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REVIEW

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REVIEW 1995-96

DEPARTMENT OF MINERALS AND ENERGY

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MINISTER FOR MINES
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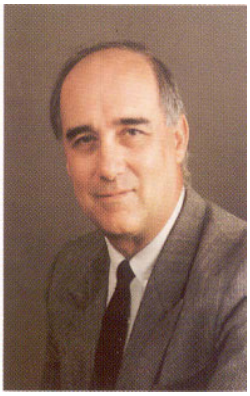
Cover:
Mississippi Valley-type marcasite–sphalerite ore from Goongewa mine, Lennard Shelf, Canning Basin. Deposit is hosted in platform-facies limestones of the Devonian reef complexes.

Frontispiece:
Helicopter taking off from base station during GSWA gravity survey of the Merlinleigh Sub-basin near Gascoyne Junction. One GPS antenna is set on a tripod over the base station and another is mounted on the helicopter to fix the gravity stations by differential GPS technique.

Foreword



It gives me pleasure to introduce you to the Geological Survey of Western Australia Annual Review for 1995–96 — our third issue.

I take this opportunity to thank you, the reader, for your constructive feedback on the previous issues which, I hope, has been reflected in an improvement in quality and relevance.

I have also been very flattered by, but have resisted, the suggestion that GSWA should charge for its Annual Review. I think of the Review as our "loss leader", the means to whet your appetite for new products to come. It is also confirmation that we care about keeping our stakeholders well informed about our programs and activities, and that we take our accountability seriously.

The Review is also meant to be a tribute to GSWA staff, to recognize their competence, effort and dedication in serving our customers and in achieving what amounted to very demanding milestones and productivity targets in 1995–96. I like to believe that they will take pride in distributing it to their most immediate clients, colleagues and associates.

I am confident, too, that the variety of feature articles and previews of significant preliminary results from various active projects will stimulate interest in new areas, and inspire new exploration and research concepts.

Finally, we have succeeded in our intention of publishing the Annual Review just before the end of the relevant calendar year; thus its content is reasonably up-to-date with the current state of play. Of course, if you have a specific interest in any of our projects, or for that matter in anything geological at all, please feel free to contact the appropriate officer who will be only too pleased to help.

Good hunting.

P. Guj
DIRECTOR

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Geological Survey of Western Australia

A century of service to a million mile State

Our vision is to be the international benchmark for delivery of high-quality geoscientific products and services to industry, Government, and the public, making Western Australia the focus of international exploration.

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 systematically record and interpret the geology of the State and to provide this information to Government, industry, and the general public to assist with the exploration, development, and conservation of the State's mineral (including groundwater) and petroleum resources. The Geological Survey also 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, especially regional geological mapping in both the Precambrian and Phanerozoic provinces of the State. The Survey is also strong in the fields of structural geology, basin studies, carbonate sedimentology, mineralization studies, hydrogeology, geochemistry, regolith studies, geochronology, geoscientific computer applications, palaeontology, and petrology.

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 petroleum 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 P. Guj

Well, when the going gets tough . . .

Truth is that, surprisingly, we just made it; we achieved all the products and services, output milestones and a total productivity target of over 7% improvement (4% real) for 1995/96. I say surprisingly, because when we agreed to finalize the restructuring of the Geological Survey of Western Australia (GSWA) within a flat (5 strata) new Departmental organization and to introduce a new Performance Enhancement Program (PEP) linking our pay increases to our performance, we took a major step into uncharted waters.

Uncharted waters in two respects. Firstly, we were embarking on a very significant cultural change for a traditional and largely static public service environment. And secondly, in retrospect, we only had a vague idea of the commitment in time and effort required to succeed in implementing effective structural reform throughout our organization, and the heavy toll it takes on its leaders.

It is always hard to realise other people's obsessions, at least until one also becomes totally committed. It is also hard to divorce one's attitudes to change from the initial perceptions that are clouded by potential, or imagined, threats to one's own self-interest. It is hard for staff to make an objective and detached assessment of the situation, of the motives and of the significant organizational and indeed personal opportunities inherent in change. It is not enough, in the first instance, that change makes considerable rational and analytical sense at the level of the decision makers.

Nonetheless, the GSWA vision to become an international benchmark for geological surveys will only be achieved with a flatter, leaner and meaner organization where, over time, more highly skilled and productive, motivated and relatively well-paid geoscientists excel in fulfilling the GSWA role of enhancing and promoting the State's prospectivity, and contributing to making Western Australia the focus of international exploration investment. For this vision to be fully realised it must be sold to, and accepted by, not only all staff but also Government decision makers.

The formality of a new stratified structure (displayed schematically elsewhere in this publication) and of performance assessment systems by themselves, however, will not realise the vision unless all GSWA staff understand, work within, and make a commitment to our new management system. A first step in this direction has also been taken in 1995–96 with the introduction of Workplace and Enterprise Bargaining Agreements within the Department of Minerals and Energy (DME). The Workplace Agreement was adopted by about three-quarters of staff who, between increases in pay, conditions trade-offs, and the effect of performance rewards, have now bridged at least part of the gap in remuneration between the public sector and private enterprise.

I think we have laid very solid foundations and that we are well on our way to embracing the new structure and management culture as a way of improving our performance. I look forward to 1996–97 as a year of consolidation which will see individual employees becoming more and more adjusted to the new regime and thus bear the initial fruits of these reforms.

Periods of change also rely on good lines of communication. Honest, indeed frank, communication will bring about solutions. Clamming up will only defer and accentuate conflicts which eventually will be harder to address.

Frank communication alerts you, among other things, to other people's perceptions of your attitudes and behaviour. For instance, during my recent performance assessment the Director General made me aware of his perception that when he deals with me on matters relating to the GSWA he always has the uncomfortable feeling of being in a negotiating mode. Furthermore, his perception is that I approach him with an expectation of getting 10, ask for 100 and get away with 20. What irks him is that at this stage, according to him, I withdraw as if I had been beaten down to the verge of bankruptcy and despair. On my side I accused him of operating on the whatever-Lola-wants-Lola (almost always)-gets principle.

The truth is, this is proof that we communicate well and that the negotiated outcome, real or perceived, is born not of an adversarial attitude but is essentially the inevitable consequence of resource constraints imposed on the Department as a whole. With the help of our main customers we have in fact established a very clear, and mutually agreed, strategic framework for the role and scope of activities of GSWA in enhancing and promoting WA's prospectivity.

Have we effectively communicated this role upwards? It is hard to say. Had you asked me at budget time last year, I would have said yes. We certainly had reasonable opportunities to explain to both the Minister for Mines and the Under Treasurer the nature of the critical strategic issues we intended to address and the scope of our proposed programs. These included, the need for additional resources in the area of Data Management and Information, and the construction of Core Library facilities. Nonetheless, in spite of a generally sympathetic hearing, and of what we believe were strong representations by industry, budgetary constraints at State level frustrated the realization of our plans. I wonder if it was a case where we needed 10, asked for 5 and got 0.5. It may be that both the Director General and I need to regroup and reconsider our funding strategies. We also must develop new and more effective ways to acquaint Government with our strategic plan, and also to persuade them as to the importance of our mission.

In the event, the Consolidated Revenue Funding (CRF) allocation for GSWA for 1995–96 increased only marginally, by $0.5 million from the previous year, to $12.5 million. This figure included funding for a basic work program of geoscientific mapping, mineral and petroleum resources assessment and exploration-data management, hydrogeology and groundwater resources exploration and assessment.

This budget also included funds for the continuation of the following exploration-incentive initiatives:

- 'Accelerated geoscience mapping' initiated in 1993–94, $2.5 million p.a., and
- 'Petroleum exploration initiatives' initiated in 1994–95, which increased from $2.5 million to $3.0 million p.a. in accordance with the original Cabinet decision.

At the end of 1995, the Hydrogeology and Groundwater Resources Branch was severed from the GSWA and consolidated in the newly formed Water and Rivers Commission (WRC) of Western Australia. This instrumentality was created as a consequence of the breakup and corporatization of the utility functions of the Water Authority of WA, to manage both surface and groundwater resources of the State. With this split, some 18 GSWA professional officers and 16 support officers were transferred to the WRC together with a budget equivalent to approximately $1.7 million p.a. An additional 11 staff on external funding were also transferred. Ten support officers in DME were offered voluntary severance including three in the GSWA.

The process of untangling people financially, physically, and intellectually was complex after such a long and successful association of the Hydrogeology Branch with the GSWA. Many ties nonetheless remain between GSWA and the Hydrogeology Branch of the WRC. These range from arrangements to complete and publish work which was in the pipeline at the time of the separation, to assisting WRC in the area of digital mapping and GIS until they establish their own facilities.

As I have already mentioned, there is no doubt that the Director General continued to have a very significant influence on the GSWA becoming better focused, not only on a year-by-year budgetary scale, but in the medium- and long-term strategic dimensions. Emphasis in the former is on efficiency, whereas in the latter it is primarily on effectiveness and outcomes. Furthermore, until now, we had not been in a position to quantify what proportion of the current investment in GSWA was directed to each of its two main strategic objectives and related components, i.e. the:

- enhancement of the State's prospectivity, and
- provision of data and information services to industry and the community.

This information is crucial to achieving an appropriately efficient allocation of available resources between projects that support exploration for:

- minerals, and
- petroleum and fossil fuels.

Similarly, to address the question of currently insufficient industry exploration investment in base metals, an appropriate split must be reached between:

- active and producing areas, and
- greenfields.

There is of course no magic available standard as to what the optimal mix of activities should be. A first step in the process, however, was to quantify what the current split is and to assess, in a subjective manner, how comfortable our industry advisers and we in GSWA felt about it. From this starting point one can then attempt to address in successive plans and budgets, any shift in emphasis that may reflect the collective perception of industry's changing needs.

This process was commenced in 1995–96 with the compilation of the first of our strategic matrices (Table 1) depicting what proportion of the expenditure planned for each project contributes to different strategic objectives. Consultation with industry and the Geological Survey Liaison Committee (GSLC) indicated that:

- our allocations were approximately correct, and
- slightly more emphasis should be placed in the future on more effective management of our data and information.

The split in resources on the basis of 63% for prospectivity enhancement versus 37% for data management and information is generally considered in tune with current industry needs and expectations.

The 2:1 ratio of resources devoted to mineral-exploration support vis-a-vis that for petroleum is also considered appropriate when it is considered that the bulk of the latter is devoted to the onshore basins of WA.

Geoscientific information provided for State development appears, deceivingly, on the low side as some of the work which is carried out by GSWA at the behest of other agencies tends to be funded by them, and is not therefore reflected in GSWA's CRF budget.

While conscious of its subjectivity and limitations, this broad-brush approach has proved extremely useful, not only in ensuring that the GSWA program is cast in a manner consistent with the broad program and strategic objectives set by Government, but also in effectively communicating the plan to our main stakeholders.

Fiscal 1995–96 was a stable year as far as staff movements were concerned. The Survey was essentially at its full complement and only towards the end of the year did we lose our Chief Geophysicist, Mr Greg Steemson, who rejoined private enterprise. There were also a number of retirements including long-serving key geoscientists such as the Assistant Director Regional Geoscience Mapping, Mr Peter Dunn, who was replaced by Dr Tim Griffin, and the Chief Geoscientists for Mineral Resources, Mr John Blockley, for Geochemistry Dr Richard Davy, and for Hydrogeology and Groundwater Resources Dr Anthony Allen. Of significance also was the retirement of key

Table 1. 1995–96 Regional Geoscience Mapping and Information project contributions to the strategic objectives of the Geological Survey of Western Australia

Strategic objectives				*All figures as $000*
ENHANCEMENT OF STATE PROSPECTIVITY *Gathering of new data and use of information* $6 690 63%	Minerals $4 508 42%	Active areas $1 831 17%	Precious metals	*704*
			Base metals	*613*
			Ferro-alloys	*463*
			Non-metallics	*52*
		Green fields $2 676 25%	Precious metals	*873*
			Base metals	*1 410*
			Ferro-alloys	*353*
			Non-metallics	*39*
	Petroleum and coal $2 183 20%	Producing areas	4%	*437*
		Frontier areas	16%	*1 746*
		PROSPECTIVITY ENHANCEMENT	**Subtotals**	*6 690*
INDUSTRY AND COMMUNITY INFORMATION SERVICES *Management, and provision of data and information* $3 976 37%	Exploration and resource information for exploration concept formulation and strategy $1 866 18%	Minerals		*1 178*
		Petroleum		*688*
	Legislation and title advice $276 3%	Minerals		*222*
		Petroleum		*55*
	Information for State development, land use planning and R&D $1 833 17%	State development		*453*
		Land access		*448*
		Research, development and education		*933*
		INFORMATION SERVICES	**Subtotals**	*3 976*
		TOTALS 1995–96 BUDGET		*10 666*

players in the cartographic and petrographic sections such as Mr Alan Smith and, more recently, Mr John Lewis. With them all went a wealth of experience and information gathered, in some cases over a period of service in excess of 30 years. Their departure, however, has opened new challenges for the 'younger turks', who will initially be making up for experience with sheer energy and enthusiasm.

During the year, GSWA also secured the services of Dr Rick Rogerson, who joined us from the Papua New Guinea Geological Survey to take up the key role of Chief Geoscientist, Mineral Resources.

Staff movements are reported in detail elsewhere in this publication.

The level of technical activity carried out by GSWA during 1995–96, including the publication of 22 geological and 4 geochemical maps, 21 Reports, and Records, and significant geophysical surveys and stratigraphic drilling, was at an all-time high. The relevant achievements for 1995–96 are summarized below:

- by geoscientific projects and information services,
- then grouped in terms of type of activity.

This summary captures the bulk of, but by no means all, GSWA's activities for the year. It does not for instance recognize significant output of scientific papers not published under GSWA cover, field excursions, presentations at conferences, technical advice to industry and government, overseas consultancies, university courses, etc.

Geoscientific projects

King Leopold and Halls Creek Orogen

A summary geology map of the King Leopold Orogen in the West Kimberley Region was published at the scale of 1:500 000, together with a 1:100 000 sheet (MOUNT REMARKABLE) in the Halls Creek Orogen.

During the year fieldwork and map preparation were completed on a further three 1:100 000 sheets (BOW, TURKEY CREEK, MCINTOSH) and two 1:250 000 sheets (MOUNT RAMSAY, LISSADELL) in the Halls Creek Orogen.

Lennard Shelf and Shark Bay

Field mapping of the Devonian Lennard Shelf reef complexes, and examination of core from the Cadjebut and Blendevale Pb–Zn deposits were completed. The fruits of this long and detailed study will now be compiled by Dr Phil Playford and his team into an ambitious Bulletin.

Studies of the Hamelin Coquina progressed.

Pilbara Craton (NGMA)

Airborne aeromagnetic and radiometric data (totalling 77 000 line kilometres at 400 m spacings) and images of the west Pilbara were collected in partnership with AGSO under the banner of the National Geoscience Mapping Accord (NGMA).

Four 1:100 000 sheets (PEARANA, ISABELLA, BRAESIDE, ROCKLEA) were finalized and published, with a further 1:100 000 sheet (SHERLOCK) being prepared for publication. Fieldwork on this project will continue to the year 2000. Two 1:250 000 sheets (ROY HILL, MOUNT BRUCE) were being printed at year end.

Glengarry Basin

Field mapping and map compilation on eight 1:100 000 sheets (BRYAH, DOOLGUNNA, MOUNT BARTLE, THADUNA, MOOLOOGOOL, GLENGARRY, PADBURY, MILGUN) were completed on this 'Accelerated Mapping Initiative' project. Considering that this project has only been active for under 3 years, a very satisfactory rate of map production was achieved with no deterioration in quality of our final products. This success has been partially attributable to the adoption of more stringent project management techniques. Work on this basin will be completed next year.

Eastern Goldfields (NGMA)

Five 1:100 000 geological map sheets (GINDALBIE, RIVERINA, DARLOT, DUKETON, SIR SAMUEL) were published together with one 1:250 000 sheet (KURNALPI) and one 1:1 000 000 sheet (ESPERANCE).

Publication of the Kurnalpi–Edjudina Terranes map, 1:250 000 scale, has attracted interest from industry and will no doubt stimulate further exploration in this region.

Field mapping was completed on two 1:100 000 sheets (WILUNA, MILLROSE).

Regional airborne geophysical data, images and magnetic-feature maps were collected in partnership with AGSO and released for two 1:250 000 sheets (DUKETON, SIR SAMUEL).

Paterson Orogen

No fieldwork was carried out in this region with the bulk of the effort being devoted to publication of two 1:100 000 geological sheets (THROSSELL, RUDALL). Completion of this project has been deferred until resources can be released from the Pilbara Craton project or additional funding secured.

Bangemall and Gascoyne regions

A total of 150 000 line kilometres of aeromagnetic and radiometric data (at 500 m spacings) was acquired as part of a major multi-client survey to support future regional geological mapping. This was precipitated to some degree by GSWA's participation, even though to a modest financial level. As a result, an embargo exists as to the timing and scope of any release.

Regional regolith geochemical mapping

This component of the 'Accelerated Geoscientific Mapping' initiative has progressed very satisfactorily resulting in the publication of regolith geochemical maps, reports and datasets for four 1:250 000 sheets (LEONORA, GLENGARRY, PEAK HILL, SIR SAMUEL).

Contract sampling, analysis, and map preparation on two 1:250 000 sheets were also undertaken (MOUNT PHILLIPS, NABBERU). In the case of NABBERU, consultation with, and the assistance of, local Aboriginal Communities were required in ensuring that in the completion of its work GSWA did not impact on sites of traditional or heritage significance.

Geological map of WA

A digital version of the 1988 Geological Map of Western Australia at a scale of 1:2 500 000 was released.

Petroleum studies — interior sedimentary basins

During the year this component of the 'Petroleum Exploration Initiative' got into full swing with the completion and release of the Savory Basin gravity survey. This helicopter-supported survey included 2300 stations forming a 50 km wide, 150 km long, northeast-trending transect across the Savory Basin to help unravel its basinal morphology and thickness of the sedimentary rock succession.

This was followed by a continuously cored stratigraphic well (Trainor 1), which was drilled to a depth of 709 m after penetrating 83 m of Neoproterozoic sedimentary rocks overlying deformed and altered sedimentary rocks of as yet unknown but probably Middle Proterozoic age.

Work in the Canning Basin comprised a comprehensive scoping study with field activities confined to the completion of structural mapping of potential reservoirs in ?Permian sediments of the Barbwire Terrace.

Petroleum studies — western margin sedimentary basins

Aeromagnetic/radiometric (44 800 line kilometres) and gravity data (4000 stations) and images for the Merlinleigh Sub-basin of the Carnarvon Basin were released to industry.

Reports and articles were also published on the hydrocarbon potential of the Merlinleigh Sub-basin, and two stratigraphic wells, Ballythanna 1 and Gneudna 1, were completed on its eastern margin. These stratigraphic drillholes were terminated at 466 m and 492 m respectively with the type section of the Devonian Gneudna Formation and the Upper Permian Wooramel Group having been cored. Geochemical analyses indicate that reasonably prospective oil source rocks may in fact exist in this sub-basin.

Other activities

In addition to ongoing projects the following activities were completed:

GIS aeromagnetic surveys catalogue

During the year a GIS index of digital regional airborne geophysical data for WA was initiated and GSWA is now in the process of formulating and agreeing with industry on a voluntary policy whereby GSWA would become the custodian of broad-range surveys carried out by industry. These broad-range surveys are not necessarily reported to Government as they are not covered by the reporting requirements of the Mining Act for more areally restricted tenements.

Geochronology

Two reports on SHRIMP U–Pb zircon data for 102 samples from the Eastern Goldfields, Paterson Orogen, Rudall Complex, Leeuwin Complex, Narryer Gneiss Complex, Pilbara Craton and Albany–Fraser Orogen were published.

Further samples have been collected and prepared for dating from the Eastern Goldfields, Pilbara and Glengarry Basin.

Resource studies

MINEDEX, the comprehensive database of the mineral resources of the State was maintained and updated as the key source of information from which to generate a range of products (e.g. Mineral and Petroleum Resources Atlas, reviews of exploration and mineral potential in WA, etc.), and as the basis for numerous briefings and requests for advice.

Regional mineralization studies

Reports on the mineral potential of the Archaean, Pilbara and Yilgarn Cratons, and on the geochemistry of granitoid rocks of the Eastern Goldfields were completed together with publication of two related 1:100 000 geological map sheets (RAVENSTHORPE, COCANARUP)

Regional mineral data prospectivity enhancement

A GIS spatial index of exploration activity for the north Eastern Goldfields was completed. This represented a very valuable pilot study for the planning of new projects in the context of prospectivity enhancement in other regions.

Industrial mineral studies

A report on the raw materials of Shark Bay was published and another, on WA talc and magnesite resources, was compiled.

Publication and promotion

Aside from maintenance and development of an efficient, high-quality map and document editorial service, two new promotional publications were introduced. These are the Annual Review of GSWA and the GSWA Quarterly Newsletters.

