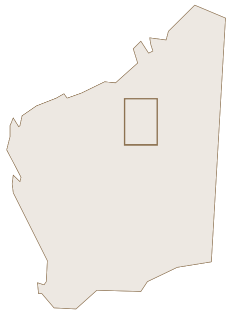
Activities during 1996–97

The Bangemall Basin project commenced in January 1997. Principal activities carried out have included the processing of detailed regional airborne geophysical data, and the acquisition of 1:25 000-scale coloured aerial photography (for MAROONAH, ULLAWARRA, MANGAROON, EDMUND, ELLIOTT CREEK, MOUNT PHILLIPS, and MOUNT AUGUSTUS), Landsat data, and digital topographic data. Some reconnaissance field work was combined with the helicopter-supported geochemical sampling project on EDMUND 1:250 000 sheet in May 1997.

In March 1997, Dr A. Thorne joined a multidisciplinary team that examined the world-class Au, Cu, Pb, and Zn deposits in the Mount Isa Inlier, Queensland. During this field visit, comparisons between the Bangemall Basin and the Western Zone of the Mount Isa Inlier were discussed with geologists from both industry and the Geological Survey of Queensland.

A. M. Thorne

Paterson Orogen Project



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

Work during 1996–97 involved the completion of the Explanatory Notes and the publication of 1:100 000-scale geological maps for Connaughton, Throssell and Gunanya. In addition, the mapping from Poisonbush and Dora was compiled, and reconnaissance mapping of Blanche and the northern half of Cronin completed (Fig. 4).

Information gained from the 1:100 000-scale mapping program of the Paterson Orogen will be used to compile a second edition of the Rudall 1:250 000 sheet.

L. Bagas

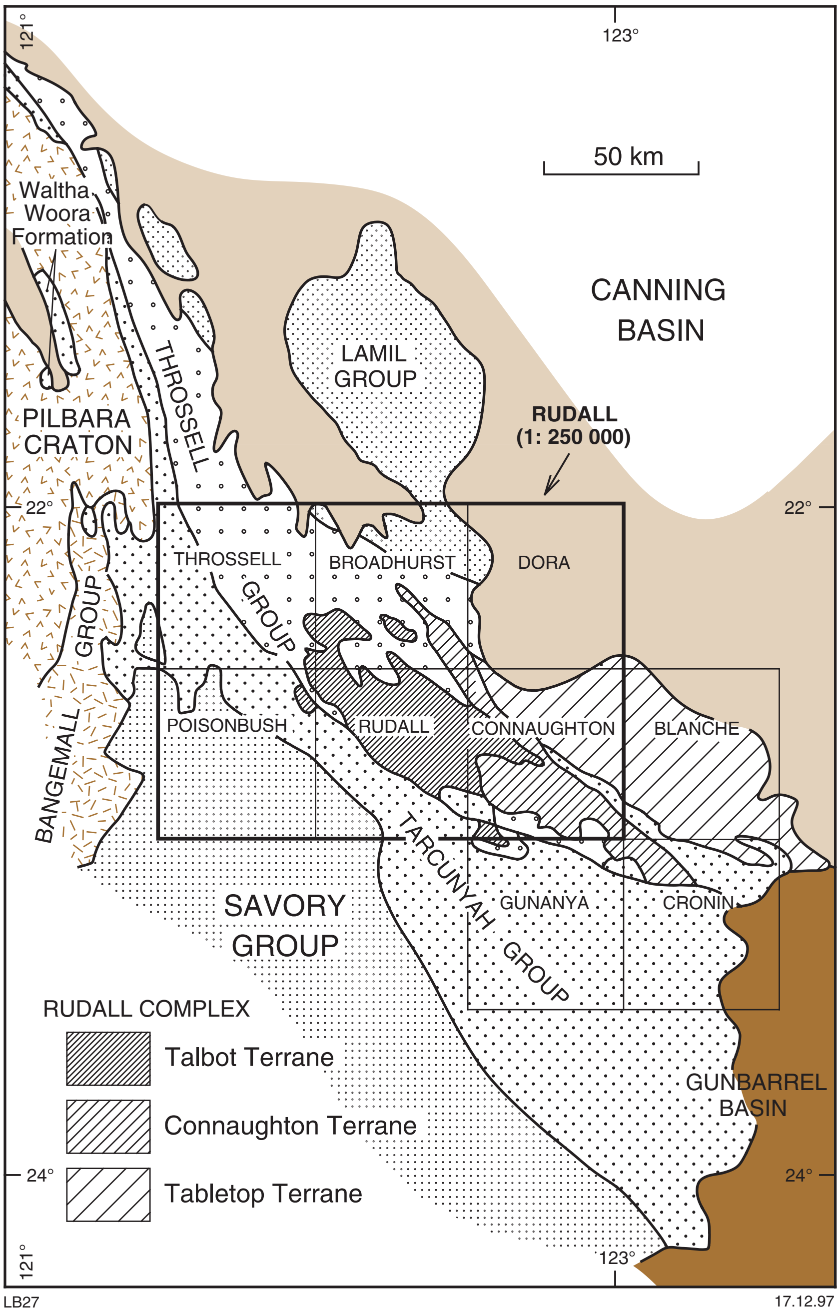
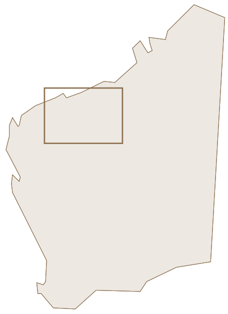


Figure 4. Location of the 1:100 000-scale mapping program in the Paterson Orogen

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.*

Progress summary

Geological mapping in 1996–97 was completed on Pinderi Hills, Roebourne, Mount Wohler, Yule, North Shaw, and Muccan, and commenced on Satirist, Wodgina, and Cooragoora. In addition, reconnaissance mapping was carried out on the remaining parts of the Dampier and Roebourne 1:250 000 sheets. Maps published during the year were the Roy Hill 1:250 000 sheet, and Dampier and Sherlock 1:100 000 sheets (Fig. 5). Explanatory Notes for the Roy Hill and Mount Bruce 1:250 000 maps were published, and a revised interpretation of the Whim Creek Belt (Sherlock) was submitted for external publication.

Aeromagnetic and radiometric data were obtained (NGMA project with AGSO) on eighteen 1:100 000 sheet areas in the central and east Pilbara, and processing and interpretation commenced. AGSO released data for the Marble Bar 1:250 000 sheet early in 1997.

The Pilbara mapping team of four geologists was increased to five in the field season of 1997, with two geologists joining and one leaving. The NGMA project with AGSO was successful during the 1996–97 year, but AGSO's funding cuts will have a serious impact in 1997–98, affecting the planned map production schedule.

Pinderi Hills

Mapping and geological interpretation of Pinderi Hills was greatly assisted by the use of radiometric images, particularly for the Fortescue Group. Previously, the Fortescue Group of this area was considered to be predominantly basaltic, but radiometric images generated from data obtained during the 1995–96 NGMA geophysical survey of the west Pilbara indicated major variations in K and Th contents. Petrography has confirmed a correlation of high K and Th with horizons of intermediate volcanic rocks, thus permitting mapping of compositional variations not evident on the aerial photography. From these data, two thick basalt formations of the Fortescue Group, the Kylena and Maddina Basalts, are interpreted to exhibit vertical compositional layering, with overall upward trends from mafic to intermediate, and locally felsic, volcanism.

In the northern part of Pinderi Hills the Fortescue Group unconformably overlies the granite–greenstone terrain of the west Pilbara. The western and central parts of this are here composed of granitoids and gneiss of the Cherratta Granitoid Complex. Detailed mapping has revealed the existence of small greenstone belts in this complex, thereby increasing the area's prospectivity.

Roebourne

Completion of mapping on Roebourne has linked the published maps of Dampier and Sherlock, and provided detailed information on the most actively explored section of the west Pilbara granite–greenstones. The new field data combined with geochronology (SHRIMP U–Pb on zircons) has resulted in a stratigraphic reinterpretation (*see* Hickman, this volume).