Computer-assisted map production (cartography) and digital drafting

Provision and maintenance of an efficient, high-quality digital map production and drafting facility improved during the year as a consequence of more stringent project management and process improvements. In many respects a fair proportion of GSWA's total productivity improvement is attributable to initiatives in these areas. Publication of the Atlas of Western Australian Mineral Deposits and Petroleum Fields, which was very well received by industry, marked the first product totally derived as a managed dump and marriage from MINEDEX and CAMP databases. During the year new techniques for integration of graphic files of various provenance were also developed and tested with publication of GSWA's mineral and petroleum prospectivity promotion posters. Both the Atlas and the posters have been much in demand for inclusion in various Mining Register publications.

Geographical information systems

The GSWA is growing increasingly dependent on provision and maintenance of an efficient, high-quality GIS facility. There is no doubt that, with time, we will evolve into the field of suitably scaled seamless maps of selected terranes. This transition is being facilitated by the experience gained in producing the Regolith Geochemistry Map packages totally in a GIS environment. Development of spatial indexes in GIS to aerial photography, airborne geophysical data, and exploration activity will provide customers with yet another, and hopefully efficient, way of accessing our databases.

Information service

The volume of work increased during 1995–96 in these areas, very much in tune with the rapid growth in exploration activities throughout the State. Highlights of activities in this area include:

Geoscience information library

- provision and maintenance of an efficient, high-quality library facility with an improved system for journal circulation, and introduction of a new News Bulletin via e-mail

Mineral exploration data (WAMEX)

- introduction of improved guidelines for reporting of exploration activities
- introduction of Internet access to WAMEX

Petroleum exploration data (WAPEX)

- ongoing capture and provision of petroleum exploration data

Geoscientific advice relating to mining legislation

- ongoing advice relating to definition of project areas, extensions, expenditure exemptions, and recommendations on exploration and mining tenements and revision of reporting conditions including Operations Report: Expenditure on Mining Tenements (i.e. Form 5)

Laboratory and field support

- development of safety and quality procedures in field and laboratory support including improved zircon separation and preparation techniques.

You will have to agree that 1995–96 was a very productive year. In part, this was due to more stringent project management bringing about the completion of a lot of work in the pipeline, and many projects that commenced in 1993–94, in the context of the new State Government's exploration incentive initiatives, starting to bear fruit. Industry feedback indicates that these GSWA projects are providing them with new, regional-scale field data vital to putting their work into context and in generating new exploration concepts.

In 1995–96, because of improved project management, every employee of the GSWA also started to truly identify with, and to feel accountable for, his or her effort in the context of completed products, not just in terms of individual contribution. The commitment shown by all staff to meeting our clients' needs and to maintaining quality in a time of change and of greater pressure to produce has been most impressive.

Meeting milestones and performance targets under trying circumstances proved to be a pleasant and stimulating outcome despite the initial feelings of many that counting only finished products ready for sale was a somewhat Draconian way of establishing productivity levels.

We have become more organized and disciplined. By and large we work harder but above all smarter.

I am sure that deep inside, every employee of GSWA knows, whether they are too modest to admit it or not, that we really have the capacity to fulfil our vision of becoming the international benchmark for the delivery of high-quality geoscientific products and services to industry, government and the public, making WA the focus of international exploration.

A history of hydrogeology in the Geological Survey of Western Australia 1888–1995

by A. D. Allen

Background

On 1 January 1996 the Hydrogeology and Groundwater Resources Branch of the Geological Survey of Western Australia (GSWA) was officially merged with the Waterways Commission and part of the Water Authority to form the Water and Rivers Commission (WRC), responsible for allocation and management of the State's water resources.

Planning to separate the regulatory and utility parts of the Water Authority to form the WRC commenced in 1993 and culminated in March 1995 when a submission to form the WRC was presented to State Cabinet. This document proposed a two-stage process involving initial restructuring of relevant areas of the Water Authority and later, if considered desirable, incorporating the Waterways Commission and the Hydrogeology and Groundwater Branch of the GSWA into the WRC.

Instead of a staged merger Cabinet decided to merge the various organizations from the outset. The Geological Survey objected to the merger on the grounds that although merging the groups into one agency appeared logical, they actually had very different activities. Considering the level of understanding of the State's groundwater resources and the geoscientific nature of the work, it was questioned whether it was appropriate for a major part of GSWA to join with an organization dedicated mainly to water planning and management. The Geological Survey suggested continuation of an existing system of staff secondment to the WRC, at least until hydrogeological mapping and reconnaissance assessment of the State's groundwater resources were completed.

Following a meeting with affected staff the Director General of the Department of Minerals and Energy confirmed that the Hydrogeology and Groundwater Resources Branch (hereafter referred to as the Section) would merge with the new organization from the outset. Ensuing concerns raised by the mining industry and consultants were allayed and there followed nine months of intensive work to facilitate merging of the groups, and to ensure an appropriate structure was in place for the Section to continue its work. The Section moved to the WRC on 16 December 1995, and officially commenced in its role as part of the new organization on 1 January 1996. This marked the end of 107 years of groundwater investigation by the GSWA, and the loss of a large and specialized group of geoscientists that had been part of the Geological Survey since 1957.

The role and contribution that the GSWA (in particular) and the Department has played in defining and obtaining the present understanding of the State's groundwater resources is not well known. This account is intended to provide a brief outline of the events that shaped the Section, and of its major achievements.

Importance of hydrogeology

Hydrogeology is the study of groundwater as a resource, a component of the environment, and an agent in geological processes. Hydrogeology is also an important factor in the design, construction and operation of many mining and engineering projects. Groundwater is generally considered to be a mineral — part of a natural cycle that embraces the ocean, atmosphere and land. It is a mineral that differs from others in that it can flow through permeable rocks and is a renewable resource replenished by rainfall.

Groundwater in variable quantities and of variable quality is hidden beneath the land surface in a wide variety of rock types and geological situations — hence the role of geoscientists in locating groundwater resources.

In Western Australia, with an area of 2.5 million square kilometres and arid to semi-arid conditions prevailing over about 60% of the State, groundwater is particularly important. Large surface-water resources are at opposite ends of the State in the extreme north and southwest. In contrast, the occurrence of groundwater is widespread throughout the State but varies considerably in quantity, salinity, and extractability.

Groundwater has been used extensively in Western Australia since the commencement of European settlement in 1829. It has been used for private and public domestic supplies, the establishment of the pastoral industry and many mining projects, irrigated agriculture, and the construction of various strategic facilities and infrastructure such as railways, roads and pipelines. Currently, almost 50% of all water used in Western Australia is obtained from groundwater.

In common with other mineral and petroleum resources, groundwater belongs to the State. However, except for local projects, there is no commercial incentive for the private sector to explore or exploit groundwater resources. Consequently, because of the essentially geological nature of the work, the location and assessment of the State's groundwater resources has historically been the role of the Geological Survey.

The contribution of the GSWA in this strategic work is not widely known. This is because the Department has never had statutory responsibility for groundwater matters and, as a result, most public comment on groundwater-based issues has been made by other agencies, generally using information obtained by the Section. Nevertheless, the work of the Section provides the main reference on groundwater matters and underpins our present understanding and management of the State's groundwater resources.

The role of hydrogeology in the Geological Survey from 1888 to 1957

After first settlement in 1829 the struggling colony of Western Australia looked to mining, especially the location of gold or coal, as a means of improving its economy. For this purpose the Government employed several 'Government Geologists': F. von Summer (1882–1885), H. Y. L. Brown 1870–1872), and E. T. Hardman (1882–1885). Hardman produced the first known major report on groundwater in Western Australia ('Report on the probability of obtaining a water supply for the city of Perth from artesian wells with remarks on other possible sources') for a Parliamentary Committee enquiring into options for Perth's water supply.

Subsequently, and following considerable political debate, it was decided to appoint a permanent Government Geologist. The position was initially offered to Hardman, who died before he was able to take it up. Eventually, H. P. Woodward was appointed the first permanent Government Geologist and commenced work in January 1888.

The Government Geologist first operated from the Department of Crown Lands, but was later transferred to the Geological Branch of the Department of Mines when it was formed in 1894. When Woodward resigned in 1895, he was replaced by A. Gibb-Maitland (1896–1926) whose appointment followed the rich gold discoveries in Coolgardie (1892) and Kalgoorlie (1893). In this climate he was able to formally establish the Geological Survey of Western Australia along lines, and with objectives, which have largely endured to the present day.

In the Annual Progress Report of the Geological Survey for 1896, Gibb-Maitland outlined what he believed were the principal objectives for the Geological Survey, which included a role for groundwater. He stated:

The organisation of a Geological Survey

'At the request of the Minister for Mines I drew up a report upon this subject, and showed that the principal object of a geological survey is to prepare geological reports and maps, such as can be used by the Government and the public in dealing with all general questions which may arise in connection with mining, water supply, agriculture, and other industrial pursuits. In a country which depends so much upon its mineral wealth, the survey must, of course devote itself to those problems in economic geology which it is essential should be solved — if that be possible — without, however, neglecting purely scientific questions; for the economic and scientific aspects cannot be entirely separated'

Early contributions

When the Geological Survey was formed, much of the State was unexplored and access into remote areas was very difficult, mainly because of lack of water and reliance on animals for transport. Hydrogeological work advanced chiefly as a result of mapping the sedimentary basins and from data from exploratory bores after the introduction in the mid-1890s of drilling rigs capable of drilling deep bores. During this period many of the projects involving exploratory drilling were of considerable State significance and consequently the Government Geologist was often directly involved.

When H. P. Woodward (1888–1895) was Government Geologist, he travelled extensively throughout Western Australia and mapped the outline of the major sedimentary basins. He wrote a Mining Handbook for prospectors in which he noted the probability of artesian water supplies in what are now referred to as the Canning, Carnarvon, Perth and Collie Basins, all of which, at least locally, have produced artesian groundwater. He is also credited with persuading C. Y. O'Connor to undertake deep drilling at Midland, the first utilization of artesian groundwater in the Perth region.

Gibb-Maitland, the longest serving Government Geologist, had a particular interest in groundwater and produced at least 40 reports on groundwater matters. Soon after his appointment he commented unfavourably on the deep drilling in the Coolgardie region for artesian water (Coolgardie Bore), after which a similar program at Kalgoorlie was abandoned and C. Y. O'Connor commenced planning of the Mundaring–Kalgoorlie pipeline. Gibb-Maitland worked closely with the Public Works Department providing advice and recording data from artesian bores drilled during a period of artesian groundwater exploration and development which lasted to about 1926. Notable work during this time was advice and reporting on bores drilled in the Eucla Basin for the Great Western Railway (Trans-Continental railway line), contributions to the Artesian Water Conferences, and the first report on the artesian groundwater resources in the State, entitled 'The Artesian Water Resources of Western Australia'. Also during this period, various passing descriptions on the availability of water supplies were made in GSWA reports to assist prospectors and exploration parties.

Following Gibb-Maitland's directorship, the periods when T. Blatchford (1926–1934) and F. Forman (1934–1945) were Government Geologist were affected by the Depression and the outbreak of World War II. During these times, only limited hydrogeological work was undertaken, of which the major components were advice on the availability of groundwater for the '1000 farms project' in the wheatbelt, correlation of the artesian bores in Perth, and sundry advice on gold-mine water supplies.

In 1945, H. A. Ellis (1945–1961) became Government Geologist during the period of post-war reconstruction, when there was an upsurge in mineral and petroleum exploration and in the demand for groundwater. Ellis took a personal interest in groundwater matters and under his direction the groundwater advisory role of the GSWA was expanded and work for other Government Departments was undertaken; in particular, for Carnarvon irrigation-water supplies, subsidized waterbore drilling on cattle stations in the Kimberley, and for land releases. Also waterbore siting for pastoralists and farmers was provided. During this period the first maps of the water resources (artesian bores and wetlands) and basic raw materials in the Perth region were published. Ellis recognized the importance of groundwater to State development and also the necessity for the GSWA to undertake groundwater work, which led to the establishment of the Hydrogeology Section and to hydrogeology becoming a major activity of the Geological Survey.

Specialization and growth of hydrogeology (1957–1995)

Formation of the Hydrogeological Section

In 1957, in response to demands being made on the GSWA and in recognition of the importance of groundwater in Western Australia, Ellis obtained Ministerial approval to establish a special section to undertake groundwater exploration in Western Australia. This was reported in the GSWA Annual Report for 1957 as follows:

> ***Hydrological Section***
>
> *'Ministerial approval was given towards the end of the year for the formation within the Geological Survey Branch of a special section whose work would be confined to underground water exploration. Two Ruston-Bucyrus water boring percussion plants were added to the equipment of the Mines Department's Drilling Section, and early in 1958 exploratory boring will take place in the Hill River Area on partially developed agricultural lands, privately owned. It is anticipated that the activities of this section will gradually expand until underground water is recognised as being of high priority in the economy of the State. Suitable additional staff have not been available and the additional work will be carried by existing staff.'*

This is considered to be the formation of the Hydrogeology Section in the GSWA and the formal commencement of hydrogeological work on behalf of the State.

In 1961 J. H. Lord (1961–1980) became Government Geologist (later re-titled 'Director'), and reorganized and expanded the Geological Survey. He also recognized the importance of groundwater and, as part of the reorganization, increased the staff and replaced the Hydrological Section with the Hydrology and Engineering Geology Division, which was split into separate Hydrology and Engineering Geology Divisions in 1977. Later, following various reorganizations, the Hydrology Division was renamed the Hydrogeology Branch (1980), Hydrogeological Section (1984), and Hydrogeology and Groundwater Resources Branch (1995).

Subsequent Directors of the Geological Survey, A. F. Trendall (1980–1986), P. E. Playford (1986–1992) and P. Guj (1992–), have all supported the activities of the Section and the retention of hydrogeological work within the GSWA.

Departmental support

The invaluable support and co-operation of other sections of the GSWA and other divisions of the Department cannot be overstated. The availability of a wide range of expertise contributed significantly to the continuing work and achievements of the Section.

The GSWA undertakes diverse geoscientific work and has the most comprehensive in-house geoscientific expertise in Western Australia. This enabled the Section to have access to specialist geoscientists, particularly in the fields of regional mapping, sedimentary geology, geophysics and palaeontology. In particular, the Geophysics Section logged about 3000 bores with an aggregate depth of 900 000 m and the Palaeontology Section prepared some 1200 reports. These contributions greatly assisted the work of the Section, especially in the evolving understanding of the hydrogeology of the Perth Basin.

The Department made substantial contributions to the efforts in defining the State's groundwater resources through the Drilling Branch, Chemistry Centre of Western Australia (formerly Government Chemical Laboratories) and the Surveys and Mapping Division. The Drilling Branch worked as an arm of the Section, until the Branch was closed in 1990, and undertook or supervised most of the exploratory drilling for the Section, specialized bore construction and various testing procedures. The Chemistry Centre provided essential expert advice on water analysis and carried out over 12 000 standard analyses, many thousands of partial analyses, and analyses of groundwater contaminants, and assistance in the operation of a tritium and carbon-14 laboratory. The Surveys and Mapping Division undertook levelling and surveying of exploratory bores and produced thousands of diagrams and maps for reports: since 1991, their computer-aided drafting of hydrogeological maps has facilitated relatively rapid and cheap map production.

Leadership

When the Section was formed, it was under the leadership of K. Berliat (1957–1962) until completion of the reorganization in 1962. Following the changes, the work of the Hydrology and Engineering Geology Division came under the direction of N. J. Mackay (Deputy Director).

In 1963, E. P. O'Driscoll (1963–1978) was recruited from the Geological Survey of South Australia to lead the Hydrology Section. He held qualifications in both geology and engineering and possessed a national reputation in hydrogeology. O'Driscoll laid many of the foundations for the present Hydrogeology Section and made particular contributions in water-supply investigations and groundwater exploration and assessment. With his background in engineering he was able to establish firm relationships with the then Public Works Department (PWD) and Metropolitan Water Supply Sewerage and Drainage Board (MWSSDB) leading to close cooperation and a great expansion of hydrogeological work.

After O'Driscoll was promoted to Assistant Director in 1978, T.T. Bestow (1978–1984) directed the activities of the Hydrogeology Section. Under his direction activities of the Hydrogeology Section underwent considerable diversification. Work was commenced in groundwater contamination, land and stream salinization and hydrogeological mapping, and a laboratory for carbon-14 and tritium age determination of groundwater was established. Also various technical innovations such as drill-stem testing, and electronic recording of pumping tests were introduced.

Following the promotion of Bestow to Assistant Director in 1985, A. D. Allen (1985–1995) was appointed to lead the Section. Building on the established foundations, Allen oversaw a highly productive period of groundwater assessment, hydrogeological mapping, increased understanding of the processes of groundwater contamination, and publication. This was accomplished during a period notable for staff stability, and for the expertise of the hydrogeologists and supporting staff.

In 1995, the Geological Survey underwent a major reorganization, and the Hydrogeology and Groundwater Resources Branch administered by an Assistant Director, A. T. Laws, was formed. Laws accelerated the introduction of computerized map production, and the finalization of a computer database for bore and well records. In particular, he played a major role in negotiating the merging of the Section into the WRC.

Staffing

At the time of its formation, the Section was staffed by three geologists. Staff numbers increased to eight when it was reorganized in 1962 and, by 1976, had grown to fourteen. Commencing in 1994, contract staff were employed, and at the time of the merger into the WRC, the professional staff comprised 11 permanent and 10 contract hydrogeologists. The Section has also included up to five technical and clerical staff.

Since the formation of the Section in 1957 about 100 geologists employed by the GSWA have passed through the Section (listed in Annual Reports of the GSWA). Initially, many of the staff were geologists who spent only a short period in the Section. Those that stayed were guided by O'Driscoll and largely self-taught, until the late 1960s when training was provided by the

Australian Water Resources Council, through its groundwater schools. However, commencing in the mid-1970s, most recruited staff have had Tertiary qualifications in hydrogeology.

The Section has developed a national reputation and helped train and provide experience for a considerable number of hydrogeologists who have gone on to form consultant companies (e.g. K. H. Morgan and Associates, Rockwater, Mackie Martin and Company) or are senior managers or specialists in various consultant organizations. This has led to the formation of networks which have been very beneficial to groundwater development and management in Western Australia.

Accommodation

When the Section was formed staff were accommodated in the Western Australian Museum in Beaufort Street. Following the reorganization in 1961, they were resettled in a still-existing, pre-fabricated building on the Museum site in Francis Street. In 1964, to accommodate the increased staff, the Section was moved into an old church at the corner of Aberdeen and Museum Streets (now TAFE campus), where it remained until 1970.

In May 1970, the Section moved with the GSWA into the newly constructed Mineral House where it occupied part of the sixth floor. However, in August 1976, because of a shortage of accommodation for the GSWA, the Section was moved to Casablanca House (now Perth Ambassadors Hotel) at 196 Adelaide Terrace. It remained at this location until August 1981 when, on expiry of the lease, the Section moved to the Western Underwriters Building in 4–6 Bennett Street. In June 1983, yet another move took place, this time to 3–5 Bennett Street, immediately across the road.

In September 1987, the Section rejoined the main body of the GSWA and occupied part of the fourth floor of Mineral House North. The Section remained with the GSWA until the merger to form the Water and Rivers Commission, when it moved to the Hyatt Centre in Adelaide Terrace.

Function and structure

From the time of formation, the Section has worked to programs as well as performing *ad hoc* activities. Until 1980, brief descriptions of work programs and reporting of results were provided in the annual reports of the GSWA, and more-detailed information recorded on file. Subsequently, planning, reporting and budgeting gradually became more formalized in accordance with Public Service requirements.

Until 1982, the work of the Section had input into the GSWA geological mapping program, in which hydrogeologists were expected to do regional mapping to improve their geological skills and to acquire regional hydrogeological data. The Section also undertook work for the PWD, the MWSSDB and the Agriculture Department, Federal- and State-funded groundwater resources exploratory drilling (assessment) programs, and *ad hoc* work such as advisory services or bore location for drought relief.

In 1982, the detailed work programs changed to a rolling five-year program, which was subsequently incorporated into a larger Departmental work program. During the 1980s, the work of the Section underwent considerable diversification, and to guarantee the relevance and cost effectiveness of the work, the Hydrogeology Sub-Committee of the GSWA Liaison Committee was established in 1988. The Sub-Committee had broad-based representation and provided valuable input, and endorsement of the work program.

Until 1985 the Section was loosely structured. However, at that time a formal structure was introduced to meet the challenges of increasingly specialized and diverse work. The Section was divided into three sub-sections, each under the supervision of a senior geologist. The responsibilities of the sub-sections are shown in Table 1 and illustrate the scope of work of the Section. The subsections were renamed and reorganized in 1995, when in recognition of the importance and specialized nature of groundwater contamination studies, a new Division (i.e. sub-section) was formed.

Table 1. Structure and responsibilities of the Hydrogeology Section 1985–1995

Advisory services	*Resource assement*	*Metropolitan and town water supplies*
Groundwater advice	Groundwater assessment	Liaison with Water Authority
Landuse research	Hydrogeological mapping	Metropolitan and town water supplies
Pollution studies		Wetlands research
Isotope laboratory		Modelling
Bore record system		Groundwater management
Technical developments		

Major influences

The activities of the Section have been shaped by an imperative to develop the State. In addition, various historical and economic factors, together with State and National issues have played a role.

The Federal–State groundwater-assessment programs which ran from 1964–65 to 1985–86, and subsequent State groundwater-assessment programs (1986–87 to 1989–90 and 1993–94 to present), more than any other factors have resulted in the current level of understanding of the State's groundwater resources. During this period, small but assured funding of $0.5 m–$1.5 m/year was expended on exploratory drilling to help define the major groundwater resources, especially in the critically important Perth Basin.

Work for the PWD and the MWSSDB and their successor, the Water Authority, provided an invaluable opportunity for the Section to obtain hydrogeological experience from a wide number of areas in the State where public water supplies were being developed. In particular, the involvement of the Section in the detailed work relating to groundwater resources, and groundwater management in the Perth region, substantially improved the experience and expertise of the Section. This was achieved firstly by having staff directly responsible for work of the MWSSDB and later for the Water Authority. These arrangements worked well, facilitating close cooperation between hydrogeologists and engineers and enhancing communication between major organizations. The Section was able to provide continuity of hydrogeological experience when major changes took place with the formation of the Water Authority.

Numerous issues have influenced the scope, nature and direction of the Section's activities. These include bauxite mining in the Darling Range, land and stream salinization, interaction of groundwater and wetlands, groundwater for drought relief, groundwater contamination, availability of groundwater in major mining areas (Eastern Goldfields, Collie, Pilbara) and availability of groundwater supplies for Perth. The input of the Section into work of the Western Australian Water Resources Council, and into various reviews, management plans, environmental impact assessments and Landcare research, has also determined some of the activities of the Section.

Achievements

During its existence, the Section has undertaken a mix of strategic, practical and scientific work. The Section has outlined to varying levels of confidence, a major State resource, provided a consultative role to government agencies, and practical advice and data to the rural and mining industries and the general public. In parallel with the work of the GSWA as a whole, the Section has made a very significant, but not widely known, contribution to State development. Some of the major achievements of the Hydrogeology Section are outlined below.

Database of bores and wells

In the course of its early work, the GSWA accumulated data on artesian bores. More recently, over the last 40 years of routine geological mapping, specific bore-census programs and groundwater-assessment work, the Section accumulated a database of information from about 100 000 bores and wells from throughout the State. It has also acquired further bore and well data from the Water Authority and its predecessors, from mapping in the sedimentary basins by the Bureau of Mineral Resources (now Australian Geological Survey Organisation), oil companies (particularly WAPET), and from consultants, drilling contractors, and the general public. This is an invaluable database of groundwater knowledge for Western Australia.

For many years, these data were recorded on a punch-card record system. However, in 1993–94, Federal funding was obtained to incorporate these data into a computerized database. The database, which has been transferred to the WRC, allows ready access to data and, linked to a Geographic Information System, will permit ready plotting of information to assist requests for information, hydrogeological mapping, or research.

Reports on groundwater

Over the life of the Section, staff have compiled over 500 reports and papers on aspects of hydrogeology in Western Australia resulting from the groundwater-assessment program and various groundwater studies. These have been published in GSWA publications or in various conference proceedings. In addition there are accounts of the availability of groundwater, bore records and water analyses accompanying many maps and bulletins published by the GSWA. There are also over 3000 unpublished reports available to the public, mainly pertaining to local availability of groundwater.

Reports are available for all major groundwater investigations that have been carried out. These include reviews of the groundwater resources of the major basins in Western Australia, descriptions of groundwater-based town water supplies, assessments of the availability of groundwater for mining and management in the Kalgoorlie region and Collie (coal) Basin, and investigations of land salinization and groundwater contamination. These reports provide descriptive and quantitive data which underpin most of the current understanding and management of the State's groundwater resources. They reflect the evolving understanding of the State's hydrogeology and some of the major issues pertaining to groundwater in the State. A bibliography of published reports by the GSWA, and a bibliography of reports on groundwater by other agencies and individuals have been published by the GSWA and provide an invaluable source of information on groundwater in the State.

Hydrogeological maps

To mark the centenary of the GSWA in 1988, the Section published in the following year a hydrogeological map of Western Australia at 1:2 500 000 scale. This map was based on geological data obtained from the GSWA mapping program and on synthesizing and generalizing various hydrogeological data. The resultant map provides a broad overview of the State's hydrogeology and is considered to be one of the milestones in the progress of hydrogeology in the State.

The systematic hydrogeological mapping of the State at appropriate scales was first considered in the early 1980s. However, a full-scale mapping program was delayed by concerns about the acceptance and cost of the maps. The first 1:250 000 scale hydrogeological map (PERENJORI) was published in 1992. Subsequently DERBY, BROOME, KALGOORLIE, WIDGIEMOOLTHA, KURNALPI, BOORABIN and part of DUMBLEYUNG have been produced. The delay in producing the maps has to a degree been an advantage. With the adoption of computer aided-drafting, and computerization of the bore and well database, the speed and efficiency of map production has been increased and the cost considerably reduced. The production of hydrogeological maps is considered to be a vitally important strategic activity assisting planning, development and management of the State's groundwater resources.

Discovery of the Gnangara Mound and Blackwood Groundwater Area

The Gnangara Mound, located in the Perth region between the Swan River in the south and Gingin Brook 70 km to the north, is the largest known single fresh groundwater resource in Western Australia. The size, proximity to Perth, and low salinity of this aquifer make the Gnangara Mound one of the State's most strategic water resources. The Section commenced exploratory work in 1961 but it was not until 1981, after work by the Section in conjunction with the Metropolitan Water Authority that the full size and importance of the resource was realized. The Section (and other organizations) have continued work on better defining the resource, the role played by wetlands, and the vulnerability of the resource to groundwater pollution. The role of the Section in identifying and describing the resource, and contributing to its protection and management, is one of the major contributions by the Section to State development.

Second in importance to the Gnangara Mound was the discovery of the Blackwood Groundwater Area in the 'sunklands' between the Leeuwin–Naturaliste Ridge and the Darling Scarp in the southern Perth Basin. The size and quality of these resources has gradually been revealed by the groundwater-assessment program, mainly in the last ten years. The work has shown the presence of a major aquifer, over 1000 m thick, which contains very large, low-salinity groundwater resources. Although the resources in the area have not yet been fully defined, their location, size and quality constitute a major, strategically located, untapped resource for future water supplies.

Raising awareness about groundwater contamination

Until about 1970, it was common practice to dispose of industrial and septic effluents at any convenient site. At that time, the PWD introduced the licensing of effluent disposal. The Section was represented on the Effluent Licensing Panel and was active in investigating groundwater contamination arising from effluent disposal. Following this, the Section studied the possible occurrence of groundwater contamination from about 100 operating or closed landfill and liquid-waste disposal sites, and groundwater contamination in the Kwinana Industrial area. This was followed by the identification of about 300 actual or potential contamination sites in the Perth region, and later, over 1000 actual or potential groundwater contamination sites in the wider Perth Basin. The large number of unsuspected groundwater-contamination sites raised concern and, to assist planning, a map was published showing the vulnerability of the shallow groundwater in the Perth Basin to contamination.

This and other detailed work on contamination from agricultural activities and from beneath urban areas showed clearly the extent, scope and vulnerability to contamination of shallow groundwater resources such as the Gnangara Mound. This work (and later research by CSIRO) raised awareness about the vulnerability of groundwater and has contributed to proposed legislative changes to protect groundwater resources.

Identification of major fresh groundwater resources

The Section has made estimates of Western Australia's groundwater resources as part of national reviews in 1962, 1975 and 1985. Other reviews of groundwater in fractured rocks and in the sedimentary basins of Western Australia have also been carried out. However, probably the most important review was undertaken in 1992 at a time of widespread public debate about piping water to the Southwest from river systems in the Kimberley region. The Section was commissioned by the Kimberley Water Resources Development Office to report on the location and availability of the major fresh–brackish groundwater resources in the State. The study synthesized various sources of descriptive and quantitative groundwater data to show the approximate location of major aquifers and to provide estimates of the renewable resources which they contained. The key role played by geology and the unsatisfactory level of understanding about the State's groundwater resources were also highlighted. Time may show that this report changed the thinking about the importance and role of groundwater in Western Australia.

Outlining groundwater resources in the Perth Basin

Most of the State's population resides in the coastal area between about Geraldton and Augusta. Fortuitously, this coincides with the extent of the Perth Basin, which contains the largest known fresh groundwater resources in Western Australia (e.g. Gnangara Mound). The geological structure of the basin is complex and this affects the location and assessment of the groundwater resources in the basin.

The Section commenced assessment of the basin's groundwater resources in 1961 and completed exploratory drilling in 1995. The complexity of the basin and the cost of drilling necessitated a slow continuing investigation, the results of which now provide a general understanding of the hydrogeology. Reports on the progressive parts of the investigations have been published by the GSWA and underpin the groundwater management of the Perth Basin and are widely used and cited. A major undertaking is now required to synthesise the available data and provide a definitive description and updated estimates of the groundwater resources in the basin.

Determining groundwater resources in the Perth region

Since the formation of the Geological Survey, various contributions have been made to the developing understanding of the extremely important groundwater resources in the Perth region. The first major description of the shallow and artesian groundwater reservoirs to provide a general understanding of their occurrence and size was produced by the Section in 1981. This was followed in 1994 by a detailed and definitive account of the groundwater resources in the Perth region published in a GSWA bulletin. This represents the culmination of many years of intensive effort by the Section and is considered to be a major milestone in hydrogeology in Western Australia. These works underpin the understanding of the occurrence of groundwater in the Perth region, and provide the data for rational groundwater management.

Town water supplies

The Section has worked with the Water Authority and its predecessors and made a substantial contribution to the location and management of groundwater-based town and community water supplies. The main contribution has been to the Perth water supply but other major work has been the location of groundwater-based water supplies for Halls Creek, Port Hedland, Exmouth, Carnarvon, Geraldton, Morawa, Jurien and Esperance among others, and the extension of water supplies for Derby, Broome, Onslow, Northampton, Augusta and Albany. The value of this work in economic terms and the benefits it has provided to the community are very substantial and not generally known.

Land and stream salinization

The problem of land and stream salinization in the wheatbelt in southwestern Western Australia is well known. The Section, on its own or in cooperation with the CSIRO, PWD and the Department of Agriculture, embarked on early studies attempting to define the processes of land salinization and to quantify the contribution of groundwater to stream flow and the effects on the groundwater of various remediation experiments. However, from the late 1980s the work was undertaken mainly by the Department of Agriculture until the Landcare Program was introduced in 1993 and the Section, in cooperation with the Department of Agriculture, commenced hydrogeological mapping to facilitate regional understanding and local management of the problems.

The land and stream salinization problem is essentially hydrogeological, and the Section has made a significant contribution to mapping and to providing some understanding of the factors affecting salinization. However, in hindsight, it is probably unfortunate that the Section was not more active in hydrogeological mapping and obtaining a broad hydrogeological overview of the problem.

Advisory services

The Section has provided a free (or at notional cost) advisory service to the rural industry, and has located hundreds of bore sites as well as providing information on drilling and testing. Also, at various times, it has undertaken bore siting and supervision of test drilling for drought-relief water supplies in the Kimberley and in the wheatbelt.

Using the database of bores and wells and data from assessment projects the Section has provided an advisory service to industry, consultants and the general public. The Section has dealt with about 1000 telephone enquiries per year seeking advice on groundwater, and some 250 counter enquiries for water supplies, geological data, foundation conditions, mineral water, geothermal water, aquaculture and other diverse topics.

In addition to the Water Authority, the Section has provided technical advice to other Government agencies, in particular to the Department of

Environmental Protection, Health Department, Main Roads Department, Department of Agriculture, Department of Resources Development, and to some Commonwealth government departments and to local government. The advice has been provided on subjects such as groundwater contamination, water quality, water supplies, land salinization, availability of groundwater for industrial projects, and bore design, in the form of written reports and, particularly, by input into many committees and project steering teams.

This advisory role fulfilled by the Section has ensured that up-to-date and expert advice has always been provided to the Government and the general public. This is considered a major practical contribution which the Section has made to assist development within the State.

Conclusions

Since 1888 the work of the GSWA has gradually been revealing the geology of Western Australia. In parallel has been a developing understanding of the State's groundwater resources, particularly since the formation of a specialist Hydrogeology Section in 1957.

Water is a mineral, but statutory responsibility for its development and management has been vested with water agencies (currently Water and Rivers Commission). However, for pragmatic and historical reasons, expertise in groundwater has resided with the Geological Survey, which has undertaken groundwater assessment on behalf of the water agencies and has provided a consultative role on groundwater matters to Government and the public at large. For the GSWA, this role ceased on 1 January 1996 when the Hydrogeology and Groundwater Resources Branch (Hydrogeology Section) was merged with other agencies to form the Water and Rivers Commission.

The present understanding of the State's groundwater resources has resulted from foresight on the part of the GSWA and continuing cooperation with the various water agencies. Other major factors have been the contribution of the Department, in an era of relative stability in Government, and the small but assured Federal and State funding that has enabled the strategic groundwater-assessment program and associated work to proceed.

The work of the Section, reported in a system of publication and mapping used by the GSWA, has facilitated the dissemination and continuing accessibility of groundwater data. However, the data are incomplete because large areas of the State remain to be assessed to a reliable level. Nevertheless, notable achievements have been accomplished, in particular a broad understanding of the State's groundwater resources, a detailed understanding of groundwater in some key areas such as the Perth region, an overview of the severity and location of groundwater contamination in the Perth Basin, and publication of various hydrogeological maps, especially a small-scale map for Western Australia. In addition, very significant contributions to State development have been made by establishing a database of bores and wells, locating groundwater for town water supplies, and advice to Government and the public. There have also been several lost opportunities, particularly in regard to the contribution that might have been made to the problem of land and stream salinization, and in the further defining of the very large fresh groundwater resources in the Canning Basin.

It is debatable whether, at this point in State development and with the current understanding of the State's groundwater resources, the work of the Section should have been continued by the Geological Survey or will best be fulfilled by the Water and Rivers Commission. History will show whether a small geoscientific group can work effectively within a management-oriented organization, or whether the previous situation where the essentially technical work was conducted under the umbrella of the GSWA, with mechanisms for input into groundwater management, was the most practical and effective way of defining, and perhaps eventually managing, the State's vital groundwater resources.

Mineral exploration in Western Australia in 1995–96

by W. A. Preston

The minerals boom continues to dominate current and planned economic development in Western Australia. Sustained mineral discoveries are critical to the continuance of project developments, although a number of evaluations currently taking place are on deposits initially identified over the last 30 years. Although the glamour is being focused on value-adding, downstream processing of our minerals, these operations are essentially reliant on the availability of suitable minerals in the ground and their improved economic exploitability. Advances in process technology, gas-price deregulation in Western Australia and, very significantly for the Eastern Goldfields gold and nickel belt, wider gas distribution with the opening of the Goldfields Gas Transmission Line, are significantly impacting on project economics and changing in some respects the focus of the exploration effort. Mineralization that perhaps was not contemplated as having significant development potential just a few years ago is now attracting major exploration effort.

The geological setting of Western Australia has certainly provided a rich endowment of mineral wealth covering a variety of mineralization styles and mineral types. In some instances, such as base metals, the geological prospectivity is still to be defined. However, in many commodities, this is being realized, as can be seen in the value and range of mineral production. Western Australia's prospectivity is acknowledged by the level of exploration effort in this State. In 1995–96, the value of mineral production alone amounted to $11.3 billion, with a further $4.1 billion from petroleum. Western Australia is a very significant producer of gold, iron ore, bauxite–alumina, nickel, diamond, heavy-mineral sands products, salt, tantalite, and spodumene in a world market context.

To sustain this pre-eminent position, Western Australia has continued to attract a high level of exploration effort. In 1995–96, mineral exploration in the State was $520 million, an increase of 4.8% on the previous year. This extends a significant exploration high over a three-year period (Fig. 1).

Despite this solid position, problems of land access and uncertainties of security of tenure, in respect to native title throughout Australia, continue to be put forward as reasons for an increased percentage of exploration by Australian-based companies being diverted from Australia. This situation has further developed through the opening up of various developing countries for exploration (with unknown, but perceived prospectivity) and in many instances linked to incentives offered to attract investors.

This situation is to be expected also for the reason that Australian exploration companies have attained a remarkable level of success over many years in the domestic arena and developed advanced techniques and considerable expertise in the exploration search, making a wider worldwide arena a natural progression. Whether figures of 30–40% of the Australian companies' exploration dollar is a real worry cannot be determined while the exploration effort, at least in this State, is at such a high level and, in many sectors, the resource base to sustain long-term growth is relatively large.

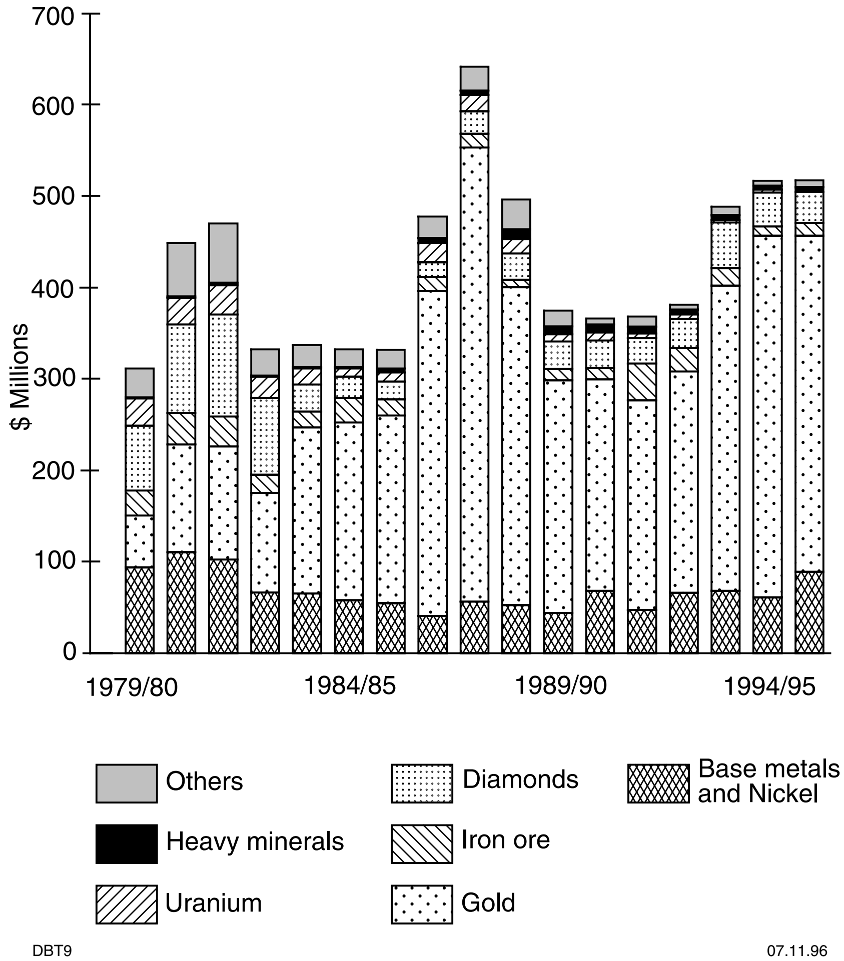

Figure 1. Mineral exploration expenditure in Western Australia by commodity sector (in 1995–96 AUS $)

Whilst Australia, as a region, occupies such an important position (2nd) in world mineral exploration with about 20% of the total, comparison with the major growth area, Latin America, puts into question this country's efforts to sustain a pre-eminent position. In just four years, between 1991 and 1995, the Latin American region has increased its mineral exploration expenditure nearly 3.5 times, and currently attracts nearly 30% of the global total.

Western Australia has consistently attracted over 50% of Australia's mineral exploration over the last 10 years. In the last two years, however, this figure has dropped 3%, to stand at just over 54% in 1995–96. A slight drop in the level attributed to the gold search, linked with increased copper–lead–zinc and diamond exploration in Queensland and the Northern Territory, could partly explain this but the lower than normal turnover and hence availability of mineral tenure in Western Australia, because of title-security issues, could be partially responsible for this decline. This may be particularly so for prospective new international entrants into Western Australian exploration, who would struggle to get a foothold in the State at a grassroots stage.

Performance in terms of exploration activity in the various mineral sectors has been quite variable over the year, with the major area of growth being in base metals, specifically nickel. However, gold exploration was still dominant, accounting for 71% of the total expenditure in the State, with base metals (including nickel) up from 12 to 17% and diamonds slightly down at just under 7%. Western Australia attracts the major part of the Australian exploration dollar in each of gold, diamond, nickel, iron ore, heavy mineral sands and uranium, and has a relatively substantial level of copper–lead–zinc exploration, despite a lack of success to date.

Gold

Gold production in Western Australia continues unabated. In 1995–96, production rose by 18 tonnes (t) of contained gold over the previous year to reach 206 t. Being traditionally the one sector with a relatively small long-term resource base, there is the need to sustain a high level of exploration. In 1995–96, gold exploration (with an outlay of $368 million) was slightly down on the previous year but, by a substantial margin, was still the major sector of exploration expenditure (71% of the State's total).