Mount Wohler

The work on Mount Wohler has clarified stratigraphic relationships between the predominantly volcanic Whim Creek Group (Sherlock), the Mallina Formation (a wide belt of turbiditic metasedimentary rocks) and volcanic rocks and banded iron-formation of the Nunyerry area (central part of the Pyramid 1:250 000 sheet). Conclusions are presented elsewhere in this Annual Review (*see* Smithies, this volume), and in a paper submitted externally. Previous interpretations invoking a major tectono-stratigraphic boundary between the Mallina Formation and the Whim Creek Group have not been supported.

Yule

Mapping of Yule was added to the program during 1996–97, following information that the Mallina Shear Zone (on Sherlock and Mount Wohler) extends across the area and provides a structural link to the Port Hedland 1:250 000 sheet area. This shear zone is interpreted to be the same age as the Sholl Shear Zone of the west Pilbara, and may have potential for economic mineralization. The Archaean geology of Yule is poorly exposed, but new aeromagnetic data indicate shallow subcrop of granitoids and greenstones, with well-defined contacts.

North Shaw

Geological mapping and mineral exploration of North Shaw has been relatively intense in recent years, encouraged by the discovery

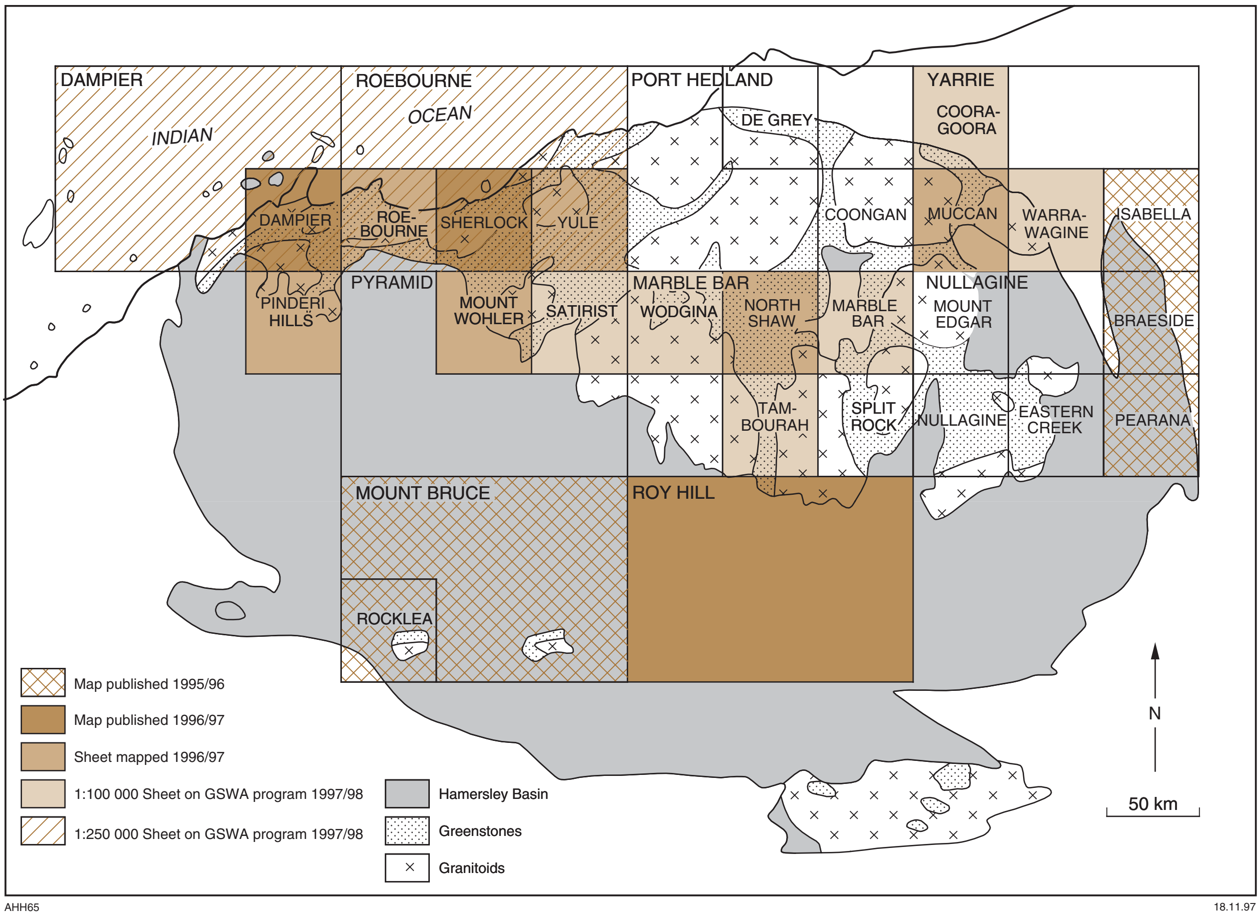


Figure 5. Progress of regional mapping in the Pilbara Craton

of Cu–Zn mineralization at Sulphur Springs, and at various other areas in the vicinity of the Strelley Granite. During 1996 Dr M. J. Van Kranendonk of the University of Newcastle mapped parts of North Shaw and Tambourah, working under contract with AGSO. In 1997 he joined the GSWA, continuing his work on the area. Apart from the necessary systematic mapping required, particular emphasis has been placed on structural geology, including the relative timing of granitoid dome formation and folding of adjacent greenstones. New stratigraphic information has also been obtained, enabling recognition of an unconformity between the 3240 Ma Strelley succession and underlying greenstones correlated with the Warrawoona Group. The main suites of granitoid rocks have been found to be coeval with the Warrawoona Group (c. 3470–3430 Ma), and the Strelley succession (3240 Ma). One of the younger suites has been dated at c. 2950 Ma, which appears to be the approximate age of the De Grey Group in this area.

The deformational history can be summarized as: D_1 — c. 3460 Ma synvolcanic doming with monoclinal tilting and folding related to intrusion of granitoids in the Carlindi Granitoid Complex and the North Pole Dome; D_2 — c. 3300–3240 Ma reactivation of D_1 domes, producing diapiric structures related to voluminous granitoid magmatism, with contemporaneous deposition of the Strelley succession in synforms between the domes; and D_3 — c. 2950 Ma sinistral transpressional deformation.

Results and conclusions from the 1996 mapping and structural studies are provided in AGSO Record 1997/23. A further two papers are in press in international journals.

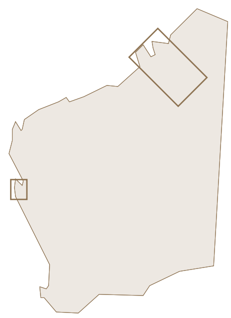
Muccan

Field mapping on Muccan was completed in October 1996, and has provided more detailed information on the stratigraphy of the Gorge Creek and De Grey Groups in the northeastern part of the Pilbara Craton. The major unit of banded iron-formation between Nimingarra, Yarri mine, and Coppin Gap, previously correlated with the Cleaverville Formation (west Pilbara), has been given a local name, the Nimingarra Iron Formation. The Nimingarra Iron Formation unconformably overlies the Muccan and Warrawagine Granitoid Complexes on northern Muccan, whereas in the central and southern parts of the sheet area, it rests unconformably on the Warrawoona Group. Formations above the Nimingarra Iron Formation are, in ascending order, the Cundaline Formation (a fine- to coarse-grained clastic succession), the Cooneeina Basalt (massive and pillowed basalt), and the Cattle Well Formation (sandstone, conglomerate, and minor felsic tuff). East of Shay Gap the Cooneeina Basalt is separated from the Cattle Well Formation by the Shay Intrusion, a norite–gabbro body.

The previously reported unconformity between strata now assigned to the Nimingarra Iron Formation and the overlying Cundaline Formation at, and just southeast of, Shay Gap could not be verified, and the two formations have a concordant, transitional contact in this area. However, east of Coppin Gap a conglomerate containing clasts of BIF and chert lies at the top of the Nimingarra Iron Formation, indicating local erosion. More striking in the Coppin Gap area is a marked angular unconformity between the Nimingarra Iron Formation and the Cooneeina Basalt — the Cundaline Formation being absent over a strike length of several kilometres. The inclusion of the Cooneeina Basalt in the Gorge Creek Group is brought into doubt despite the apparently conformable nature of the Cundaline Formation – Cooneeina Basalt contact near Shay Gap.

A. H. Hickman

Lennard Shelf and Shark Bay Projects



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.*

Progress summary

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

The compilation of five detailed maps of the outcrop belt at a scale of 1:100 000 was completed in 1996–97, as well as more detailed maps of the Bugle Gap area (1:50 000) and Windjana Gorge (1:25 000). These maps are due for release in 1997–98. A regional map at 1:500 000 will also be produced. Some field work was conducted during the year, primarily in connection with surface mineralization. The manuscript of a Report on the subsurface geology was completed, and the preparation of the manuscript for a Bulletin on the surface geology has commenced.

The Geological Survey has been involved in geological studies of the Shark Bay area since the early 1970s. The present project, which commenced in 1992, has concentrated on the modern stromatolites of Hamelin Pool, and the sedimentology and geological history of the Hamelin Coquina. This unit has long been subject to small-scale mining operations, which are still continuing. A report on the ecology of the bivalve *Fragum erugatum*, the main constituent in the coquina, was completed in association with the WA Museum of Natural Science and will be published in 1997–98.

Highlights

Work during the year has confirmed a link between Mississippi Valley-type mineralization and a stromatolite–barite association that is recognized in outcrop at several localities. This association occurs as void fillings associated with faulting and various stratigraphic discontinuities. It may also have been formed at some localities as exhalative deposits on the Devonian sea floor. This work may be very important in establishing links between organic processes and mineralizing fluids.

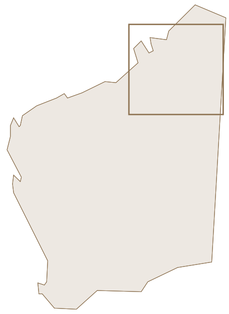
Future work

Further work on the field relationships and petrography of the stromatolite–barite deposits will be carried out during 1997–98 in association with Melbourne University. Collections will be made of conodont-bearing material from significant localities, and field relationships in several places will be clarified. It is hoped that negotiations for the establishment of a conservation reserve over the Mimbi Caves and McWhae Ridge areas, two of the most important geological localities in the area, can be satisfactorily concluded. The manuscript of a comprehensive Bulletin on the results of the field program is scheduled for completion in 1998.

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

Phillip Playford

King Leopold and Halls Creek Orogens



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

The King Leopold and Halls Creek Orogens are major geological units that contain significant mineralization, including the world's largest diamond mine. The area has potential for major discoveries of base and precious metals, uranium, rare-earth elements (REE), and diamonds.

Progress of maps and other publications

With the completion of remapping of the Halls Creek Orogen during the 1995 field season, work has concentrated on the compilation and preparation for publication of a number of 1:100 000- and 1:250 000-series geological map sheets, and their accompanying Explanatory Notes. Some of these have been mapped jointly with AGSO as part of the NGMA, and are shown on Figure 6.

During 1996–97 progress was made on the following sheets:

- MCINTOSH and TURKEY CREEK (part of the DIXON RANGE 1:250 000 map sheet and mapped jointly with AGSO) were published.
- BOW, on LISSADELL 1:250 000 map sheet, and which includes the Argyle diamond mine, was mapped and published.
- Explanatory Notes for MOUNT REMARKABLE were released.
- Explanatory Notes for DOCKRELL and ANGELO were compiled.
- AGSO had responsibility for the production of the 1:100 000 sheets that make up the GORDON DOWNS 1:250 000 map sheet, producing preliminary colour plots of HALLS CREEK, RUBY PLAINS (both mapped jointly with GSWA), ANTRIM, COW CREEK, NICHOLSON, and GORDON DOWNS. Map commentaries for HALLS CREEK and RUBY PLAINS are in press.

Assistance to the tourist industry

A booklet, *Geology and landforms of the Kimberley*, was written at the request of the Western Australian Department of Conservation and Land Management, and was published by them as part of their Bush Book series. GSWA geologists contributed also to a guidebook to the Bungle Bungle Range that is being produced by AGSO, describing the rocks, landforms, flora, fauna, and cultural heritage of the Purnululu National Park. Both these publications are intended to help the increasing number of tourists and tour operators in the Kimberley region understand the geological processes that produced the landforms and geological features they have come to see.

Future work

During 1997–98 GSWA will publish DIXON 1:100 000 sheet, as well as the MOUNT RAMSAY, LISSADELL, and DIXON RANGE 1:250 000 geological maps. A 1:500 000-scale geological map, and a structural and metamorphic interpretation map will be compiled. Explanatory notes for MCINTOSH, TURKEY CREEK, and BOW, and for the LISSADELL and DIXON RANGE 1:250 000 map sheets will be compiled.

Papers describing Neoproterozoic fossil stromatolites derived from the c. 800 Ma Ruby Plains Group and the c. 610 Ma glacigene rocks of the Louisa Downs Group are in preparation, for submission to national and international geoscientific journals. Further publications describing other fossil stromatolites from the Kimberley region will also be prepared during the year.