Commentators during the year referred to the worry of there having been no major gold discovery for over 12 months, until the comparatively modest half a million ounces Curara deposit at Kirkalocka, south of Mount Magnet, was announced early in 1996. It had come to be expected that a Kanowna Belle-, Chalice-, or Bronzewing-size orebody would be discovered at regular intervals and, if not, the explorers were failing. However, the tight availability of ground, the consolidations of holdings, and more effort concentrated around the centres of production has possibly meant more-effective use of the exploration dollar. Discovery cost is estimated at around $21/ounce for 1995–96. This is below the estimated average of about $25/ounce over the sixteen years of gold boom in Western Australia. At such rates investment in gold exploration continues to be very good value for money.

However, the State has little control over the vagaries of the gold price, and the effects on the exploration industry would be major if prices were to decline much more. Over-reliance on gold continues to represent a significant risk to the State's exploration, particularly as average costs continue to rise with increasing underground or deep-pit exploitation. On the positive side, significantly lower production costs are expected in the Eastern Goldfields as natural gas power generation is established.

The 1995–96 year will be seen largely as one of extending resources either below existing pit limits or around major centres of production, with the continuing trend of regional consolidation of activities. Three notable examples of this are in the Bullfinch–Southern Cross–Marvel Loch Belt where Sons of Gwalia's recent entry into the area has resulted in almost total amalgamation of the region, including the recent moves involving extension into the nearby Yilgarn Star operations. Another is Centaur Mining's takeover of Ora Banda to go with its existing interests in gold and nickel in the Mount Pleasant–Black Flag area. A third is the merger of the two major Coolgardie operations of Bayleys–Greenfields and Three Mile Hill.

The Eastern Goldfields continue to be the prime focus of activity, with discoveries in the Yandal Belt in the northeast further extending its recently identified massive potential. Operations started up at Jundee and Nimary during the year and exploration continues to delineate other prospective zones such as Plover Bore. The Darlot area has been the subject of some spectacular drilling intersections, in a new mineralized zone to the east of the mine area, of 33 m at 8 g/t and 59 m at 6.6 g/t at around 350 m depth.

Still farther to the east, the Duketon greenstone belt continues to attract significant renewed exploration activity, and both this northern area and that to the south of Laverton are now being intensively explored. The fruits of the last few years of exploration in the southern area are being realized with the development of Keringal and Sunrise, as part of the Granny Smith project, and now Sunrise Dam as a standalone development with resources of 3.1 million tonnes (Mt) at 4.2 g/t, plus another 5.0 Mt inferred resource.

Whilst a significant part of Eastern Goldfields exploration is at a relatively mature stage, new grassroots, conceptual exploration projects have emerged in areas previously considered to be unprospective. After the Yandal Belt at the beginning of the 1990s, the area around the Chalice discovery, on the west of the Pioneer Dome, was one such in the last couple of years. The Yilgarn Extension project, to the south and southeast of Norseman, is another to have emerged in the last year. Here, a complex geological setting with significant mineral potential is being postulated for an area of ill-defined greenstones on the edge of the Yilgarn Craton. This is still at a very early grassroots exploration stage.

The new Badgebup development near Katanning, in the Wheatbelt, is another modest example of gold potential in the southwest Yilgarn. However, the importance of this area is dominated by the Saddleback Greenstone Belt, with the Boddington and Hedges mines. After the phase of large-scale lateritic gold development, the extent of bedrock (basement) mineralization is now being delineated, with over 150 t of contained gold at 1.1–1.2 g/t identified below existing pits in the Wandoo, Pipeline and Diorite zones. This resource is seen as providing the long-term continuity of production from the Boddington area and is being planned for development.

The Murchison region has generally been an area in decline in recent years, with the closure of operations at Meekatharra and Gullewa. However, brighter events include the extension of resources to allow the Reedy operation to continue for at least another couple of years, development of the small Dalgaranga project, and the previously mentioned Curara discovery.

The Marymia Dome and vicinity continue to be a most productive exploration area, extending the massive gold resource potential of a locality discovered only over the last seven years. The Telfer region also continues as a focus of gold exploration.

One of the most active grassroots exploration areas in the last 12 months is in the Granites–Tanami, in the southeastern part of the Kimberley region, where successful discoveries in the Northern Territory are now being repeated in similar settings on the Western Australian side of the border. Several, moderate-grade, thick intersections of mineralization at shallow depth are being made, below a masking blanket of sand. The more advanced prospects are approaching resource definition stage.

Another area previously considered of only minor gold prospectivity, the Ashburton Basin, is providing some very significant drill intersections to the south of Paraburdoo.

Base metals

The combined exploration effort on base metals and nickel was $89 million in 1995–96, an increase of 50% over the previous year. It is estimated that the base-metal (copper–lead–zinc) search was relatively static with just over one-third of the total. All of the increased outlay is expected to have been in nickel.

Base-metal activity is spread widely throughout the State targeting a number of styles of mineralization. The dearth of huge economic discoveries over a long period of exploration, in what must be seen as favourable geological settings, has not been conducive to sustaining the required stimulus in Western Australia, in a commodity sector which is the prime exploration focus worldwide. It has been estimated that about 36% of investment for projects under evaluation globally is for copper.

The Panorama project, targeting copper–zinc–silver volcanogenic massive sulfide (VMS)-type mineralization in the North Pilbara granite–greenstones, continues to be a significant centre of attention. Eight mineralized areas have been identified and so far resources on the project total 11.4 Mt at 5.7% Zn and 1.8% Cu in the measured and indicated class, and a further 6 Mt of inferred resources at 12% Zn. The search has been broadened over a wider region.

The Kimberley region provides another focus for base-metals exploration. Drilling of VMS-style zinc–copper–silver mineralization at Koongie Park, near Halls Creek, has extended and upgraded the known mineralization, especially with new zones identified at shallow depth. With respect to Mississippi Valley-type (MVT) lead–zinc mineralization along the northern boundary of the Canning Basin, activities have been focused on development rather than exploration. The Goongewa mine has been developed and supplements Cadjebut output. Development is progressing to bring the larger Kapok orebody into production within the next year. Construction of an exploration decline has also commenced at the largest of the deposits in the area, Blendevale. It is geared to support a large underground drilling program and will also provide the base for any ensuing commercial development.

The redevelopment of oxide copper resources at Whim Creek and Horseshoe are being evaluated utilizing new process technology in leaching/solvent extraction/electrowinning for low-grade ores.

Elsewhere, exploration for large sediment-hosted base-metal deposits continues, most notably in the Rudall, Glengarry, and Bangemall regions. There is evidence that large exploration companies continue to actively review the potential of the Proterozoic sedimentary basins in Western Australia, despite a long history of searching with little success.

Nickel

The surge in evaluation and exploration effort to upgrade largely long-known occurrences for 'fast-tracking' to development further advanced in 1995–96. This is despite recent production capacity already increasing dramatically over the last couple of years to over 100 000 t per annum of contained nickel. The need to establish further early development is seen to be critical for market penetration, as the massive, high-grade nickel–copper–cobalt discovery at Voiseys Bay on the Labrador coast of Canada threatens to dominate new market supplies from the turn of the century.

In addition to detailed exploration around existing operations and major deposits, there is a significant amount of regional exploration being conducted throughout the known nickel provinces, such as the Wiluna–Leinster Belt, the Forrestania – Lake Johnston Belt, and farther north in the Southern Cross Province (north of Bullfinch).

Although of small size, the most significant new discovery in 1995–96 was the Silver Swan deposit, north of Kalgoorlie, where a very high-grade lens containing 440 000 t at 14% Ni has been identified. This deposit is already being developed and has created a rush of exploration activity in an area blanket-pegged previously for gold.

The large, low-grade deposits of the Northeastern Goldfields (Yakabindie, Honeymoon Well) continued to attract exploration and evaluation effort, with Yakabindie probably undergoing a more modest level of development initially, based on a comparatively higher grade (1% Ni) mineralized zone. Bioleaching technology is being looked at as a potential route for processing ore from the Maggie Hays deposit, in the Lake Johnston area.

However, the most notable impact of the nickel search and evaluation 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 process technology (long applied in Cuba) and cheaper power from the Goldfields Gas Transmission Line and suggests that lateritic nickel projects could potentially now be very cost competitive with sulfide operations.

Bulong, which has now been evaluated over a number of years, has been committed for development, whilst considerable effort is being expended on the Murrin Murrin – Central Bore deposits, to the east of Leonora, to realize a large-scale development. Although known to be a mineralized area for many years, resource delineation has been completed only in the last eighteen months. Resources now total 125 Mt at 1.02% Ni and 0.06% Co.

The Cawse lateritic nickel deposit has been discovered during palaeochannel gold exploration work in the last two years near Ora Banda. Extensive drilling has defined demonstrated resources of 53 Mt at 0.8% Ni and 0.05% Co. A further 140 Mt of inferred resources have been estimated. The project has quickly advanced to the stage of development.

Diamonds

The major cutback in diamond exploration in 1994–95 has steadied in 1995–96, with expenditure only slightly down to $33.8 million for the year.

The Kimberley region, both onshore and offshore, continues to be the main focus of activity at a number of defined target areas, with broader regional reconnaissance work being undertaken in the Yilgarn, Bangemall, Gascoyne and Pilbara areas.

In the Central Kimberley region, exploration continues on the large alluvial diamond potential in Police Valley, even though the Aries pipe has been shown to be uneconomic. The Beta Creek – Lower Bulgurri and the more recent Ashmore kimberlite discoveries in the King George River area of the North Kimberley region are providing encouraging expectations of a significant economic discovery in this field in the not too distant future. Striker Resources, the main operator in the area, has acquired most of the remaining land in the northeastern Kimberley, including the Pteropus and Seppelt diamondiferous pipes. These discoveries have attracted others to the region making the area the main focus of activity at present.

The Proto-Ord project near Kununurra has provided encouraging results with diamonds recovered from drilling, encouraging the operator to embark on plans for a large-scale bulk-sampling program. Calwynyardah, near Noonkanbah in the southwest Kimberley region, and the large alluvial tracts near Blina, are other areas where bulk sampling has recently been undertaken.

With respect to new areas, the region to the north and northeast of Kununurra is providing encouraging early-stage reconnaissance results suggesting a number of potential kimberlitic structures in the area.

Although diamond exploration off the North Kimberley coast continues to attract some press, and requires large expenditures in the search, the prospectivity of the region is still not defined despite the recovery of some diamonds within palaeochannel gravels. CRA has recently withdrawn from its farm-in ventures, but WMC continues its involvement. A drilling ship has recently returned to continue exploration in Cambridge Gulf.

The Bow River alluvial operation ceased at the end of 1995 after exploration had failed to identify further reserves. This leaves Argyle as the State's only producer. The decision whether to continue AK1 pipe production to exploit underground resources by the middle of the next decade is still to be made.

Iron ore

The reported level of iron-ore exploration in Western Australia indicated by ABS figures at $14 million for the year may be underestimated. The iron-ore sector is experiencing a very high level of interest, although a large percentage is in projects at the feasibility study stage and in developments of downstream processing (direct-reduced ironmaking and steelmaking). However, the level of acquisition of new ground in the Hamersley Basin is at its highest for many years, with commensurate exploration budgets.

A significant proportion of the exploration effort is on the search for low-phosphorus Brockman ores and detrital or screes ores in the Hamersley Basin. Detailed reserve definition is also being conducted on some of the large undeveloped deposits that are being assessed for development, such as Yandicoogina, Mining Area C, and West Angelas. There is a trend for the major producers to increase their diversity of products in the market to maintain and expand upon their market share and position themselves for the long-term future. As a result, a diverse number of mineralization types are being targeted in the exploration effort of all of the companies. This is particularly so for channel iron deposits, the ore from which has now gained a high level of market acceptability, and for Marra Mamba ores, which are seen as the long-term base of Pilbara production.

One of the integrated process-development projects, the Fortescue project, has for some years been promoting the use of primary banded iron-formation (magnetite-rich ores) to produce a very high-grade product, through beneficiation, suitable for the direct-reduction process. Further interest is being shown in primary ores, with exploration being conducted in Archaean greenstone belts of the North Pilbara and the western Yilgarn (Mount Gibson and Koolanooka).

Other minerals

Although at a low level of exploration activity ($5 million in 1995–96), Western Australia remains the major focus of expenditure in Australia for **heavy-mineral sands**. The relevant buoyant market, improved pricing for most of the mineral-sands products, and the need to replace depleting operations have led to a number of new developments proceeding. Construction at the large Beenup deposit, near Augusta in the Lower Southwest, is now nearing completion for a planned output of 600 000 t per year of concentrate products. Because of the low titania of the ilmenite, the project is being developed for a processing joint venture (titania slag → pigment) with a Norwegian partner. Replacement developments near Capel, the Maidment and Higgins deposits, are underway, and plans are in progress to re-open the original Yoganup mine and develop two new operations farther to the north, near Roelands and Yarloop.

For a number of years, green fields exploration effort has concentrated in the Lower Southwest and near the South Coast with considerable success. This success has continued with identification of another deposit, at Metricup, north of Cowaramup.

A consolidation of the two **manganese ore** operations in the East Pilbara under a single ownership took place during the year. Much of the focus has been in the definition of metallurgical-quality ore zones to support the short- and medium-term production plans.

Policy change at a Commonwealth Government level has enabled **uranium** projects to be considered for development. At this stage, the large Kintyre deposit, in the Rudall River area, is the only one being actively promoted. Moreover, there does not appear to be any increase in uranium exploration in the State, which has for some years been at a low 'holding' level.

A number of **industrial mineral** and **semi-precious gem** prospects continue to be evaluated around the State, with some of the more significant involving kaolin, limestone, gypsum, diatomite, silica sand, graphite, pigments and dimension stones.

Summary and conclusions

This commentary has highlighted the high percentage of the Australian exploration budget being spent in Western Australia. This budget is overwhelmingly geared towards the search for gold to satisfy the need to sustain an unprecedented production base. The discovery cost of gold is relatively low and resources inventory, at greater than 10 years of supply at current production levels, is very high compared with historical levels. Interest in this sector continues to be very high and there are no signs of any changes in the short to medium term. The over-reliance on gold puts the exploration sector at significant risk on the vagaries of an unpredictable commodity.

The large resource bases of bauxite and iron ore are adequate to sustain long-term production. Accordingly, exploration expenditure is relatively low considering the size of these sectors. However, in the case of iron ore, high-quality ores on which the large production base developed are now in limited supply and the search continues for replacements and increasing diversity in product types to give a wider spread of market outlets.

The discoveries of the nickel boom in the late 1960s – early 1970s are now realizing their potential with a massive increase in nickel production capacity. However, an upgrading to exploitable resource evaluation levels is required as well as exploration on many occurrences which are now coming into economic consideration as new technologies develop. Exploration expenditure substantially increased over the last year, with an emphasis for development on lateritic nickel ores.

In the other base metals (copper, lead and zinc) the geological settings suggest that Western Australia could host a variety of types of mineralization. However, large base-metal orebodies are yet to be discovered in this State. The prospectivity is still far from being realized and to an extent the search has been less intensive in recent years.

Economic diamond prospectivity is very difficult to predict. Western Australia has been shown to possess a number of diamondiferous pipes and alluvial concentrations. However, apart from the unique AK1 lamproite pipe, no major bedrock deposits in either areal extent or grade have been shown to be economic to date. As a result diamond exploration expenditure has been down for the last two years. The North Kimberley Field appears to provide the most prospective area for a significant discovery.

Whilst discovery, prospectivity, the fiscal rules of mineral legislation and fair, efficient and effective mineral title allocation are key factors in attracting exploration to a region, it must be acknowledged that security of title and access to land are having an effect on the attractiveness for exploration in Australia overall. Increasing expenditures of Australian resource companies are being diverted to overseas exploration. The weighting of the reasons for and significance of this still need to be decided, given the complexity of factors. This is particularly so in a situation where Western Australian exploration continues at a high level. Would it be higher, in fact, but for concerns about land access and security of tenure?

Inside the GSWA

Nell Stoyanoff

If the word *doyenne* was ever to have its fullest meaning, it was created for Nell Stoyanoff! For over thirty years Nell has held the key position of personal secretary to the Director of the Survey, and thus been privy to more than most of us have ever even speculated about. Over this period, she has served, indeed at times advised, four directors from the earliest, heady days of Survey expansion under Joe Lord. Loyal to the point of frustration (some would say) in the keeping of her own counsel, let no one doubt that she not only knows the skeletons, but precisely in which cupboards they dwell.

When one ponders what it is that makes Nell so consistently popular with all levels of staff, her qualities jostle for recognition. Foremost must be her well-balanced good nature at all times and in (nearly!) all circumstances, underpinned by the great good fortune of having been blessed with an advanced, medium-dry and yet compassionate sense of humour. A fine appreciation of the ridiculous has sustained her through life thus far, and nothing will change that.

Nell has been the much appreciated mentor over the years to those of her colleagues who have had the wit to listen to real expertise. Moreover, her generosity in time and energy for those who need a quick typing job or a sympathetic ear is legendary. However — don't push! The sign often seen at her desk says it all: 'Lack of planning on your part is no excuse for panic on mine'.

Born in Manjimup of Bulgarian parents, Nell was brought up in Perth, and educated at Perth Girls School ('up the road' from the Survey) and Perth Technical College in Leederville. In 1970 she took off for Europe on extended long-service leave and acquired what has proved to be a lifelong taste for travel. Since then, Nell has sailed up the Nile (Agatha Christie style), shot up the Andes, braved the Balkans and, most recently, meandered through New Zealand.

What has Nell found most rewarding about her years here? The people she's worked with, of course, with their subtle blend of warmth, independence and droll humour, without which the geologist struggles to survive. Her work has been exacting and often enjoyably challenging — few others, for instance, have managed to justify a document, both right and left, on a manual typewriter!

Nell's other abiding interest is sport — playing squash, tennis and golf. One has to have known her a long time before discovering that the winning of events and trophies has been going on for years. Nowadays, golf takes first place, and the better male squash players at the Survey can all breathe a little more easily.

Close friends and family do seem to be the essence, the driving force, of a life Nell happily finds full of interest — a life she firmly believes is, above all, for enjoying.

Sergey Shevchenko

Sergey Shevchenko was born in Tashkent, the capital of Uzbekistan, a former Soviet republic in Central Asia. Uzbekistan's vast barren deserts, picturesque valleys and beautiful snowy mountains drew him to the earth sciences and inspired him to become a geophysicist.

Sergey graduated from Tashkent University in 1980 after successfully completing a course in Applied Geophysics. For the next thirteen years he worked for a local geophysical company mainly in gravity and magnetic surveys in the Kizil-Kum desert and Tyan-Shan Mountains. His duties included conducting, and later supervising, both ground and helicopter surveys, and the management of field crews. In 1987 he was promoted to Project Geophysicist, allowing him to interpret the acquired data.

Sergey has also worked with seismic crews in the Black Sea and conducted gravity surveys in Eastern Siberia. Not surprisingly, Sergey's beard dates back to this winter Siberian sojourn.

Sergey migrated to Australia in 1993 and soon found a niche with the Survey where he provides the Petroleum Initiatives Project with gravity and magnetic maps and images. In spite of being converted to the use of modern geophysical imaging software, Sergey is still convinced that a hand-drawn Bouguer anomalies contour map is the most useful outcome of a gravity survey. He is also convinced that in the next decade the gravity method will undergo a major revival as a petroleum exploration tool, thereby keeping him employed well into the next century.

He is married to Elena and has a young teenage daughter Marsha. For a long time his passion was downhill skiing and mountaineering, but when he moved to Western Australia he not only discovered minimalist topography, but also that the only frost to be found is in the family fridge. One must adapt, of course, and the ever-flexible Sergey now finds immense satisfaction in working up a sweat jogging with colleagues during his lunch break.

Angus Davidson

Where does one start when describing Angus Davidson! Do we start with his childhood memories of Pakistan, his humerous anecdotes of life at Muresk Agricultural College, or his wondrous rough-stuff stories of life as a station manager on Oobagooma Station in the far Kimberley? The wide variety of his career prior to joining the Geological Survey has been such that numerous books could be written.

However, to confine our exposé to the last 27 years, Angus joined the Survey in 1968 and was immediately thrown into the deep end in hydrogeology, working in the northern Perth Basin and in particular in the Pilbara. Such was his love of the latter area that a short bore census ended up lasting several months, with his return to Perth being delayed till Christmas Eve. His relationship with the Pilbara continued with studies in the Millstream area, work on the De Grey River project, and a highly interesting program at Cooya Pooya of drilling, under explicit instructions, into several hundred of metres of solid basalt looking for non-existent water-bearing fractures.

In the mid-70s Angus took over work on the investigations of the groundwater resources of the Perth region, and this continued until 1994 when he commenced writing up the one and only hydrogeological Bulletin ever issued by the Survey — Hydrogeology and Groundwater Resources of the Perth Region. Needless to say this is a highly regarded Bulletin and copies of it disappear as quickly as they can be put on shelves. A major outcome of this work is a soon-to-be-granted PhD.

Even through this period of his hydrogeological career Angus still found time to travel north and to regale us with his exploits of success at Halls Creek and Nullagine (locating water!) while managing to be buzzed by Coastal Surveillance on a working trip to Wood Island off the Kimberley coast.