I. M. Tyler

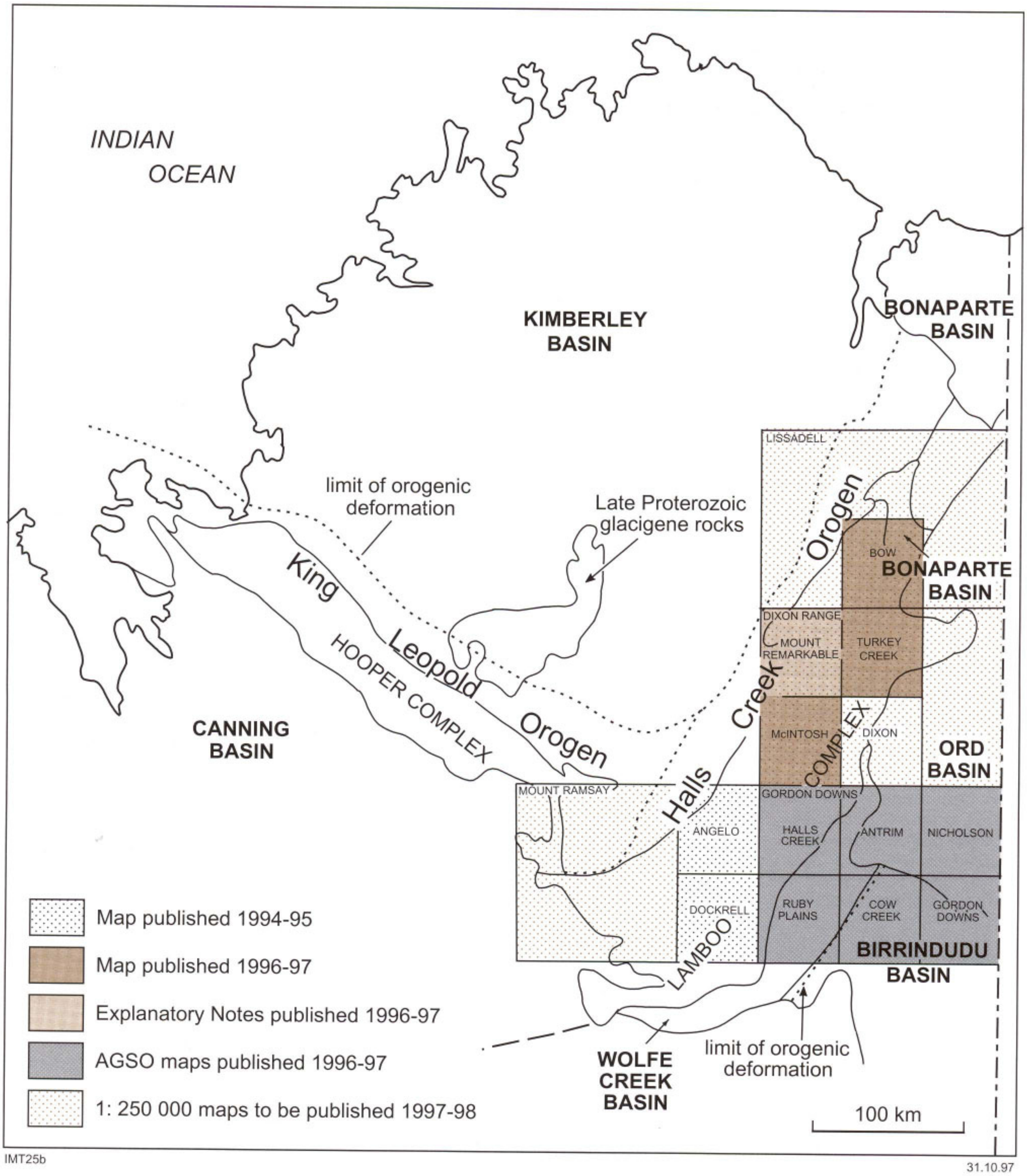


Figure 6. Progress of mapping across the Halls Creek and King Leopold Orogens

Geochemical mapping project

Objective: *To map the distribution of regolith over selected 1:250 000 map sheets. To sample and chemically analyse regolith collected at regular intervals on these map sheets in order to identify areas of element anomalies, relate regolith to bedrock, and understand the chemical changes during the formation of regolith from bedrock.*

Summary of progress

During the year, Explanatory Notes for the Robinson Range, Nabberu, and Mount Phillips 1:250 000 sheets were published. Regolith samples were collected on the Mount Egerton and Glenburgh 1:250 000 sheets, and preliminary work on regolith distribution maps for these sheets was commenced.

Nature of program

From its inception in 1993–4, the regional regolith and geochemical mapping program has aimed to provide information on the distribution and chemistry of regolith over selected areas of Western Australia. The data resulting from this program are used by mineral-exploration companies, pastoralists, and environmental agencies. Each set of maps and explanatory notes includes:

- a map showing the distribution of regolith;
- a series of element-concentration maps showing the concentration of up to 48 components in regolith;
- a compilation of mineral-exploration company activity in which geochemistry of surface sediments has been used.

These data are used to identify areas of potential mineralization. They also complement regional mapping and have been used in regional environmental studies.

Appropriate map sheets are selected with the assistance of an advisory group drawn from industry and government instrumentalities. The initial focus of the program was on the northeastern part of the Archaean Yilgarn Craton, but more recent projects have been in Proterozoic basinal rocks between the Yilgarn and Pilbara Cratons (Fig. 7).

Sampling is carried out at a nominal density of one sample per 16 km^2. The preferred sample medium is stream sediment, but colluvium or sandplain samples are collected in areas where drainage is absent or poorly defined. Lake samples have been collected from some map sheets. The < 2 mm to > 0.45 mm fraction is analysed for approximately 40 elements and a 4–5 kg sample of the -2 mm fraction is archived for future use by either GSWA or industry. At the sample collection site, a standard set of information is recorded, detailing the nature of the regolith and surrounding bedrock. These data are used in construction of the regolith distribution map.

The regolith distribution map utilizes remotely sensed data (Landsat TM, radiometrics, magnetics), aerial photography, existing geological maps, and the regolith sample site information.

Project status

Mapping and sampling on new map sheets was only carried out late in 1996–97 because of funding constraints. Explanatory Notes were published for the Robinson Range, Nabberu, and Mount Phillips 1:250 000 sheets. In April 1997, helicopter-supported sampling of the Mount Egerton and Glenburgh 1:250 000 sheets was undertaken by GSWA and contract staff. Each sheet was sampled in about 13 days, despite inclement weather. Analysis of the approximately 2000 samples collected during the program will be made in early 1997–98, and planning is underway to sample a further two sheets early in the new financial year, also by helicopter (Fig. 7).

The Explanatory Notes published in 1996–97 have continued the trend toward providing baseline geochemical information in areas of relatively unknown mineral potential. In addition, the move toward increased statistical treatment of regolith chemical data has been continued, in particular the use of indices maps, where element associations typical of mineralization types are statistically treated and then summed to produce an index value, whose magnitude can be related to the likelihood of mineralization. This has proved particularly valuable in areas where there is a strong contrast in composition between adjacent lithologies, such as between sedimentary and igneous rocks of the Bangemall Group, and the predominantly granitoid rocks of the Gascoyne Complex on the Mount Phillips 1:250 000 sheet.

Issues raised during the year include the need to further assess the variations in chemistry according to grain size, and the simplification of the regolith-landform scheme used on the regolith materials map. With regard to the first issue, a program is now in hand to analyse various grain-size fractions of different sample media (i.e. sheetwash, stream sediments, sandplain) to determine compositional variations. In conjunction with the Survey's regional mapping group, GSWA has developed a simplified regolith scheme for both regional regolith and geochemical mapping products, and regional geological maps. This

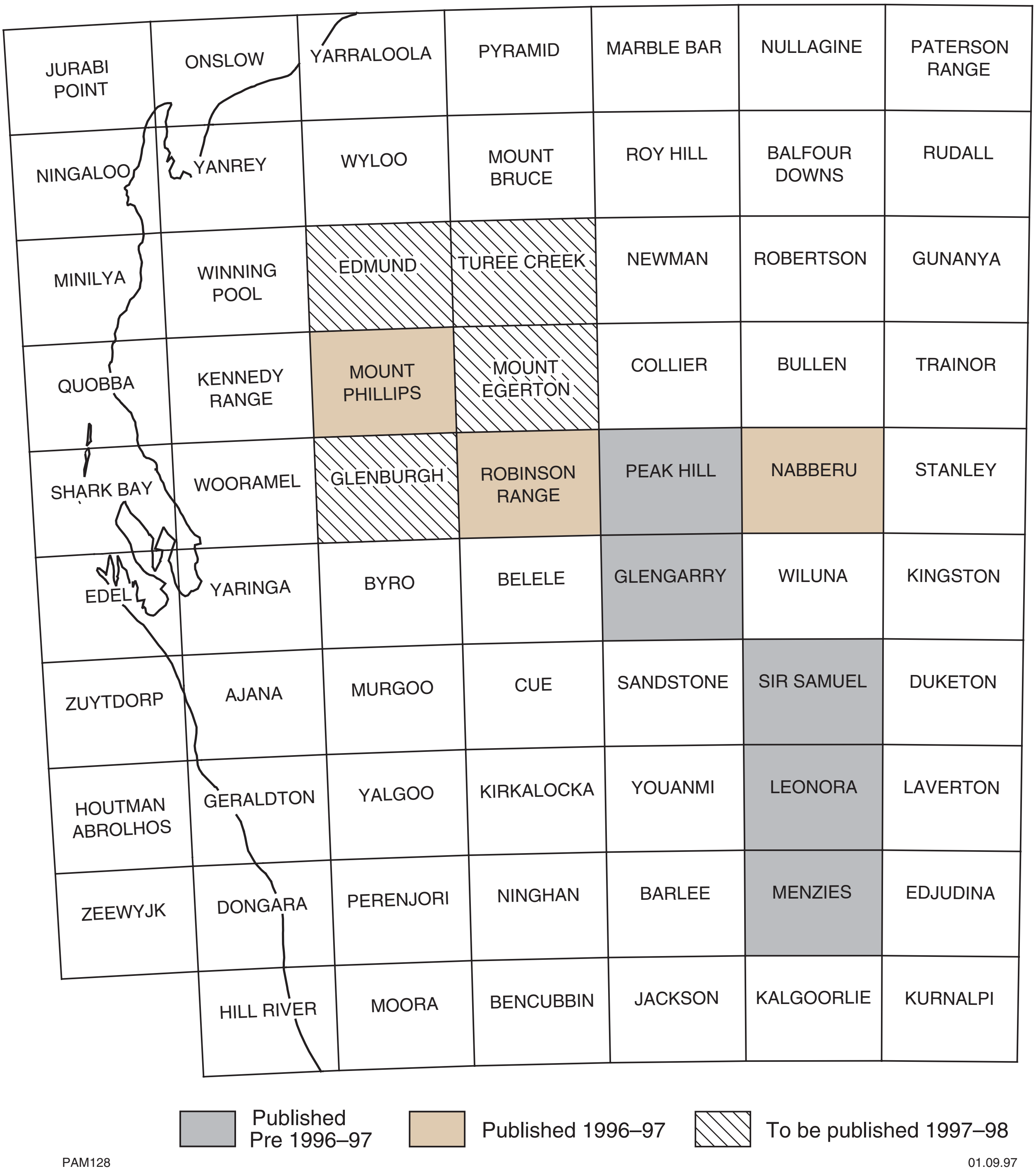


Figure 7. Summary of progress of the regional regolith and geochemical mapping program

is seen as a move toward a unified regolith scheme, and should accelerate production of 1:250 000-scale maps as well as facilitating production of smaller scale maps (i.e. 1:500 000) from existing regolith materials maps.

The requirement by the exploration industry for located regolith chemical data was met in early 1997 with the instigation of an early-release procedure, whereby the analytical data for regolith on the NABBERU and MOUNT PHILLIPS 1:250 000 sheets were released, on disk, prior to the Explanatory Notes. Such requests for data are seen as evidence of the increasing importance of the regional regolith and geochemical mapping program to the exploration industry. Access by exploration companies to sub-samples of archival material began in 1996–97, with material from the PEAK HILL and ROBINSON RANGE 1:250 000 sheets being accessed.

In November 1996, a poster presentation was made at the Regolith '96 Conference in Brisbane, outlining the use of regolith chemistry on SIR SAMUEL to highlight areas of gold mineralization. The presentation emphasized the statistical treatment of gold pathfinder elements, for both GSWA and company data, to highlight areas of known and potential gold mineralization, even when regolith gold concentrations are low.

Program methodology

The sampling methodology, previously outlined in the 1993–94 and 1994–95 Annual Reviews, was simplified for the recent helicopter-supported sampling program, in that many of the samples were wet (and could not, therefore, be sieved at the sample site), and the nature of the program restricted the time spent at each sample site to approximately ten minutes. As a result, approximately 5 kg of sample was collected at each site, for subsequent sieving prior to analysis.

P. A. Morris

Subprogram 3104 SCIENTIFIC, TECHNICAL AND FIELD SUPPORT

Geophysics

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

During 1996–97, the GSWA continued its program of airborne data acquisition to support its geoscience mapping efforts. Over the course of the year, almost 300 000 line km of data at 400 m line spacing (equivalent to seven 1:250 000 sheet areas) were acquired under a variety of arrangements.

Arrangements were made, jointly with AGSO, for the purchase of 100 000 line km of multi-client data covering the BARLEE and JACKSON 1:250 000 sheets (also at a line spacing of 400 m) for delivery in 1997–98.

All multi-client data purchases are made under conditions that the data may eventually be released to the public after a specified period.

Table 1. Program of airborne data acquisition, 1996–97

Area	*Survey size*	*Acquisition arrangement*
Marble Bar	45 000 km	AGSO survey (NGMA)
East Pilbara	30 000 km	Joint AGSO–GSWA contracted survey (NGMA)
Nabberu (North)	22 000 km	AGSO survey (NGMA)
Nabberu (South)	22 000 km	Joint AGSO–GSWA contracted survey (NGMA)
Bangemall Basin	150 000 km	Multi-client data purchase (for internal use)
Menzies	30 000 km	Multi-client data purchase (for internal use)

Thus, during 1996–97, 62 000 km of data previously acquired under such arrangements were released for the Glengarry Basin (19 000 km) and the WILUNA 1:250 000 sheet (43 000 km).

Digital data were released to industry through AGSO; and, from the Survey, hardcopy images, contour maps and interpretative products were available.

MAGIX Airborne Survey Index

The new MAGIX airborne-survey index database was developed and built. The database currently includes the location and basic specifications of surveys in the following categories:

- Reported under the 1997 WAMEX survey-reporting guidelines;
- Open-File surveys, held in the WAMEX system, for which digital data have been submitted;
- Survey boundaries from the earlier MAGCAT index (which will no longer be supported);
- Commercially available multi-client data (as advised from time to time by the airborne-survey contracting companies).

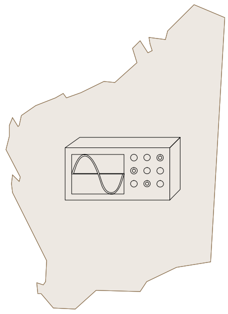
It is planned that surveys reported under the WAPEX petroleum reporting guidelines will also be included.

Future work

The MAGIX airborne-survey index database will be released to industry progressively through 1997–98. ArcView- and MapInfo-compatible files were made available in August 1997.

S. H. D. Howard

Geochronology and scientific support



Objectives: *To increase knowledge of the geology of Western Australia by the collection, integration, interpretation, synthesis and dissemination of new geological and geochronological information.*

Publications were prepared on the regional evolution, and implications for mineralization, of the Eastern Goldfields. Recent advances in the geological sciences continue to be integrated into GSWA maps and reports.

Geochronology sampling and dating of samples from the Narryer Complex, the Eastern Goldfields, the Southern Cross and Pilbara granite–greenstone terranes, and from the Bryah, Earaheedy, Padbury and Yerrida Basins, and the Savory Sub-basin of the Officer Basin was undertaken during 1996–97. Results for the calendar year 1996 were published in GSWA Record 1997/02.

D. R. Nelson

Carlisle Operations

Objectives:

- *To provide quality laboratory services including preparation of samples for petrology, geochronology, palynology, and geochemistry*
- *To provide, administer, and allocate field assistants to support geoscientists in the field*
- *To provide field support services in the way of vehicles and associated equipment, and provide a safety backup for all GSWA field parties*
- *To provide and maintain core-library facilities to service the needs of industry and the GSWA*
- *To ensure that these services are provided in an efficient and timely manner.*

From July 1996, the technical and support services of the Geological Survey, including the core library, were amalgamated and grouped under the new title Carlisle Operations. The Carlisle Operations team carries out a wide range of support services providing geoscientists with vehicles, equipment, field assistants, and laboratory services. A core store is also maintained as a service to industry and utilized as an archive for rock, fossil, and soil samples collected by the Geological Survey. A high-frequency radio communications base is also maintained.

The most significant event of the year for the Carlisle Operations was the announcement of government support and funding for a core library to be built at Kalgoorlie and a second facility to be constructed in Perth at Carlisle. Consideration is also being given to the construction of a third core library in one other regional centre. These initiatives will provide excellent research facilities to assist future exploration programs.

The Geological Survey's laboratory at Carlisle has maintained its focus on the preparation of samples for zircon separation for SHRIMP analysis. A total of 61 samples was processed for SHRIMP analysis for the year. In addition to this work, 1476 thin sections, including 275 polished thin sections were produced, and 295 palynology samples were prepared for examination. Other work carried out in the laboratory included heavy mineral separations, crushing and pulverising samples for geochemistry, specific gravity determinations, polishing rock faces, staining rock chips and many other minor procedures.

The 1996–97 year has been a busy one for the Transport and Stores Section of Carlisle Operations. Additional work was generated for staff with the increase in field activities, in particular with the initiation of accelerated geochemical sampling programs. Carlisle staff have now acquired full responsibility for maintaining and monitoring DME's high-frequency radio communications base, which is the focal point for monitoring and maintaining safety in the field. The section has also continued to provide maps and publications to Mineral House for sale at the public counter.