A highly regarded professional officer, Angus is married to Sylvia, and has two daughters, both of whom have now left school. He regards himself as a bit of a one-eyed darts player, and in his youth could bowl a pretty vicious fast ball, although there was always some suspicion over his action (but then Darryl Hair wasn't umpiring). Renowned as never being without an excuse for not attending functions, Angus will always be remembered for the consternation he caused back in Perth by once sending off his monthly report in an official Marble Bar Prison envelope.

Now, like all former Survey hydrogeologists a member of the Water and Rivers Commission, Angus is rounding off his professional contribution as officer in charge of groundwater assessment for the State. We can only wish him and his colleagues the very best in all things in their reincarnation.

Staff list
(30 June 1996)

GUJ, Pietro (Director)

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MYERS, John (Chief Geoscientist)

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CAREW, Eugene
OCCHIPINTI, Sandra
PIRAJNO, Franco
SWAGER, Cees

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FERGUSON, Kenneth
LANGFORD, Richard
MAYER, Ian
WYCHE, Stephen

Kimberley

SHEPPARD, Steve
THORNE, Alan
TYLER, Ian

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SMITHIES, Hugh
WILLIAMS, Ian

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LEWIS, John

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GOZZARD, Bob

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MORY, Arthur
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SVALBE, Andrew
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COOPER, Roger
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RUDDOCK, Ian
TOWNSEND, David
WESTAWAY, Jane
WITT, Walter

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BACKHOUSE, John
GREY, Kath

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CRESSWELL, Brian
STOYANOFF, Nell

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BARRETT, Kevin
FAIR, John
LOCKYER, Stuart
MOORE, Brian

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McGRATH, Bob
LENNOX-BRADLEY, Sean

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ELLIOT, Ian
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SMITH, Daniel
WONG, Henrietta

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McGORRIN, Yvonne
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PAGEL, Jutta
SAINT, Joan
STAPLETON, Gladys

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GOZZARD, Margie
JOHNSTON, Jean
MIKUCKI, Jennifer
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STRONG, Caroline
THEEDOM, Erica
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LENANE, Tom
LOAN, Geoff
PRAUSE, Michael
SUTTON, Dellys
TAYLOR, Peter
TOMICH, Don
URBINI, Simon
VANN, Delma
WILLIAMS, Brian

GIS

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CATALANO, Paul
JOSE, Geoffrey
KIRK, John
KUKULS, Liesma (Les)
OATES, Jodie
VAN BURGEL, Gerrit
WHITFORT, Matt

[1] Consultant

Staff movements

(1 July 1995 to 30 June 1996)

Internal appointments

BONER, Peter — to Level 2
CHACKRABORTY, Kalyan — to Level 2/4
FAULKNER, Joan — to Level 2/4
GRIFFIN, Tim — to Assistant Director
HOLMES, Mario — to Level 2
LANGFORD, Richard — to Project Leader; Level 7
PIRAJNO, Franco — to Project Manager; Level 8
TYLER, Ian — to Project Leader; Level 7

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HUGHES, Bernard
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ROGERSON, Richard
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SPRY, Steve
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WHITFORT, Matt
YASIN, Raza

(*fee for service*)

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GARNETT, Roger
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GROVES, Lara
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HOLLAND, Trevor
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LE BLANC SMITH, Guy
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LIU, Songfa
McLEOD, Fiona
PINTO, Gavin
REGENSPUGER, David
SMITH, Kathryn
STEEMSON, Greg
VARGA, Steven

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DB8

2.12.96

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Technical papers

The Gindalbie Terrane as a target for VMS-style mineralization in the Eastern Goldfields Province of the Yilgarn Craton

by W. K. Witt, P. A. Morris, S. Wyche, and D. R. Nelson

Abstract

The base metal prospectivity of the Archaean Gindalbie Terrane in the Eastern Goldfields Province is highlighted by a comparison with greenstone sequences that host volcanogenic massive sulfide deposits in the Superior Province, Canada. The Gindalbie Terrane is interpreted to lie on the eastern margin of a back-arc or marginal basin represented by the Kalgoorlie Terrane. More than 80% of VMS deposits in the Superior Province occur within bimodal volcanic sequences and the majority of these are associated with high-SiO_2 rhyolites that have flat rare-earth element patterns. The Gindalbie Terrane is a bimodal volcanic sequence in which the felsic component is high-SiO_2 rhyolite that is characterized by flat REE patterns. This sequence contrasts with the andesitic to dacitic volcanic rocks in the Kalgoorlie Terrane, which mostly overlie ultramafic and mafic volcanic rocks and have steep REE patterns.

KEYWORDS: Archaean, Yilgarn Craton, Eastern Goldfields Province, Gindalbie Terrane, felsic volcanic rocks, geochemistry, volcanogenic massive sulfides

Modern volcanogenic massive sulfide (VMS) deposits are forming in marginal and back-arc basins behind volcanic arcs. Examples include deposits in the Manus Basin (Binns and Scott, 1993), the Okinawa Trough (Halbach et al., 1993) and the Lau Basin (Fouquet et al., 1993). During the 1970s, considerable exploration effort was directed toward the discovery of base metals within volcanogenic massive sulfide (VMS) deposits in the Yilgarn Craton of Western Australia (Marston, 1979; Blockley, 1971; Ferguson, in prep.). Although exploration interest was predicated on the discovery of several important VMS deposits in the Archaean granite–greenstone terrains of the Superior Province, Canada, results of exploration in the Yilgarn Craton were disappointing. Only two economic discoveries (Golden Grove in the Murchison Province, and Teutonic Bore in the Eastern Goldfields Province, Fig. 1) were identified. Subsequently, there has been much informal discussion as to whether the Yilgarn Craton is intrinsically impoverished in VMS deposits, or whether it is underexplored.

Recent 1:100 000 mapping by the Geological Survey of Western Australia, supported by some whole-rock geochemistry and comparison with empirical observations from the Abitibi Subprovince in Canada, has prompted a reassessment of the VMS potential of the Eastern Goldfields Province. Canadian felsic volcanic sequences that host VMS deposits have distinctive rare-earth element (REE) and trace element signatures (Lesher et al., 1985; Barrie et al., 1993). Specific geochemical plots distinguishing barren and mineralized sequences, include $(La/Yb)_{CN}$ versus Yb_{CN}, Th/Yb versus Yb_{CN}, and Zr/Y versus Y. The distinctive trace element geochemistry of mineralized volcanic sequences in Canada is believed to be due to high-level magma fractionation in subvolcanic magma chambers (Lesher et al., 1985). There is some evidence that mineralized felsic volcanic sequences in Western Australia have geochemical features similar to those in Canada (Barley, 1992), and modern sea-floor mineralization in the Lau Basin is similarly associated with highly differentiated volcanic rocks.

Canadian VMS deposits

In the Abitibi Subprovince of Canada, more than 80% of VMS deposit-hosted base metals occur in interbedded bimodal volcanic sequences (Barrie et al., 1993). Examples of such mineralized sequences are at Kamaskotia, Matagami, Chibougamau and Noranda. The majority of these volcanic associations consist of mafic tholeiites and high-SiO_2 rhyolites. At Noranda, tholeiitic mafic rocks are interbedded with calc-alkaline andesite and rhyolite. Barren volcanic sequences, such as the Skead Group, consist of a lower sequence of tholeiitic basalt and an upper sequence of calc-alkaline to alkaline felsic volcanic rocks. Felsic volcanic rocks in mineralized volcanic sequences have relatively

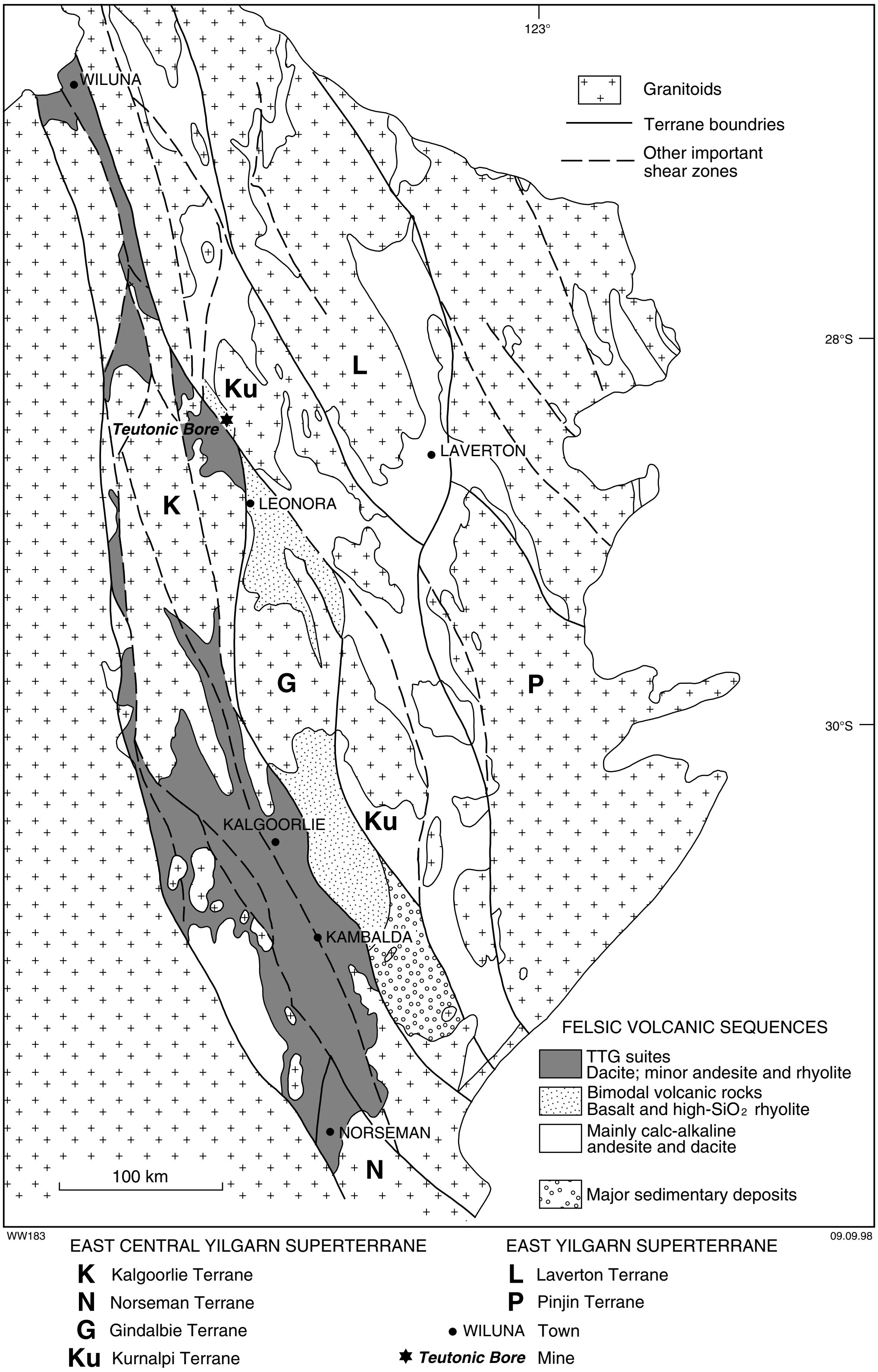

*Figure 1. Geology of the Eastern Goldfields Province showing terranes and distribution of various felsic volcanic associations (**modified after** Hallberg et al., 1993). Locations: B (Burton Dam), BT (Bulong townsite), BW (Bore Well), C (Carosue Dam), FM (Four Mile Hill), GHR (Gibson–Honman Rock), J (Jeedamya), M (Maggies Dam), ML (Melita), MS (Mount Shea), P (Perkolilli), PA (Pipeline Andesite), R (Reidy Swamp), RD (Rocky Dam), S (Spring Well), TF (Trans Find), WFL (White Flag Lake), X (Christmas Gift Dam). This map highlights the distribution of different types of felsic volcanic components of greenstone belts (but not, at this scale, the significant component of ultramafic to mafic rocks)*

flat REE patterns (as indicated by $(La/Yb)_{CN}$ <5) whereas barren felsic volcanic sequences have steep REE patterns (Fig. 2). A similar distinction between barren and mineralized volcanic sequences emerges from plots of Zr/Y versus Y (Fig. 3).

Several volcanogenic factors appear to be important for the formation of VMS deposits in Canada and elsewhere (Franklin et al., 1981; Lydon, 1984; Large, 1992):

- A subaqueous depositional environment which provides a large source of hydrothermal fluid to circulate through the volcanic pile (Cathles, 1993).
- Host rocks of permeability sufficient to allow pervasive access of the hydrothermal fluid to the volcanic pile. Thus, many deposits are hosted by volcaniclastic sediments. At Noranda, some deposits occur in lava-dominated, intra-caldera sequences where synvolcanic faults and fracture networks act as critical permeability controls (Kerr and Gibson, 1993).

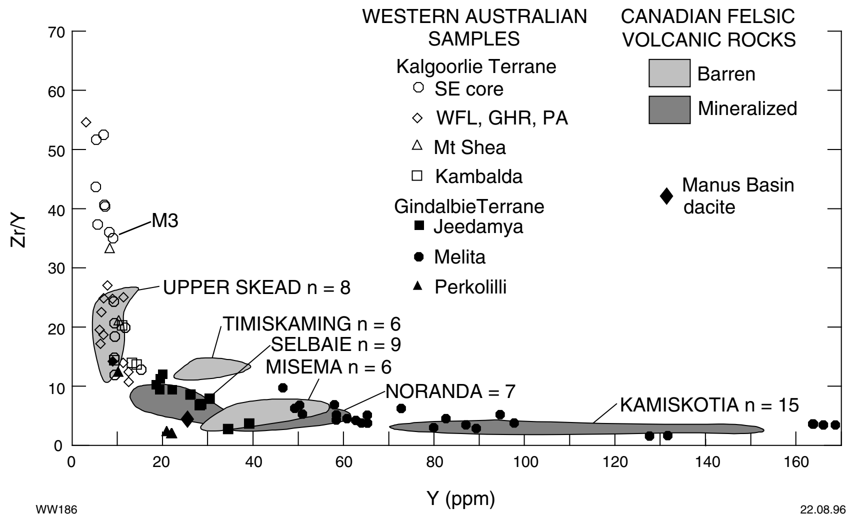

Figure 3. Zr/Y versus Y comparing felsic volcanic rocks from the Kalgoorlie and Gindalbie Terranes, Eastern Goldfields Province with mineralized and barren felsic volcanic rocks from the Abitibi Subprovince in Canada (Canadian data from *Barrie et al., 1993). Dacite hosting actively forming, sea-floor base-metal sulfide deposits in the Manus Basin is shown for comparison*

- An appropriate heat source to drive the hydrothermal system. High heat flow is likely to occur in or close to volcanic centres so that near-vent environments, including volcanic calderas, are typical loci for sulfide mineralization (e.g. at Noranda: Kerr and Gibson, 1993). Subvolcanic intrusions, more likely to be found in a proximal volcanic environment, are present in most VMS camps and play a crucial role in providing the energy to sustain a mineralizing hydrothermal system (Barrie et al., 1993; Kerr and Gibson, 1993; Cathles, 1993).

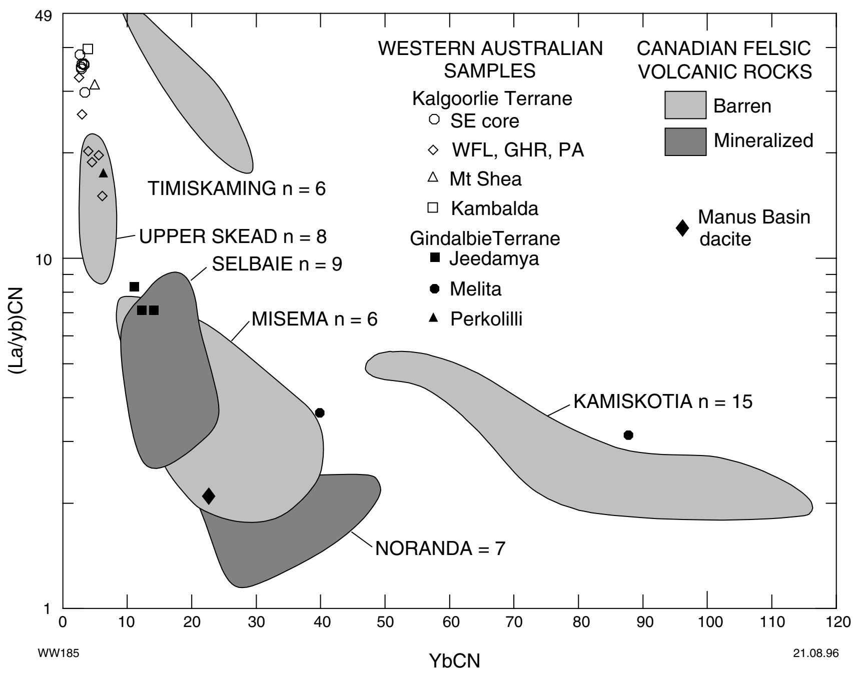

Figure 2. $(La/Yb)_{CN}$ versus Yb_{CN} comparing felsic volcanic rocks from the Kalgoorlie and Gindalbie Terranes, Eastern Goldfields Province with mineralized and barren felsic volcanic rocks from the Abitibi Subprovince in Canada (Canadian data from *Barrie et al., 1993). SE core samples are from near Kalgoorlie. Normalizing factors are* from *Boynton (1984). Dacite hosting actively forming, sea-floor base-metal sulfide deposits in the Manus Basin is shown for comparison*

Eastern Goldfields Province

Swager et al. (1992) and Swager (1993) distinguished several greenstone terranes in the Eastern Goldfields Province, based on lithostratigraphic associations and architecture of greenstone sequences. Hallberg et al. (1993) showed that specific felsic volcanic associations occur in some of these terranes (Fig. 1). Felsic volcanic rocks in two of these terranes are compared with mineralized sequences in the Abitibi Subprovince, in terms of their potential for hosting VMS-style mineralization. The Kalgoorlie Terrane has been interpreted as a possible marginal or back-arc basin (Barley et al., 1989; Swager et al., 1992). Witt (1994) suggested that the Gindalbie Terrane formed, during extension, on thicker crust at the margins of the extensional basin represented by the Kalgoorlie

Terrane. These interpretations suggest that the Kalgoorlie and Gindalbie Terranes formed in tectonic environments similar to those in which modern VMS deposits are found.

The Kalgoorlie Terrane

The Kalgoorlie Terrane is characterized by a thick mafic–ultramafic volcanic pile overlain by andesitic to dacitic lavas and volcaniclastic metasedimentary rocks (Morris, in prep.). This stratigraphic succession is similar to that of the Skead Group and other barren felsic volcanic sequences in the Superior Province, Canada (Barrie et al., 1993). Felsic volcanic rocks in the Kalgoorlie Terrane were erupted between approximately 2710 and 2675 Ma (Nelson, 1995). Whole-rock geochemistry indicates that the felsic volcanic component of this succession (the Black Flag Group) comprises a high-Al tonalite–trondhjemite–granodiorite (TTG) suite which was probably derived by partial melting of subducted oceanic crust (Morris, in prep., Morris and Witt, in prep.). Black Flag Group dacites and rhyolites have steep REE patterns with $(La/Yb)_{CN}$ ≥10 (Fig. 4), low Y and high Zr (Fig. 3). If the results of Barrie et al. (1993) can be extended to the Yilgarn Craton, it appears that the stratigraphy and geochemistry of the Black Flag Group felsic volcanic rocks are not an ideal environment for VMS-style mineralization.

The Gindalbie Terrane

The Gindalbie Terrane lies to the east of the Kalgoorlie Terrane (Fig. 1) and is characterized by bimodal volcanism and an absence of komatiitic lavas. Komatiitic to basaltic volcanic rocks, which overlie the felsic volcanics at Mount Monger, are interpreted as a thrust slice of Kalgoorlie Terrane rocks that was emplaced prior to regional folding, and are therefore not intrinsic to the Gindalbie Terrane. The Teutonic Bore Cu–Pb–Zn–Ag deposit occurs within a bimodal basalt–rhyolite association (Hallberg and Thompson, 1985; Barley, 1992) which is here interpreted as a tectonic slice of Gindalbie Terrane rocks that has been displaced across the Keith–Kilkenny Fault. Similar bimodal associations of high-SiO_2 rhyolite, interbedded with basalt and basaltic andesite, occur at Jeedamya and Melita (Witt, 1994). Ahmat (in press) has documented another bimodal association (in which the felsic component is dominated by andesite and dacite) in the Gindalbie area. High-SiO_2 rhyolite, similar to that at Melita, also occurs at Perkolilli (east of Kanowna) and north of Mount Monger (Trans Find, Bulong Anticline; Fig. 1). All these felsic volcanic associations occur within the Gindalbie Terrane. Felsic volcanic rocks in the Gindalbie Terrane were erupted between approximately 2710 and 2670 Ma (Nelson, 1995), making them approximately coeval with Black Flag Group volcanics.