This is the first year that the requirement for additional field assistants has been outsourced from an employment agency. This method of employment has provided a degree of flexibility in employing field staff at short notice for short-term appointments.

G. T. Williams

Subprogram 3105
GEOSCIENTIFIC EDITING AND PUBLISHING

Publication 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 a public venue for the display of representative samples of rocks and minerals of the State; exploration, mining, and rehabilitation models; and historical and educational displays*
- *To provide information and advice for the general public on all aspects of Western Australian geology.*

Editing and publishing

Under Subprogram 2.1 during 1996–97, sixteen 1:100 000 and three 1:250 000-scale geological series maps were released, as well as four maps at other scales. A further eighteen plates (comprising maps, cross sections and well correlations accompanying Report 46) were also printed and released. Thirteen processed images and contour maps resulting from interpretation of two aeromagnetic datasets and two gravity datasets were also released. Geoscientific manuscripts published for the year totalled twenty-five; see Appendix for listing. At year end one 1:100 000 scale map and two manuscripts were at the printer in preparation for release in early July 1997.

In addition to the above program, three 1:250 000-scale hydrogeological maps and one manuscript edited and printed on behalf of the Water and Rivers Commission were released during 1996–97. A further three 1:1 000 000 maps were produced to illustrate a Regional Mineral Prospectivity Study of the Kimberley Region commissioned by the Department of Resource Development.

Considerable attention was given to process improvement during 1996–97. The manuscript publication process was reviewed, with the result that the previously informal peer review of manuscripts prepared by GSWA geoscientists was strengthened and formalized, with peer reviewers being assigned by a newly constituted editorial panel.

Continuous improvement initiatives within the Computer Aided Drafting and Design (CADD) group included upgrading of archiving systems, more efficient processing of seismic sections and images for publication at A4 size, and technological advances in compilation of complex promotional material bringing together multiple and varied images into single A0-size posters.

The map publication process also came under close scrutiny. Editorial staff participated with cartographic staff in a process improvement team to investigate ways to spread the historical year-end surge of published output more evenly over the year. Although the cyclicity of published map output imposed by the regularity of the field season is a big obstacle, recommended changes to the process were being formulated at year end and are expected to considerably streamline the process in the future.

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, the Kalgoorlie Miner, Register of Australian Mining, the Western Australian Geologist, Industrial Minerals magazine, Register of Australian Petroleum, Oil and Gas Gazette, PESA Journal, and Petroleum in Western Australia magazine. Media releases were prepared for all published GSWA products released during the year.

Four volumes of FIELDNOTES (the GSWA quarterly newsletter first published in January 1996) were issued during the year. This newsletter has provided industry with up-to-date information on progress of GSWA work programs, recent publications and maps, and general information about the products and services of the Survey.

Displays of ongoing and completed geoscientific work by GSWA were presented at the following industry events:

- Australian Society of Exploration Geophysicists 12th

Geophysical Conference and Exhibition (Sydney, February 1997)

- WALIS Forum '97 (Perth, March 1997)
- Australian Petrographic Symposium (Corowa, NSW, March 1997)
- Minerals and Energy Week (Perth, March 1997)
- American Association of Petroleum Geologists Annual Convention (Dallas, Texas, April 1997)
- Western Australian Exploration Technology Overview: Geotrain Australia (Perth, April 1997)
- Australian Petroleum Production and Exploration Association Annual Conference (Melbourne, April 1997)
- Institute of International Research: Western Australian Resources and Energy Boom Conference (Perth, May 1997)
- Institute of International Research: Native Title Conference (Perth, May 1997)

Three geoscientific seminars or courses were held in Perth during the year. Displays of GSWA products relevant to those events were mounted as follows.

- *Yilgarn Extension Project (October 1996)*
- *Proterozoic Granites Course (October 1996)*
- *Volcanic Successions Short Course (May 1997)*

The Geological Survey, in partnership with AGSO, presented displays of recent outputs of mapping in the Eastern Goldfields under the umbrella of the NGMA in Kalgoorlie (October 1996) and Perth (November 1996).

In the latter half of the year work commenced on upgrading the Department's internet home page. The revised website, including improved GSWA content, is expected to be operational in early 1997–98.

In early 1997 a 'Promotion and Publicity Policy' and a draft 'Marketing Plan' for the Geological Survey were prepared and endorsed by the Geological Survey Executive. The latter documented those promotional and marketing initiatives already being undertaken, and provided guidelines for expansion and new directions. The expansion and execution of the marketing plan is anticipated in late 1997–98.

Museum

The Museum has been in care and maintenance mode since 1995. However, educational use of the Museum facilities continued with four school groups (approximately 100 students) from primary and secondary schools, TAFE and Universities being entertained with presentations by GSWA staff on topics relating to geology, mining, and the activities of both the department and the Geological Survey.

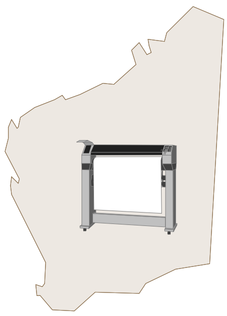
Public enquiries

The rate of response to public enquiries in 1996–967 was steady through the year apart from surges coinciding with geoscience and mining units appearing in the school syllabus. Non-geological enquiries have continued to be handled either by the Public Affairs Branch, or the first floor sales counter. Consequently, geoscientists in the Publications Section received and responded mainly to enquiries requiring geoscientific expertise. Areas covered included information and assistance for prospectors, tourists and amateur fossickers, urban geology for land owners, mining and its environmental implications, and educational geology for students and teachers.

A. S. Forbes

Computer-assisted map production (CAMP)

Objectives:
- *To assist in the dissemination of geological information by the production of high-quality maps*
- *To produce digital spatial data*
- *To provide geoscientists with base maps for geological map compilation.*



The core business of the CAMP section is the production of multi-coloured lithographic printed maps. Maps completed by CAMP for printing in 1996–97 included:

- three 1:250 000-scale geological maps
- three 1:250 000-scale hydrogeological maps
- sixteen 1:100 000-scale geological maps
- one plate to accompany Report 49 — Eastern Goldfields granitoids.

Products completed by CAMP for short run (plotter or plan printer) output included:

- eight 1:100 000 Total Magnetic Intensity contour maps.

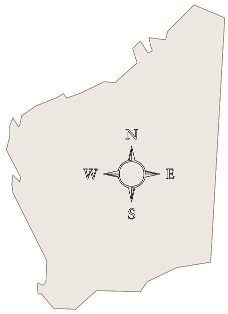
Spatial data digitally captured by CAMP to be published by other agencies were:

- simplified geological maps for inclusion in Geological Digital Data Packages
- regolith maps and sample sites for Regolith Geochemistry program.

The CAMP Section continued to respond to a high demand for base maps to support field activities of Geological Survey geoscientists undertaking field mapping. The section is committed to an ongoing process-improvement program and continues to provide technical advice and assistance on mapping and cartographic reproduction issues.

B. Dawson

Spatial Information Systems (GIS and database coordination)



Objectives: *To deliver quality spatially related geoscientific information in a timely manner to satisfy our clients needs by:*

- *designing, developing, and maintaining spatial databases for analysis and modelling*
- *disseminating spatially related geoscientific information in the form of hard-copy maps and digital products*

GIS continued to be used as an analysis and map production tool during 1996–97. Milestones and productivity goals for 1996–97 were achieved.

Geophysical images

ER Mapper dynamically linked to ARC/INFO has provided an opportunity to produce high-quality geophysical images using the imaging processing of ER Mapper and the cartographic processing of ARC/INFO. A total of six images have been produced covering Giralia, central Southern Carnarvon Basin and the northern Perth Basin.

Geochemical and regolith mapping

Three Geochemical and Regolith packages (for the ROBINSON RANGE, NABBERU, and MOUNT PHILLIPS 1:250 000 sheets) consisting of maps and digital data were released.

Databases

The design, development, and implementation of WAROX and WAMIN databases using Microsoft Access were completed.