High-SiO_2 rhyolite from Melita, Jeedamya and Perkolilli have relatively flat REE patterns (Fig. 4), high Y and low Zr/Y (Fig. 3) and low Th/Yb. Jeedamya and Perkolilli samples plot in a zone of overlap in which barren and mineralized sequences in the Superior Province are not readily distinguished. Heavy REE depletion in the Perkolilli rhyolite probably reflects fractionation of accessory phases such as zircon whereas the depleted patterns of the Black Flag Group samples are characteristic of unfractionated samples. However, the contrast with felsic volcanics of the Black Flag Group is clear (Fig. 4). Other samples from the southern Gindalbie Terrane also plot in the zone of overlap, together with the Jeedamya volcanics (Figs 5,6). Thus, the lithostratigraphic associations, greenstone architecture and felsic volcanic geochemistry of the Gindalbie Terrane are, by comparison with the Superior Province, prospective for VMS-style mineralization.

Volcanology of the Gindalbie Terrane

The Teutonic Bore Cu–Pb–Zn–Ag deposit occurs in metamorphosed pyritic black shale, chert and tuffaceous, epiclastic sedimentary rocks (Hallberg and Thompson, 1985). These rocks were deposited in deep water with pyroclastic debris, possibly derived from a shallow-water to subaerial source. Sulfides accumulated in a small sub-basin related to syndepositional faulting (Greig, 1984).

Rhyolitic volcanic rocks at Melita were deposited in shallow water (Witt, 1994). The volcanic centre is interpreted to lie beneath a large area of poor exposure southeast of Melita, and was probably emergent (Hallberg, 1985; Witt, 1994). However, if pyroclastic eruptions were accompanied by caldera

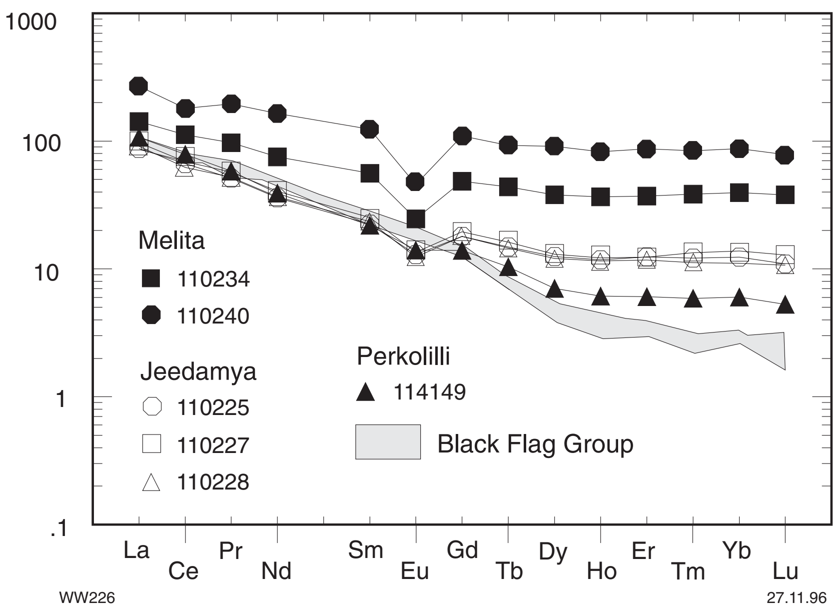

Figure 4. Chondrite-normalized REE curves for Black Flag Group dacite and rhyolite (Kalgoorlie Terrane) and rhyolitic rocks from the Gindalbie Terrane.

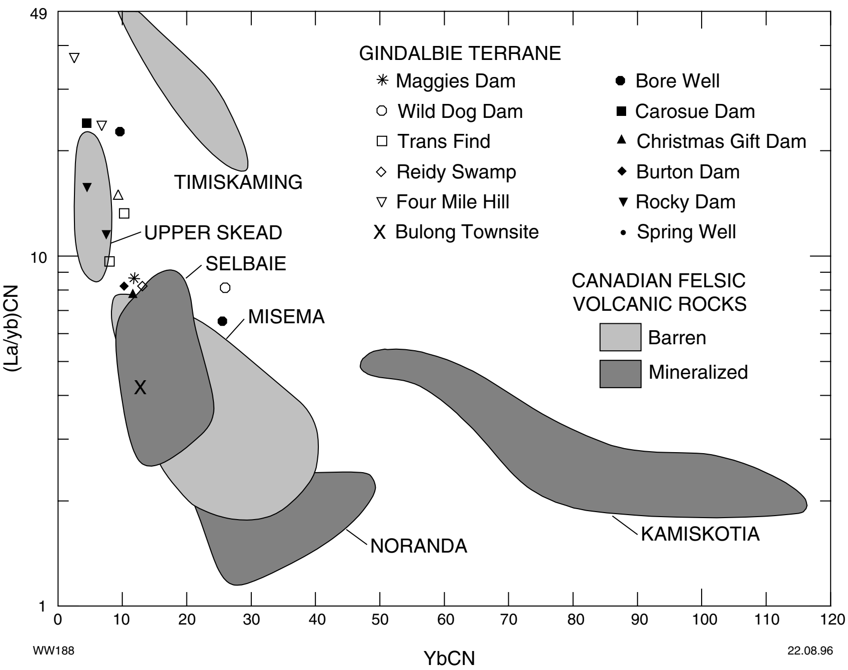

Figure 5. *$(La/Yb)_{CN}$ versus Yb_{CN} comparing felsic volcanic rocks from the Gindalbie Terrane, and other terranes to the east, with mineralized and barren felsic volcanic rocks from the Abitibi Subprovince in Canada (Canadian data* from *Barrie et al., 1993). See Figure 6 for key to Western Australian samples*

collapse, the central vent area may have been subaqueous and may therefore be prospective for VMS mineralization. Pillowed basalt interbedded with pyroclastic rocks of the Jeedamya volcanic complex indicates subaqueous deposition. The Jeedamya pyroclastics are interpreted as distal deposits compared with the Melita pyroclastics (Witt, 1994). Relatively proximal pyroclastic deposits exist in the southwest corner of the complex but the volcanic centre may have been stoped out by granitoid intrusions such as the Dead Horse Syenogranite and the Galah Monzogranite. The prospectivity of the Melita and Jeedamya volcanic sequences is further enhanced by the contemporaneous intrusion of mafic (leucodolerite) sills (Witt, 1995) which would have provided effective heat sources to stimulate hydrothermal circulation.

Explosive rhyolitic volcanism and subaqueous deposition of volcanic and volcaniclastic units also occurred in the Perkolilli area (Morris, in prep.). Taylor (1984) noted evidence for widespread synvolcanic faulting and hydrothermal alteration.

More-detailed mapping of volcanic facies than is currently available through the GSWA 1:100 000 sheet series is required to identify suitable targets for VMS exploration in the Gindalbie Terrane. This more detailed mapping should be directed toward identification of

- various subaqueous and subaerial depositional environments,
- synvolcanic faults and zones of synvolcanic faulting,
- volcanic centres, especially volcanic calderas and cauldrons, and
- subvolcanic intrusive phases.

Primary volcanic structures are widely preserved in low-strain domains in the Eastern Goldfields Province and this should assist in the task of identifying primary depositional environments in the multiply deformed and metamorphosed Gindalbie Terrane.

Other terranes

In the Superior Province, bimodal sequences in which the felsic component is dominated by calc-alkaline andesite and rhyolite host roughly one-third of VMS deposit-hosted base metals, including those in the deposits at Noranda. Terranes to the east of the Gindalbie Terrane have stratigraphically complex greenstone sequences in which felsic volcanic units are dominantly calc-alkaline andesite and dacite with some rhyolite. One of these andesitic centres, at Spring Well (Giles, 1981), displays geochemical characteristics

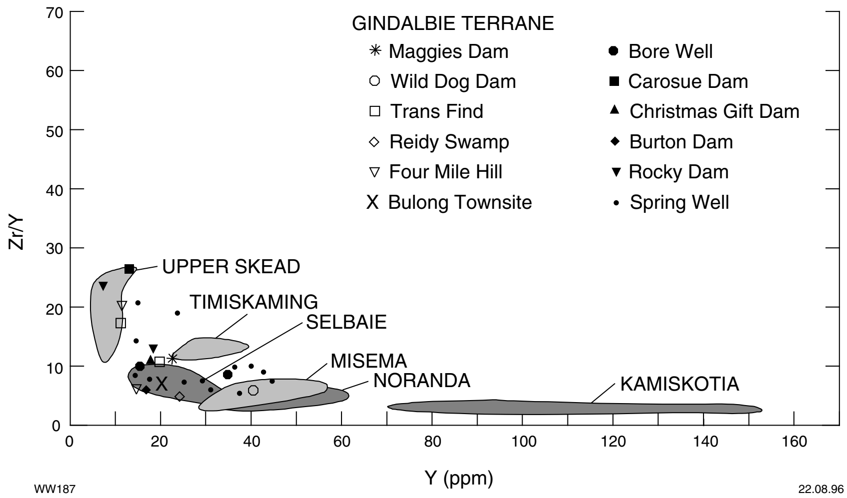

Figure 6. *Zr/Y versus Y comparing felsic volcanic rocks from the Gindalbie Terranes, and other terranes to the east, with mineralized and barren felsic volcanic rocks from the Abitibi Subprovince in Canada (Canadian data* from *Barrie et al., 1993)*

which are similar to those of the Jeedamya Volcanics (Fig. 6). Spring Well volcanics were deposited in a shallow-water to subaerial setting (Wyche and Westaway, in prep.). Geochemical data from other volcanic centres are too limited for unequivocal conclusions. Most samples plot in the zone of overlap between mineralized and unmineralized volcanic sequences in Canada (Figs 5,6). More geochemical data, and more-detailed mapping, are required before the prospectivity of these other terranes can be adequately assesssed.

Conclusions

The Gindalbie Terrane emerges as a prospective regional target for VMS-style mineralization following a geochemical survey of felsic volcanic rocks in the Eastern Goldfields Province. The ideal exploration target for VMS deposits in the Gindalbie Terrane is a subaqueous volcanic centre, possibly a volcanic caldera, into which immature volcaniclastic rocks have been deposited. Within this environment, fine-grained sediments, indicative of a period of relative quiescence, should be identified. A high degree of synvolcanic faulting, especially if the sequences are dominated by volcanic flows, and contemporaneous subvolcanic intrusions, are additional positive attributes. Present knowledge of the volcanology of the Melita volcanics suggest they may have been deposited in a subaerial or shallow-water environment. Deeper water volcanic centres should be sought along strike. However, in seeking deeper water environments for VMS-style mineralization, the potential for epithermal deposits of base and precious metals in subaerial volcanic environments, especially calderas, should not be overlooked.

References

AHMAT, A. L., in press, Geology of the Gindalbie 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

BARLEY, M. E., 1992, A review of Archaean volcanic-hosted massive sulphide and sulphate mineralization in Western Australia: Economic Geology, v. 87, p. 855–972.

BARLEY, M. E., EISENLOHR, B. N., GROVES, D. I., PERRING, C. S., and VEARNCOMBE, J. R., 1989, Late Archean convergent margin tectonics and gold mineralization: a new look at the Norseman–Wiluna belt: Geology, v. 17, p. 826–829.

BARRIE, C. T., LUDDEN, J. N., and GREEN, A. H., 1993, Geochemistry of volcanic rocks associated with Cu–Zn and Ni–Cu deposits in the Abitibi Subprovince: Economic Geology, v. 88, p. 1341–1358.

BINNS, R. A., and SCOTT, S. D., 1993, Actively forming polymetallic sulfide deposits associated with felsic volcanic rocks in the Eastern Manus back-arc basin, Papua New Guinea: Economic Geology, v. 88, p. 2226–2236.

BLOCKLEY, J. G., 1971, The lead, zinc and silver deposits of Western Australia. Western Australia Geological Survey, Mineral Resources Bulletin 9, 234p.

BOYNTON, W. V., 1984, Cosmochemistry of the rare earth elements: meteorite studies, *in* Rare earth element geochemistry *edited by* P. HENDERSON: Developments in Geoscience 2, Amsterdam, Elsevier, p. 63–114.

CATHLES, L. M., 1993, Oxygen isotope alteration in the Noranda mining district, Abitibi greenstone belt, Quebec: Economic Geology, v. 88, P. 1483–1511.

FERGUSON, K., in prep., Lead, zinc and silver deposits of Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 15.

FOUQUET, Y., VON STACKLEBERG, U., CHARLOU, J. L., ERZINGER, J., HERZIG, P. M., MUHE, R., and WIEDICKE, M., 1993, Metallogenesis in back-arc environments: The Lau basin example: Economic Geology, v. 88, p. 2122–2153.

FRANKLIN, J. M., SANGSTER, D. F., and LYDON, J. W., 1981, Volcanic-associated massive sulphide deposits: Economic Geology, 75th Anniversary Volume, p. 485–627.

GILES, C. W., 1981, Archaean calc-alkaline volcanism in the Eastern Goldfields Province, Western Australia: Geological Society of Australia, Special Publication 7, p. 275–286.

GREIG, D. D., 1984, Geology of the Teutonic Bore massive sulphide deposit, Western Australia: Australasian Institute of Mining and Metallurgy, Proceedings, v. 289, p. 147–156.

HALBACH, P., PRACEJUS, B., and MARTEN, A., 1993, Geology and mineralogy of massive sulfide ores from the central Okinawa Trough, Japan: Economic Geology, v. 88, p. 2210–2225.

HALLBERG, J. A., 1985, Geology and mineral deposits of the Leonora–Laverton Area, Northeastern Yilgarn Block, Western Australia: Perth, Hesperian Press, 140p.

HALLBERG, J. A., and THOMPSON, J. F. H., 1985, Geological setting of the Teutonic Bore massive sulphide deposit, Archean Yilgarn Block, Western Australia: Economic Geology, v. 80, p. 1953–1964.

HALLBERG, J. A., AHMAT, A. L., MORRIS, P. A., and WITT, W. K., 1993, An overview of felsic volcanism within the Eastern Goldfields Province, Western Australia, *in* An International Conference on Crustal Evolution, Metallogeny and Exploration of the Eastern Goldfields *compiled by* P. R. WILLIAMS and J. A. HALDANE. Australian Geological Survey Organisation, Record 1993/54, p. 29–32.

KERR, D. J., and GIBSON, H. L., 1993, A comparison of the Horne volcanogenic massive sulfide deposit and intracauldron deposits of the Mine sequence, Noranda, Quebec: Economic Geology, v. 88, p. 1419–1442.

LARGE, R. R., 1992, Australian volcanic-hosted massive sulphide deposits: features, styles and genetic models: Economic Geology, v. 87, p. 471–510.

LESHER, C. M., GOODWIN, A. M., CAMPBELL, I. H., and GORTON, M. P., 1985, Trace element geochemistry of ore-associated and barren felsic metavolcanic rocks in the Superior Province, Canada: Canadian Journal of Earth Sciences, v. 23, p. 222–237.

LYDON, J. W., 1984, Ore deposit models — 8. Volcanogenic massive sulphide deposits; part I. A descriptive model: Geoscience Canada, v. 11, p. 195–202.

MARSTON, R. J., 1979, Copper mineralization in Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 13, 208p.

MORRIS, P. A., in prep., Archaean felsic volcanism in the Eastern Goldfields Province, Western Australia: Western Australia Geological Survey, Report.

MORRIS, P. A., and WITT, W. K., in prep., The geochemistry and tectonic setting of two contrasting Archaean felsic volcanic associations in the Eastern Goldfields Province, Western Australia: Precambrian Research.

NELSON, D. R., 1995, Compilation of SHRIMP U–Pb zircon geochronolgy data, 1994. Western Australia Geological Survey, Record 1995/3.

SWAGER, C. P., 1993, Stratigraphy and structure in the southeastern Goldfields Province, *in* An International Conference on Crustal Evolution, Metallogeny and Exploration of the Eastern Goldfields *compiled by* P. R. WILLIAMS and J. A. HALDANE. Australian Geological Survey Organisation, Record 1993/54, p. 69–72.

SWAGER, C. P., WITT, W. K., GRIFFIN, T. J., AHMAT, A. L., HUNTER, W. M., McGOLDRICK, P. J., and WYCHE, S., 1992, Late Archaean granite–greenstones of the Kalgoorlie Terrane, Yilgarn Craton, Western Australia, *in* The Archaean: Terrains, Processes and Metallogeny; Proceedings Volume for the Third International Archaean Symposium, Perth, Western Australia *edited by* J. E. GLOVER and S. E. HO. Geology Department (Key Centre) and University Extension, University of Western Australia Publication no. 22, p. 107–122.

TAYLOR, T., 1984, The palaeoenvironment and tectonic setting of Archaean volcanogenic rocks in the Kanowna district, near Kalgoorlie, Western Australia: University of Western Australia, MSc thesis (unpublished).

WITT, W. K., 1994, Geology of the Melita 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

WITT, W. K., 1995, Tholeiitic and high-Mg mafic/ultramafic sills in the Eastern Goldfields Province, Western Australia: implications for tectonic settings: Australian Journal of Earth Sciences, v. 42, p. 407–422.

WYCHE, S., and WESTAWAY, J.M., in prep., Geology of the Darlot 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

The Cadjebut Formation: a Givetian evaporitic precursor to Devonian reef complexes of the Lennard Shelf, Canning Basin, Western Australia

by R. M. Hocking, I. A. Copp, P. E. Playford, and R. H. Kempton[1].

Abstract

The Cadjebut Formation is a cyclic evaporitic unit of Givetian age, 30–60 m thick, at the base of the Devonian succession on the eastern Lennard Shelf, in the Canning Basin of Western Australia. It hosts Zn–Pb Mississippi Valley-type mineralization and was previously included in the Pillara Limestone. The Cadjebut Formation was deposited in a local hypersaline basin at the start of a long-term transgression that was responsible for the Givetian–Frasnian Pillara cycle of the Devonian reef complexes. The formation is divisible into four facies — basal lag, siltstone and dololutite, evaporite, and dolomitic grainstone facies — of which the last three occur in cyclic alternations. Individual horizons within each facies persist laterally over several kilometres.

KEYWORDS: evaporites, cyclic deposition, stratigraphy, Devonian reef complexes, Canning Basin.

Devonian sedimentary rocks are exposed on the Lennard Shelf along the northern margin of the Canning Basin (Fig. 1), where the succession is dominated by the Givetian, Frasnian and Famennian 'Great Barrier Reef', as described by Playford and Lowry (1966) and in subsequent papers by Playford and by other workers (e. g. those *in* Purcell, 1984; and Purcell and Purcell, 1994). This paper formalizes terminology for the peritidal evaporite and dolomite unit that immediately underlies and grades up into the reef complexes in the western Emanuel Range area. This unit constitutes the initial deposits of the Middle to Upper Devonian depositional system on the Lennard Shelf, and hosts Mississippi Valley-type (MVT) Zn–Pb mineralization in the Cadjebut mine (Murphy, 1990). Previously it has been referred to informally as the 'lower dolomite' and 'basal arkose' of the Pillara Limestone. However, the unit is sufficiently distinctive and significant to be recognized as a separate formation, and it is defined here as the Cadjebut Formation.

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Stratigraphic framework

Playford's model for the Devonian reef compexes (*see* Playford, 1980; Playford et al., 1989) distinguished a Givetian bank facies, which developed prior to the establishment of reefal deposits, and a Frasnian platform facies, which accumulated as part of a series of reef complexes (Fig. 2). His usage of the name Pillara Limestone included all the Givetian platform (bank) and marginal-slope (fore-bank) facies and the Frasnian platform facies (Fig. 2). Geologists working with BHP Minerals in the Cadjebut area recognized several informal units within the Pillara Limestone in the Emanuel Range. In ascending order, these were the 'basal arkose', 'lower dolomite', 'vuggy dolomite', '*Argutastrea* limestone', 'silty stromatoporoid limestone', 'fenestral limestone', and 'silty cyclic limestone'.

The 'vuggy dolomite' and '*Argutastrea* limestone' of the BHP usage are Givetian, based on the presence of the brachiopod *Stringocephalus*. They are underlain by the 'lower dolomite' (which hosts the Zn–Pb mineralization at Cadjebut) and 'basal arkose', which together form a distinct mappable unit, up to 60 m thick, that is here named the Cadjebut Formation. The name Pillara Limestone is retained for the overlying platform carbonates, beginning with the 'vuggy dolomite'.

Cadjebut Formation

The type section of the Cadjebut Formation, 52 m thick (Fig. 3), is located on the southwest side of the Emanuel Range about 300 m north of Emanuel Creek. There are about 2 m of non-exposure between the lowest Cadjebut Formation and the highest Ordovician rocks. A reference section is designated in BHP drillhole CD 113, between 421.8 and 458.3 m. Both this section and that in drillhole PHD 4 contain well-developed evaporites, but lack significant mineralized zones.

The Cadjebut Formation is exposed along the front of the Emanuel Range, extending as far northwest as the Prices Hill area. It lies with angular unconformity on the Ordovician Prices Creek Group (Gap Creek Formation and Emanuel Formation), and is transitional upwards into the Pillara Limestone.