Geological data packages

The SIR SAMUEL 1:100 000 geological data package was released.

Other digital and map products

Other digital data and short-run map products completed by GIS included:

- revision of the Pilbara Iron Ore Assessment map and dataset
- South West Regional Forest Agreement (RFA) project
- Blackwood Catchment GIS project
- spatial index to digital geophysical datasets (MAGIX)
- spatial index to exploration activity (SPINDEX) for seventeen 1:100 000-scale map sheets
- translation of digital data in Microstation format into a format suitable for use in the GIS environment for 22 geological series maps
- release of the Information System Strategic Plan to the Year 2000.

S. Bandy

Subprogram 3106 GEOSCIENTIFIC AND EXPLORATION INFORMATION

Geoscience Information Library

Objectives: *To respond appropriately and efficiently to the geoscientific information needs of the Department, mineral and petroleum industry, educational institutions and the general public.*

During the year 7174 users visited the library, a decrease of 21% on last year. The number included 1594 users of the microfiche facilities to access open-file exploration data, an increase of 28.5% on last year. Library staff dealt with 6212 enquiries, the first full year that statistics have been kept.

Automated library system

During the year the library's bibliographic database was transferred from the Chemistry Centre (WA) to the GSWA SUN server and upgraded to Version 6.0.

A Windows version of the database was also installed, so that the library now operates both a character-based and GUI version of the software. A computer was made available for public access to the database within the library, and DME staff were provided with telnet access to the database, allowing them to interrogate the database remotely.

Development of the library's automated catalogue system continues to be focused on data capture and the consolidation of the library's bibliographic databases into a single system. To date, approximately 75% of the book collection has been added to the OLIB database. Version 6.2 of the software will be loaded shortly, after which data entry of the library serial collections will commence.

Library redevelopment

Library staff were heavily engaged throughout the year in planning and preparing for the library redevelopment. This included a complete review of serial holdings in the library at Mineral House in order to determine core material to be retained prior to redevelopment. The library redevelopment was completed in June 1997, providing a more spacious and functional layout that has allowed improved service to customers and a more efficient working area for staff. The library now maintains a core collection of books, reprints, reference material and serials in the main library. All material received on exchange from overseas is shelved in the storage facility at Carlisle, and a small store has been built on Level 4 of Mineral House to hold the aerial photograph collection.

Extra shelving was acquired for the library's Carlisle storage facility to accommodate the increasing quantities of material now required to be stored there.

Library collections

All WA Government Gazettes from the years 1894 up to 1916 were re-bound. The Gazettes are heavily used by Mineral Titles Division in capturing data for the TENGRAPH database and form one of only a few collections held in the State.

The library has a significant collection of maps (30 000), which is currently being reviewed by Mr P. Dunn, former Assistant Director of the GSWA. The collection is being reorganized in order to ensure future access to the dataset. It is planned to have a computer database of the maps in this collection available for public access.

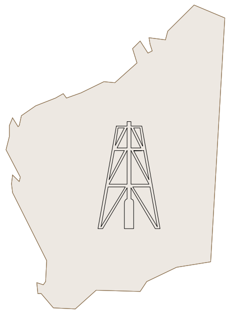
A complete photocopy set of the text and plans of the Aerial, Geological and Geophysical Survey of Northern Australia (Western Australia) was produced, providing customers with full access to this material without needing to refer to the rapidly deteriorating originals.

Library services

This year was another extremely busy year for library staff. However, good progress was made to eliminate processing backlogs and provide normal library services during the renovations. A great effort was made in reorganizing, stocktaking, and re-shelving prior to the library redevelopment. This is currently being followed up with further re-shelving and re-labelling to ensure ease of customer access.

B. J. Knyn

Mineral and petroleum exploration data (WAMEX, WAPEX and WAPIMS)



Objectives: *To administer the collection and storage of mineral and petroleum exploration company statutory reporting on tenements in Western Australia, and to ensure the efficient dissemination of information in these reports to industry, as they are released onto open file.*

This sub-program covers all aspects of the submission, management, and release of both mineral and petroleum exploration data through WAMEX (the Western Australian Mineral Exploration database) and WAPEX and WAPIMS (the Western Australian Petroleum Exploration database and Western Australian Petroleum Information Management Systems).

Highlights for 1996–97

- The mineral and petroleum exploration data-management sections have combined and moved to a refurbished workplace closer to the library, which is where most external clients access the data.
- Funds have been made available for a scoping study into the future developments needed in the management of exploration data to facilitate an effective and efficient delivery of information to our clients.
- Preliminary consultations are taking place with clients prior to the exploration data scoping study.
- The changes to the Western Australian Mining Act (1978) that clarify requirements for technical reporting have led to an improvement in quality control resulting in more deficiencies being followed up. This has helped ensure that quality data, presented in an appropriate format, is submitted to the Department.
- Access to the WAMEX database was made available to outside users via the Internet from August 1996.
- The 'Schedules of petroleum exploration wells' for the Perth, Canning, Officer, Eucla, and Bremer Basins have been released.
- Work on the prototype Paradox database (WAPIMS) for the management of petroleum information has continued, with digital downloads being made available to clients.
- Work is underway to compile a complete record of onshore seismic work in the State and the section is involved with SNIP (Seismic Navigation Integration Project), which is undertaking a similar compilation of offshore seismic work.

Report submission

Mineral exploration

During the year, 3698 volumes of mineral-exploration reports on 10 083 tenements were received, representing an increase of 15.8%. This brings the total number of volumes held to 56 006. 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 is increasing and about 11% of reports contain some data in this format. Submission of mineral-exploration digital data is expected to rise steadily.

Reporting standards for mineral exploration

This year has been the first full year of required compliance with the 'Guidelines for Mineral Exploration Reports on Mining Tenements'. These guidelines outline standards for format and content of mineral-exploration reports as required under the Act. Forfeiture action may now be taken where mineral-exploration reports have either not been submitted or were unsatisfactory in that they did not follow the Guidelines in format or content. With the increased quality-control checking by departmental staff it was found that 37% of the reports submitted this year required format and/or content to be rectified.

The Department is currently involved with two projects relevant to reporting. One is an interdepartmental working group that looks at the standardization of reporting across States and Territories; the other is an industry- and government-sponsored project to develop an Australian standard data model for geoscientific data.

Petroleum exploration

During 1996–97 there were 227 active petroleum tenements of which two expired and 30 were awarded or renewed during a year that had the lowest recorded onshore exploration activity. Twenty-three surveys, 62 wells and 23 general studies were conducted in the state. These activities generated 55 113 sets of data, a 26% increase over the previous year, to make a total of 531 853 registered sets of petroleum data held or administered by the Department. These sets of data include reports, seismic sections, well logs, digital data, maps, cores and cuttings, and palaeontological data.

WAMEX, WAPEX and WAPIMS databases

No significant enhancements of the WAMEX and WAPEX databases were carried out during the year as it is highly unlikely that the database will remain on the mainframe computer. However, from August 1996 access to the

WAMEX database was made available to outside users via the Internet. To date there are 420 registered users.

Work on the prototype Paradox database (WAPIMS) for the management of petroleum data has continued with digital downloads being made available to clients. There has been an excellent response from petroleum data users and a growing number of requests for downloads of data to clients. Response time has decreased markedly as the increased functionality of the database has facilitated the fulfilment of these requests.

Combined reporting (mineral exploration)

The Western Australian Mining Act now legally recognizes 'combined reporting status', i.e. the ability to submit one mineral-exploration report on a group of tenements on a chosen date, provided a number of requirements are met.

During the year, 336 reporting groups covering 2668 tenements were formalized. The total number of current combined reporting groups is 1444 covering 14 921 tenements.

Data release

Mineral data

During the year 1062 reports were released to Open File, bringing the total number of mineral-exploration reports on Open File to 22 881 volumes.