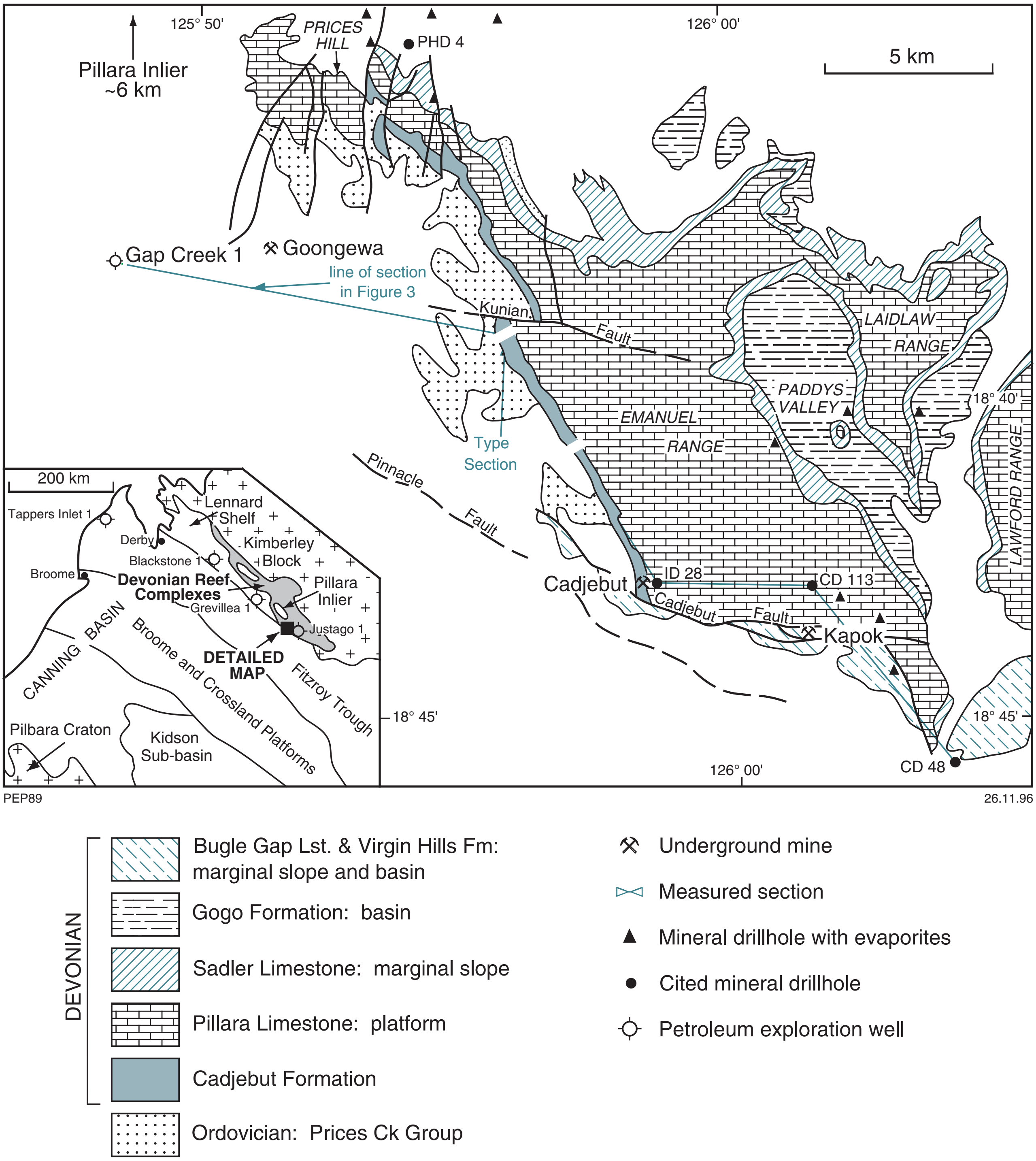

Figure 1. Geology of Emanuel Range area, showing location, simplified surface geology, relevant drillholes, and mine locations. Post-Devonian rocks omitted

The upper contact is taken at the first appearance of a characteristic vuggy dolomite in which the vugs are recognizably after stromatoporoids (stick-like or club-like) or corals. The base-Devonian unconformity shows significant topographic relief, especially northwest of Emanuel Creek. The formation has been intersected in mineral exploration drillholes from the Emanuel Range to Paddys Valley, and as far southwest as the Pinnacle Fault (Fig. 1). Neither the Cadjebut Formation nor the underlying Prices Creek Group extends as far north as the Pillara Inlier, where Precambrian rocks are directly overlain by Pillara Limestone. To the northwest, Grevillea 1 intersected a siliciclastic

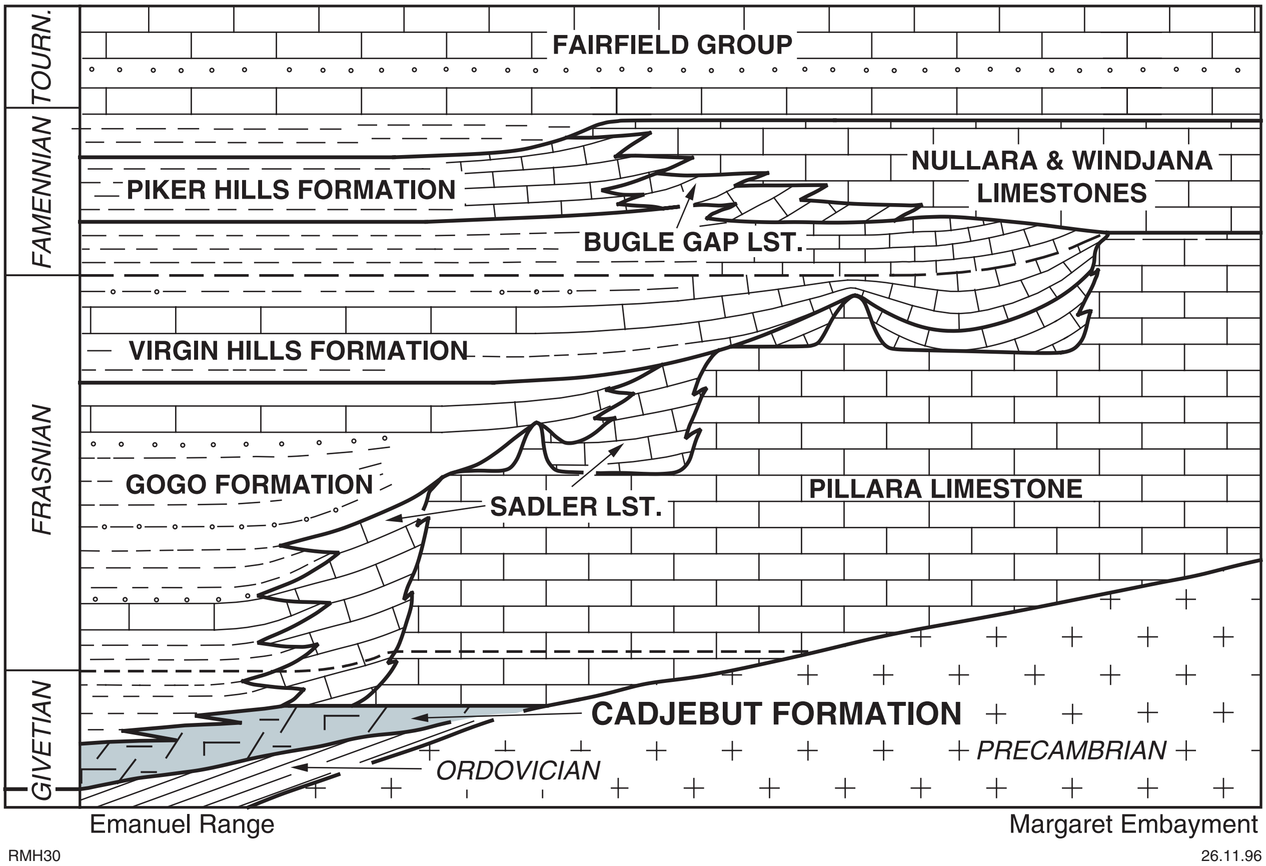

Figure 2. Lithostratigraphy and generalized development through time of Devonian reef complexes and related units on the eastern Lennard Shelf (modified from Playford 1984)

and dolomitic unit at the base of the Pillara Limestone, between 1817 and 1953 m, which has a similar wireline-log response to that of the Cadjebut Formation, but the characteristic evaporite lithofacies is not present. To the southeast, the formation may be present in Justago 1 between 2240.5 and 2277.5 m.

The miospore *Geminospora lemurata* occurs in the 'handspan marker' of the Cadjebut Formation (Grey, 1992). This species ranges in age from middle Givetian to early Famennian (Playford, G., 1995, pers. comm.), and as the overlying part of the Pillara Limestone is known to be Givetian (because of the occurrence of *Stringocephalus*), the Cadjebut Formation must also be of Givetian age.

Poulton Formation and Dominic Shale

Nicoll et al. (1993) used the name Poulton Formation for exposures of Cadjebut Formation in the Prices Hill area. We consider that this correlation is not appropriate. The Poulton Formation is a silty red-bed unit about 300 m thick, of Middle Devonian age (Playford et al., 1975; Towner and Gibson, 1983), which is known from the subsurface in the northwest Lennard Shelf. Cores from the type section in Blackstone 1 (Fig. 1) are lithologically distinct from the Cadjebut Formation. In addition, spores from core 3 (6503–6509 ft), near the top of the Poulton Formation, are early Givetian to early Eifelian (*devonicus–naumovae* or *velata–langii* zones) in age (Backhouse, 1996). *G. lemurata* is absent, suggesting that the Poulton Formation predates the Cadjebut Formation. Spores from core 14 (6985 ft) show a distinctly higher thermal maturity (Backhouse, 1996), which may indicate an unconformity within the Poulton Formation, as shown by Lehmann (1984, fig. 5).

Lehmann (1984) defined the Dominic Shale from Tappers Inlet 1 near Derby (Fig. 1) and extended it in the subsurface around the southern margin of the Fitzroy Trough and into the Kidson Sub-basin. The Dominic Shale appears to be lithologically similar to the Cadjebut Formation, and the two units are of comparable thickness. Consequently, the two units may prove to be equivalent. The age of the Dominic Shale in Tappers Inlet 1 is not sufficiently constrained to support or reject the correlation.

Deposition

Four broad lithofacies — basal lag, siltstone and dololutite, evaporite, and dolomitic grainstone — have been recognized in the Cadjebut Formation, based on outcrop in the the Emanuel Range, drillhole information, and exposures in the Cadjebut mine (Fig. 4). The three last-mentioned facies form cyclic sequences.

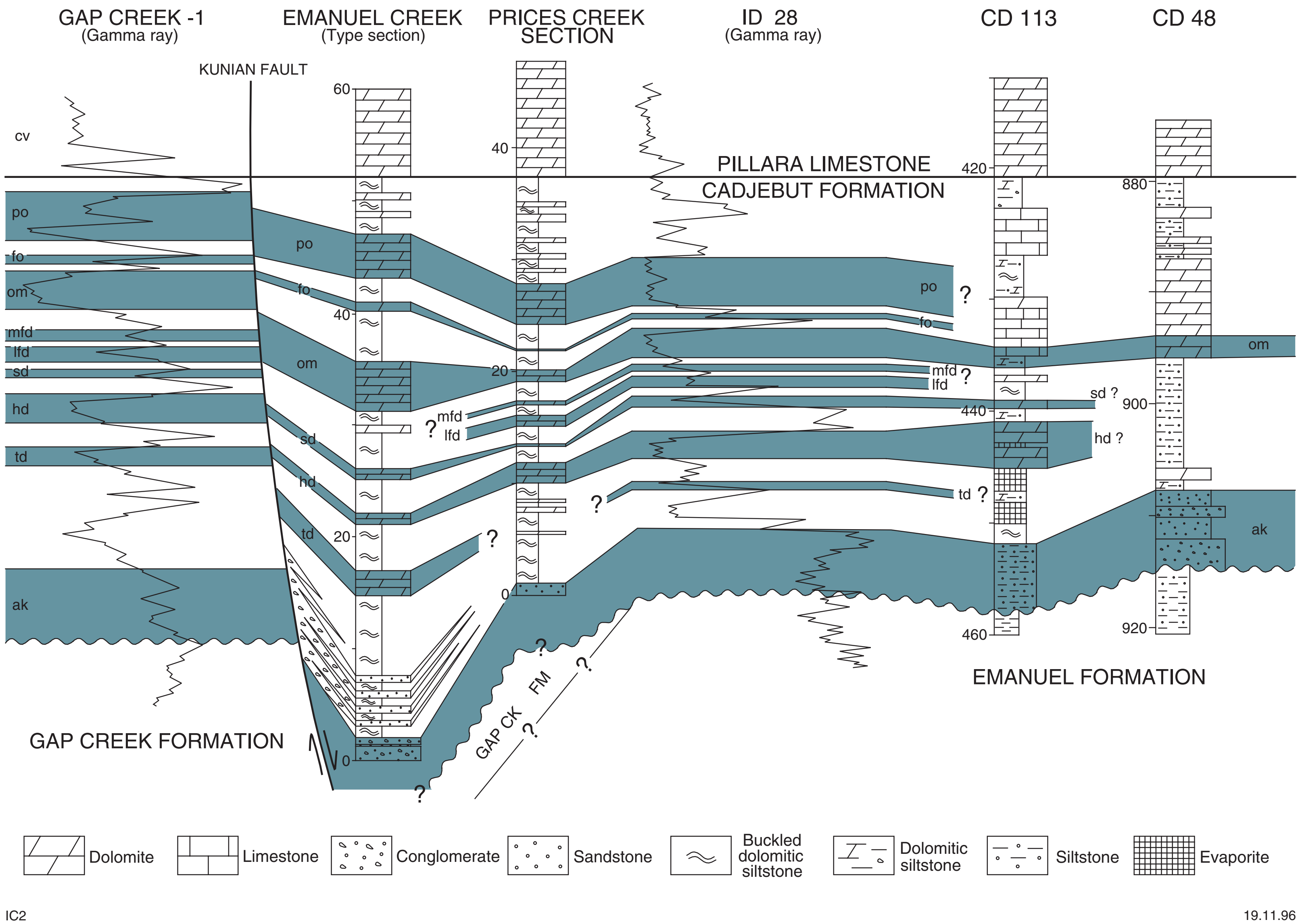

Figure 3. Representative sections of Cadjebut Formation, showing lateral extent of marker horizons, and correlation between outcrop, core, and gamma-ray logs. All the markers were established by BHP workers from borehole cores and underground mining of the Cadjebut Formation. Marker beds are as follows, using BHP mnemonics and informal names: ak — basal arkose; td — tri-dolomite; hd — handspan dolomite; sd — sill dolomite; lfd — lower-face dolomite; mfd — mid-face dolomite; om — oncolite marker; fo — fresh oolite; po — pseudo-oncolite; cv — vuggy dolomite

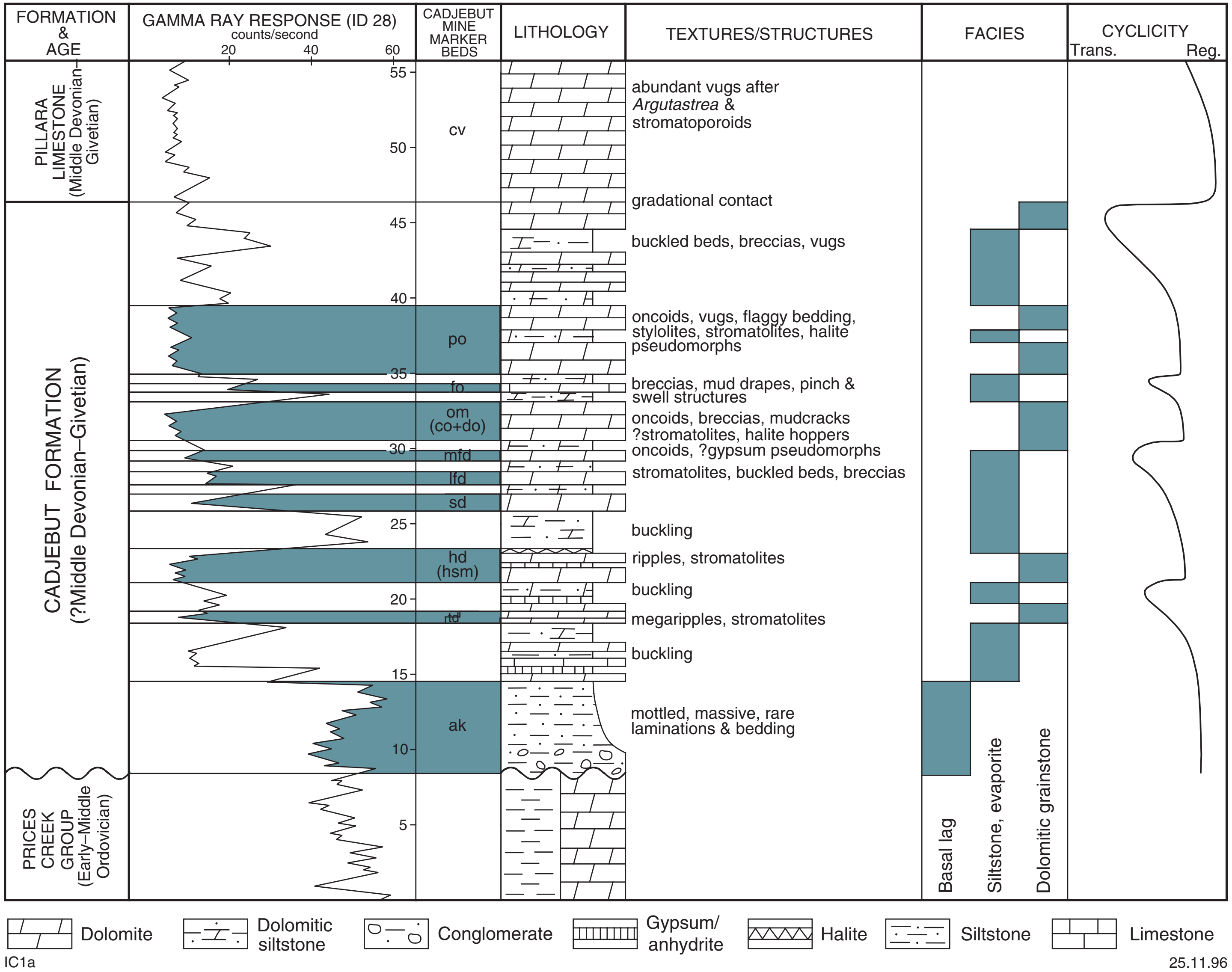

Figure 4. Idealized summary section of the Cadjebut Formation, based on drillhole, outcrop and mine data. The thickness, from drillhole ID 28, is slightly exaggerated, because it is a vertical drillhole and the Devonian sequence dips southeastward about 10°. See Figure 3 reference for key to Cadjebut mine marker beds. Within handspan dolomite hd, hsm is handspan marker. Within oncolite marker om, co is clean dolomite and do is dirty oncolite

The *basal lag facies* consists of grey siltstone, lithic wacke and conglomerate at the base of the Cadjebut Formation, and is equivalent to the 'basal arkose'. The conglomerate is commonly dominated by clasts of reworked Ordovician dolomite and siltstone, and it is interpreted as a transgressive lag deposit. The basal unconformity has pronounced topographic relief, so that the thickness and stratigraphic level of the lag facies varies along the outcrop belt. Primary evaporites are interbedded with conglomerate of this facies in drillhole PHD 4.

The *dolomitic grainstone facies* is dominated by hard, relatively clean, oolitic dolomite, with some horizons of coarse oncoids and scattered stromatolites. Dolomitization was essentially syndepositional (Pedone, 1990). Ripples and megaripples can be recognized in outcrop and in the Cadjebut mine, generally towards the base of dolomite intervals. Two clay-draped megaripple sets form the 'handspan marker', one of the main markers in the mine. In a typical sequence through a dolomite interval in outcrop, the ripples are overlain by columnar stromatolites, then by oncoids, and finally by laminated to thin-bedded dolomite. Fenestral texture is common above the rippled horizons. This typical succession is interpreted as a shallowing-upward shoaling sequence. Pseudomorphs of expansive halite hoppers and gypsum roses occur near the top of some intervals, indicating subaerial exposure.

Pebbles and cobbles, primarily dolomite of the Gap Creek Formation, increase in size and concentration northwards towards Gap Creek in this facies, and dolomite intervals grade laterally into conglomerate of the basal lag facies north of Emanuel Creek. There, they form the basal deposits of the formation, lying on a series of wave-cut shoreline benches eroded into the Gap Creek Formation.

Three of the main markers in the Cadjebut Formation are composed of the dolomitic grainstone facies, and can be traced throughout the formation in outcrop, BHP drillholes, and electrically logged drillholes. These are the 'pseudo oncolite' (po), 'oncolite marker' (om) and 'handspan dolomite' (hd). The thickness of the markers and the sediment thickness between them is relatively uniform over the extent of the Cadjebut Formation in the Emanuel Range (Fig. 3).

The dolomitic grainstone facies is interpreted as a bank or shoal accumulation that separated basinward areas of normal salinity (not seen in exposures of the Cadjebut Formation) from hypersaline lagoonal and sabkha areas (see below) in which evaporitic siltstone and dololutite accumulated. The facies marks the highest energy episodes of deposition in the Cadjebut Formation.