Petroleum data

As part of the legislative requirement of release of data, 173 edited reports, 489 unedited reports, 106 sets of well logs, and 62 sets of seismic sections were released. The increased use of digital data is evident from the 100.8% increase in seismic tapes being reprocessed (32 290 tapes) as a result of 135 requests received by the Department. Additionally, 50 requests for sample drillcore or cuttings and 16 requests for palaeontological data were satisfied.

M. J. Ellis

Appendices

Planned achievements and publications released

Major planned achievements for 1996–97

The GSWA had an ambitious project-based program of work designed to promote Western Australia's exploration potential. Planned achievements for 1996–97 included:

- release of sixteen 1:100 000 geological maps, and five geological maps at other scales
- release of images, interpretative maps, and data packages for two aeromagnetic and two gravity surveys
- publication of three GIS-based 1:250 000 regolith and geochemical maps and data packages, and accompanying notes
- publication of 25 Reports, Bulletins, and other papers
- continued provision of geoscientific data and exploration-information services to industry.

These publication milestones were achieved (as listed below) and contributed to a 3.2% real productivity improvement through relevant, customer-endorsed and strategically spread projects.

Maps and volumes published in 1996–97

Geological maps

1:100 000 geological series

Bryah
Doolgunna
Mount Bartle
Connaughton
Glengarry
Sherlock
Milgun
Dampier
McIntosh
Thaduna
Mooloogool
Turkey Creek
Bow
Gunanya
Millrose
Padbury

1:250 000 geological series

Roy Hill
Kurnalpi
Byro

1:250 000 hydrogeological series

Ravensthorpe*
Bremer Bay*
Esperance*

Regolith geochemistry GIS packages (1:250 000 scale)

Robinson Range
Nabberu
Mount Phillips

Geological maps at other scales

- Granitoid geology of the southwest Eastern Goldfields (Report 49, Plate 1, 1:500 000)
- Basic raw materials of the Shark Bay World Heritage Area (Record 1996/9, Plate 1, 1:500 000)
- Pre-Cainozoic geology of the onshore northern Perth Basin (Report 46, Plate 10, 1:500 000, and seventeen associated plates in the form of geological cross sections, well-log correlations, seismic structure maps, and seismic sections at assorted scales)
- Pilbara Iron Ore Assessment (1:500 000 map output from GIS dataset)

Aeromagnetic packages

- West Pilbara TMI contour maps (eight sheets at 1:100 000)
- WILUNA 1:250 000 sheet TMI images (six at 1:100 000 and one at 1:250 000)

Gravity data packages

- Giralia gravity (onshore Carnarvon Basin, two images at 1:250 000)
- Byro–Coolcalalaya gravity (onshore Carnarvon and Perth Basins, four images at 1:500 000)

Mineral Resources Bulletins

16. **Talc, pyrophyllite and magnesite in Western Australia** by P. B. Abeysinghe

Reports

46. **Stratigraphy and structure of the onshore northern Perth Basin, Western Australia,** by A. J. Mory and R. P. Iasky
50. **Groundwater: the strategic resource (a geological perspective of groundwater occurrence and importance in Western Australia),** by A. D. Allen

Records

1995/6 **Onshore northern Perth Basin gravity project,** by R. P. Iasky and S. Schevchenko

1996/1 **Program 2 — Industry Support: Geological Survey plan for 1996–97 and subsequent two years**

1996/2* **A baseline survey of non-point source groundwater contamination in the Perth Basin, Western Australia,** by K-J. B. Hirschberg and S. J. Appleyard

1996/3 **North West Cape petroleum exploration: Analysis of results to early 1995,** by A. Crostella

1996/6 **GSWA Gneudna 1: Well Completion Report (Merlinleigh Sub-basin, Carnarvon Basin, Western Australia),** compiled by A. J. Mory

1996/7 **GSWA Ballythanna 1: Well Completion Report (Byro Sub-basin, Carnarvon Basin, Western Australia),** compiled by A. J. Mory

1996/9 **Basic raw materials of the Shark Bay World Heritage area,** by D. B. Townsend

1996/10 **A compilation and review of data pertaining to the hydrocarbon prospectivity in the Canning Basin,** by S. N. Apak and G. M. Carlsen

1996/11 **Permo-Carboniferous petroleum reservoir data, selected wells, Canning Basin, Western Australia,** by P. J. Havord, S. N. Apak, and G. M. Carlsen

1996/13 **Mineral resources and locations, Western Australia: Digital dataset from MINEDEX,** by D. B. Townsend, W. A. Preston, and R. W. Cooper

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* These publications were in progress at the time of the departure of the GSWA Hydrogeological Section to become part of the Water and Rivers Commission (December 1995). Although published in 1996–97 they have not been considered as 'Planned Achievements' as the editorial and publishing effort was funded by WRC.

Explanatory Notes

1:100 000 geological series

MOUNT REMARKABLE
RAVENSTHORPE–COCANARUP

1:250 000 geological series

MOUNT BRUCE
ROY HILL

1:250 000 regolith geochemistry series

ROBINSON RANGE
MOUNT PHILLIPS
NABBERU

Miscellaneous publications

GSWA Annual Review for 1995–96

Schedule of petroleum exploration wells: Perth Basin

Schedule of petroleum exploration wells: Canning, Officer, Bremer and Eucla Basins

Geology and mineralization of the Chencai–Suichang uplift, Zhejiang Province, southeast China (in cooperation with the Department of Geology and Mineral Resources, Zhejiang Province — Peoples Republic of China)

GSWA Field Safety Manual

FIELDNOTES vol. 3–6

Catalogue of Geological Maps, April 1997

Major planned achievements for 1997–98

The GSWA will continue to pursue a project-based program of work and maintain a vigorous level of output to match increased funding in 1997–98. Planned achievements for 1997–98 include:

- release of 32 geological maps at various scales covering areas throughout Western Australia
- publication of 39 geoscientific Reports, Bulletins, Records, Explanatory Notes and other papers
- publication of four GIS-based regolith geochemistry data packages
- publication of three GIS-based prospectivity enhancement packages
- images, interpretative maps and a data package for one gravity survey
- release of core from two (minimum) stratigraphic core holes in onshore sedimentary basins
- 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 (WAPEX) exploration databases.

External publications

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Note: GSWA authors are in italics

List of acronyms and abbreviations

ABS	Australian Bureau of Statistics
AGSO	Australian Geological Survey Organisation
AMIRA	Australian Mineral Industries Research Association Limited
AMSS	Airborne multispectral scanner
APEA	Australian Petroleum Exploration Association Limited
APPEA	Australian Petroleum Producers and Explorers Association Limited
ASX	Australian Stock Exchange
BIF	Banded iron-formation
BMR	Bureau of Mineral Resources
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAWA	Department of Agriculture of Western Australia
DME	Department of Minerals and Energy
GIS	Geographic Information System
GSA	Geological Society of Australia
GSWA	Geological Survey of Western Australia
JV	Joint Venture
Landsat TM	Landsat Thematic Mapper
LCD	Land Conservation District
LIS	Land Information System
LME	London Metals Exchange
MERIWA	Minerals and Energy Research Institute of Western Australia
MINEDEX	Mines and mineral deposits information database
NGMA	National Geoscience Mapping Accord
OLIB	Oracle Libraries database
PC	Personal Computer
PGE	Platinum Group Elements
RFA	Regional Forest Agreement
RMS	Record Management System
SHRIMP	Sensitive High-Resolution Ion Microprobe
SNIP	Seismic Navigation Integration Project
SPOT	Système Probatoire de l'Observation de la Terre
TENGRAPH	DME's electronic tenement-graphics system
WAMEX*	Western Australian Mineral Exploration database
WAMIN	Western Australian Mineral Index database
WAPEX*	Western Australian Petroleum Exploration database
WAPIMS	Western Australian Petroleum Information Management System
WAROX	Western Australian Rock Index database

Note: * WAMEX and WAPEX are registered Trade Marks

Geological Survey Liaison Committee

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Dr David Blight, Secretary
Mr Terry Walker
Dr Dennis Gee
Dr David Haig
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