The *siltstone and dololutite facies* forms the bulk of the Cadjebut Formation. It occurs as intervals 2 to 5 m thick of poorly exposed, soft, dark-grey siltstone to claystone with interbeds of harder, laminated to massive, light-grey dololutite. Several of these interbeds are recognized as markers in the Cadjebut mine (e.g. 'lower micrite marker', 'tri-dolomite marker', and 'lower face dolomite'; *see* Tompkins et al., 1994a), and can be traced away from the mine.

The dololutite layers commonly exhibit buckling that extends for tens of metres horizontally and ranges in amplitude from tens of centimetres to about three metres. The buckling is interpreted as enterolithic deformation caused by the expansive growth of replacive and displacive sulfates in the capillary zone of a sabkha. These buckled dololutite layers are commonly truncated and overlain by flat-bedded dolomite. Displacive halite crystal growth in some dololutite intervals and displacive anhydrite pseudomporphs in outcrop suggest deposition in the upper supratidal zone of the sabkha. As a whole, the facies is interpreted as a back-barrier, restricted-circulation, lagoonal deposit.

The *evaporite facies* is dominated by anhydrite and gypsum (after anhydrite), interbedded with dolomite and siltstone. Evaporites are preserved in this facies in drillholes (e.g. CD 113 and PHD 4), but only scattered evaporite pseudomorphs remain in outcrop. Massive, nodular to chickenwire-textured anhydrite is present in cores, and following Warren and Kendall (1985), is interpreted as a subaqueous deposit in evaporitic lagoons up to to a few metres deep. Thinly bedded anhydrite and dolomite units are generally found at the base of individual evaporite beds, and some dolomite interbeds contain evidence of displacive halite growth.

The evaporite beds were originally more widespread than their present-day extent. Residual collapse-breccias resulting from evaporite dissolution occur in the subsurface as beds 30 to 50 cm thick. They are composed mainly of siltstone and dololutite clasts supported by siltstone matrix. Individual rhythmically banded, mineralized zones in the Cadjebut mine correlate laterally with evaporite dissolution breccias to the north and south of the mine and evaporite beds distal to the mine (Kempton et al., 1994).

A supratidal sabkha to hypersaline lagoon setting is inferred for the siltstone and dololutite and the evaporite facies. Deposition occurred initially in hypersaline conditions with limited circulation, to form the siltstone and dololutites. Evaporites developed at times of greater restriction in the lagoon, in mudflats that oscillated from subaerial to subaqueous.

Discussion

The Cadjebut Formation is an evaporitic precursor to the main Devonian succession of the Lennard Shelf. After deposition of the Gap Creek Formation in the Early to Middle Ordovician, the eastern Lennard Shelf was uplifted and eroded, and deposition recommenced in the Middle Devonian following regional downwarping. Continued Givetian faulting in the Emanuel Range and Prices Hill area is indicated by discordant relationships and changes in thickness over faults. The evaporitic nature of the Cadjebut Formation suggests that the arid climate of the Silurian (Baillie et al., 1994) persisted until at least the Middle Devonian. Continued downwarping and transgression eventually submerged the evaporitic basins, and reef growth began.

Four major cycles in the Cadjebut Formation above the basal lag facies are recognized from field mapping and wireline-log interpretations. Each cycle is about 10 m thick, and consists of dolomitic grainstone facies at the base, overlain successively by siltstone and dololutite facies and evaporitic mudflat facies (Fig. 4). Sub-cycles can be recognized within some cycles, especially near the top of the formation. The cycles are progradational-infill types, but interpretation of the driving force is unsure. A tectonic component may have been involved, because of the known active faults in the area, but orbital forcing may also have been a factor.

Economic significance

Mississippi Valley-type mineralization is hosted within the Cadjebut Formation at the Cadjebut mine, which was the first underground MVT mine to be developed in Australia. The deposit is zinc rich, and several models have been proposed to explain the location, areal extent, and timing of mineralization (Vearncombe et al., 1995; Kempton et al., 1994; Tompkins et al., 1994 a,b; Wallace, 1994; McManus and Wallace, 1992).

Tompkins et al. (1994b) deduced that evaporites in the Cadjebut Formation were the primary source of sulfur in the ore sulfides, by showing that the S-isotope values in those sulfides are similar to those in the evaporites. The evaporites formed the precursor to the high-grade banded ore at Cadjebut. Residual hydrocarbons are associated with the ore sulfides at Cadjebut, and Wallace (1994) proposed that the mineralization was localized by a weak anticlinal flexure into which hydrocarbons and mineralizing fluids migrated in the latest Devonian to Early Carboniferous (McManus and Wallace, 1992).

The possible correlation of the Dominic Shale with the Cadjebut Formation raises the possibility of MVT mineralization occurring in the Dominic Shale, provided that suitable evaporite host facies are present. However its prospectivity is diminished by the fact that the shallowest recorded intersection of the formation is at about 340 m in Barbwire 1, on the southern side of the Fitzroy Trough, and most intersections are at depths of 1000 m or more.

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References

BACKHOUSE, J., 1996, Blackstone 1 — palynology of three samples from the Poulton Formation, Canning Basin: Western Australia Geological Survey, Palaeontology Report 1996/13 (unpublished).

BAILLIE, P. W., POWELL, C. McA., LI, Z. X., and RYALL, A. M., 1994, The tectonic framework of Western Australia's Neoproterozoic to Recent sedimentary basins, *in* The sedimentary basins of Western Australia *edited by* P. G. and R. R. PURCELL: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1994, Proceedings, p. 46–62.

GREY, K., 1992, Miospore assemblages from the Devonian reef complexes, Canning Basin, Western Australia: Western Australia Geological Survey, Bulletin 140, 139p.

KEMPTON, R. H., KLOPPER, J. S., and WARREN, J. K., 1994, The association of breccias, evaporites, dolomites and hydrocarbons in the Cadjebut region, Canning Basin — clue to the origin of MVT deposits: Geological Society of Australia, Abstracts no. 37, p. 212.

LEHMANN, P. H., 1984, The stratigraphy, palaeogeography and petroleum potential of the Lower to lower Upper Devonian sequence in the Canning Basin, *in* The Canning Basin, W.A. *edited by* P. G. PURCELL: Geological Society of Australia and Petroleum Exploration Society of Australia Symposium, Perth, Western Australia, 1984, Proceedings, p. 253–275.

McMANUS, A., and WALLACE, M. W., 1992, Age of Mississippi Valley-type sulphides determined using cathodoluminescence cement stratigraphy, Lennard Shelf, Canning Basin, Western Australia: Economic Geology, v. 97, p. 189–193.

MURPHY, G. C., 1990, Lennard Shelf lead–zinc deposits, *in* Geology of the mineral deposits of Australia and Papua New Guinea *edited by* F. E. HUGHES: Australasian Institute of Mining and Metallurgy, Melbourne, p. 1103–1109.

NICOLL, R. S., LAURIE, J. R., and ROCHE, M. T., 1993, Revised stratigraphy of the Ordovician (Late Tremadoc–Arenig) Prices Creek Group and Devonian Poulton Formation, Lennard Shelf, Canning Basin, Western Australia: AGSO Journal of Australian Geology and Geophysics, v. 14, p. 65–76.

PEDONE, V. A., 1990, Geology and diagenesis of Middle Devonian (Givetian) bank deposits, Emanuel Range, Canning Basin, Western Australia: State University of New York, Stony Brook, PhD thesis (unpublished).

PLAYFORD, P. E., 1980, Devonian 'Great Barrier Reef' of the Canning Basin, Western Australia: AAPG Bulletin, v. 64, p. 814–840.

PLAYFORD, P. E., COPE, R. N., COCKBAIN, A. E., LOW, G. H., and LOWRY, D. C., 1975, Phanerozoic, *in* The Geology of Western Australia: Western Australia Geological Survey, Memoir 2, p. 223–433.

PLAYFORD, P. E., HURLEY, N. F., KERANS, C., and MIDDLETON, M. F., 1989, Reefal platform development, Devonian of the Canning Basin, Western Australia, *in* Controls on carbonate platform and basin development *edited by* P. D. CREVELLO, J. L. WILSON, J. F. SARG and J. F. READ: Society of Economic Paleontologists and Mineralogists, Special Publication 44, p. 187–202.

PLAYFORD, P. E., and LOWRY, D. C., 1966, Devonian reef complexes of the Canning Basin, Western Australia: Western Australia Geological Survey, Bulletin 118, 150p.

PURCELL, P. G., (editor), 1984, The Canning Basin, W.A.: Geological Society of Australia and Petroleum Exploration Society of Australia, Canning Basin Symposium, Perth, W.A., 1984, Proceedings.

PURCELL, P. G., and PURCELL, R. R., (editors), 1994, The sedimentary basins of Western Australia: Petroleum Exploration Society of Australia, Western Australian Basins Symposium, Perth, W.A., 1994, Proceedings.

TOMPKINS, L. A., PEDONE, V. A., ROCHE, M. T., and GROVES, D. I., 1994a, The Cadjebut deposit as an example of Mississippi Valley-type mineralisation on the Lennard Shelf, Western Australia - single episode or multiple events?: Economic Geology, v. 89, p. 450–466.

TOMPKINS, L. A., RAYNER, M. J., GROVES, D. I., and ROCHE, M.T., 1994b, Evaporites: *in situ* sulfur source for rythmically banded ore in the Cadjebut MVT Zn–Pb deposit, Western Australia: Economic Geology, v. 89, p. 467–492.

TOWNER, R. R., and GIBSON, D. L., 1983, Geology of the onshore Canning Basin, Western Australia: Australia BMR, Bulletin 215, 51p.

VEARNCOMBE, J. R., DORLING, S. L., DENTITH, M. C., CHISNALL, A. W., McNAUGHTON, N. J., PLAYFORD, P. E., RAYNER, M. J., and REED, A. R., 1995, Zinc–lead mineralization on the southeast Lennard Shelf, Canning Basin, Western Australia: Society of Economic Geologists, Guidebook Series v. 23, 218p.

WALLACE, M. W., 1994, Burial diagenesis, Pb–Zn sulphides and hydrocarbon maturation in the Devonian reefs of the Lennard Shelf, Western. Australia: Geological Society of Australia, Abstracts, no. 37, p. 448–449.

WARREN, J. K., and KENDALL, C. G. St C.,1985, Comparison of sequences formed in marine sabkha (subaerial) and salina (subaqueous) settings; modern and ancient: AAPG Bulletin, v. 69, p. 1013–1023.

Mafic–felsic magma mingling in the Bow River batholith of the Halls Creek Orogen

by S. Sheppard

Abstract

Textures indicative of magma mingling between granitoid and gabbro are extensively developed and spectacularly exposed in the Palaeoproterozoic Bow River batholith in the Halls Creek Orogen. There is no evidence that mixing and hybridization of mafic and felsic magmas took place at depth. The paucity of intermediate rocks, and lack of identifiable cumulates, precludes generation of the granitoids by crystal fractionation from mafic parent magmas. The compositional range in the batholith is primarily a function of the composition of the source rocks and the degree of partial melting. Simultaneous intrusion of mafic and felsic magmas from different sources was followed by limited crystal fractionation and mingling at high levels in the crust.

KEYWORDS: Halls Creek Orogen, Bow River batholith, granitoid, gabbro, magma mingling, hybridization

Mingling and mixing between coeval mafic and felsic magmas is very common in calc-alkaline granitoid batholiths worldwide (Didier and Barbarin, 1991; Pitcher, 1993). Mingling is defined as the physical interaction of two magmas where they retain their separate identities or produce heterogeneous rocks, whereas mixing results in a compositionally homogeneous hybrid melt (Sparks and Marshall, 1986; Frost and Mahood, 1987). Although commonly spectacular, magma mingling and mixing in the upper crust account for only limited variability in granitoid composition (Pitcher, 1993). However, some workers have suggested that the compositional range in calc-alkaline batholiths could result largely from mixing and hybridization of gabbroic and granitic magmas in the lower crust (Reid et al., 1983, 1993) with a secondary role for fractional crystallization.

The Halls Creek Orogen mostly consists of low- to high-grade metasedimentary and metavolcanic rocks, intruded by extensive granitoid and less voluminous massive and layered gabbroic intrusions (Tyler et al., 1995). All the contiguous granitoid and massive gabbro in the Halls Creek Orogen is grouped into the Bow River batholith (Fig. 1), which is subdivided into the 1865–1850 Ma Paperbark supersuite and the 1835–1800 Ma Sally Downs supersuite. These are equivalent to the ‘Bow River batholith’ and ‘Sally Downs batholith’, respectively, of Sheppard et al. (1995). Field relationships indicate broadly coeval intrusion of granitic and gabbroic magmas within each supersuite (Blake and Hoatson, 1993), although a range of field relationships is apparent between individual granitoid and gabbro intrusions. For instance, granitoid may intrude solidified or partially molten gabbro; gabbro and granitoid magma may be synchronous; or, gabbro may intrude solidified or partially molten granitoid. This paper deals with the Paperbark supersuite but many of the conclusions are also applicable to the Sally Downs supersuite.

Paperbark supersuite

In the Halls Creek Orogen the Paperbark supersuite (Fig. 1) is about 25–30 km wide and over 300 km long, and consists of more than 20 I-type granitoid plutons and subordinate coeval gabbro intrusions. Most of the supersuite is composed of medium- to coarse-grained, porphyritic, biotite-bearing monzogranite, syenogranite and granodiorite, with subordinate tonalite. Rapakivi granite is common in the northern part of the supersuite. In general, the intrusions are homogeneous and show few indications of compositional zoning.

Coeval gabbro in the supersuite is massive and fine to medium grained, contains widespread biotite and quartz, and little or no olivine. The relationship to the layered mafic–ultramafic intrusions in the Lamboo Complex is unclear, although U–Pb SHRIMP dating by Page et al. (1995) indicates that at least some of the layered intrusions are the same age as the granitoid and massive gabbro.

Description of field relationships between granitoid and gabbro

Widespread textures involving granitoid and gabbro in the Bow River batholith include net-vein complexes; extensive, irregular veins of granitoid cutting gabbro in conjunction with hybrid rock and xenocrystic gabbro; widespread

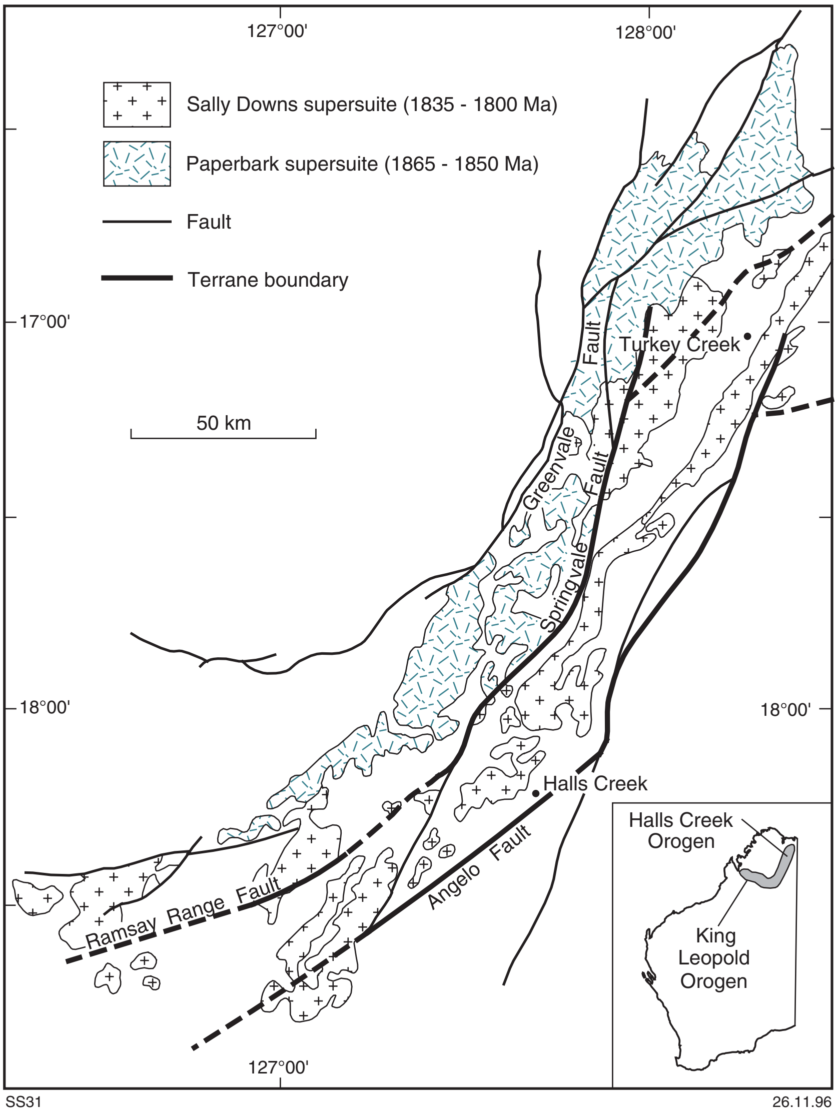

Figure 1. Sketch map of the Bow River batholith, including coeval, massive gabbro intrusions

rounded mafic inclusions in granitoid; and subvertical pegmatitic granitoid pipes in gabbro.

Net-vein complexes are present at the contact between many biotite-gabbro and granitoid intrusions (Blake and Hoatson, 1993). The complexes are up to 100 m wide, and consist of abundant rounded and angular inclusions of biotite gabbro enclosed and veined by heterogeneous biotite granitoid (Fig. 2). Mafic inclusions in the net-vein complexes are similar in composition and texture to rocks from the biotite-gabbro intrusions.

Mingled gabbro–granitoid consists of massive biotite- and quartz-bearing gabbro with veins and irregular patches of xenocrystic hybrid rock, both cut by irregular veins of biotite granitoid up to 30 cm wide (Fig. 2). Hybrid rocks are mafic to intermediate rocks that contain a component of both gabbro and granitoid; they have a mineralogy and grainsize (~1–2 mm) similar to those of the gabbros, but are more felsic and contain xenocrysts derived from the granitoids. Field relationships consistently indicate an order of intrusion, from oldest to youngest, of gabbro, hybrid rock, and granitoid. Contacts between hybrid veins and patches, and mafic rocks, are generally sharp (<0.5 cm wide) and curvilinear to cuspate, although more diffuse contacts are present. Most granitoid veins terminate abruptly, but some gradually merge into a trail of partially resorbed plagioclase xenocrysts within hybrid rock.

Granitoids in the Paperbark supersuite, and in particular the mafic varieties, contain widespread mafic inclusions with an igneous texture. Fine-grained mafic inclusions may be dispersed throughout the pluton, but are more numerous near the margins and especially close to net-vein complexes. Less abundant are fine- to medium-grained porphyritic inclusions that have an identical mineralogy to the host granitoid, but are more mafic.

Locally, biotite-gabbro intrusions contain cylindrical, subvertical pipes of pegmatitic biotite granitoid about 5–10 cm in diameter and 20–40 cm long, surrounded by a narrow zone of hybrid rock.

Interpretation of field relationships

Igneous net-vein complexes form when mafic magma intrudes a cooler granitoid magma (Blake et al., 1965; Frost and Mahood, 1987; Didier and Barbarin, 1991), or a rigid granitoid at temperatures close to its solidus (Blundy and Sparks, 1992). The mafic magma chills against the granitoid, and is broken up into pillows of mafic rock enclosed by the granitoid. Owing to its much higher solidus temperature, the mafic magma solidifies, and melt derived from remobilization of the granitoid hydraulically fractures and veins the gabbro.

The textures in the hybrid rocks are consistent with incomplete mixing between mafic magma and small amounts of felsic magma. Xenocryst abundance in the hybrid rocks generally shows no spatial relationship to enclosing tonalite veins, indicating that most of the xenocrysts were incorporated at depth. The irregular nature of the granitoid veins, and exposures which show them merging into trails of plagioclase xenocrysts, suggest that the gabbro and hybrid rock were not entirely solid when veined.

The rounded shape of the mafic inclusions in the granitoids, the presence of phenocrysts straddling

Figure 2A. ***Irregular veins of porphyritic biotite monzogranite cutting massive biotite-bearing microgabbro in an intrusion of mingled gabbro–granitoid. Note hammer for scale***

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Figure 2B. ***Net-vein complex from the Paperbark supersuite. Numerous rounded to angular mafic inclusions are enclosed and veined by medium-grained biotite monzogranite. Note hammer for scale*** inclusion–granitoid contacts and widespread acicular apatite indicate that the inclusions represent mafic liquids quenched in granitoid magma (Vernon, 1983; Didier and Barbarin, 1991). Experimental and field studies on pegmatitic granitoid pipes (D'Lemos, 1992) indicate that they form by the diapiric intrusion of granitic magma into overlying gabbroic magma.

The field relationships outlined above indicate that granitoid and gabbro magmas in the Paperbark supersuite mingled extensively at high levels in the crust. However, to what extent did they mix and hybridize to form intermediate rock types?

Geochemistry

In the Paperbark supersuite, samples of intermediate composition (~53–63 wt% SiO_2) are poorly represented, which reflects the predominance of felsic and mafic compositions. This contrasts with calc-alkaline granitoid batholiths in which intermediate compositions are abundant. The compositional gap between the mafic and felsic rocks in the Paperbark supersuite is illustrated in Figure 3. The gabbros and granitoids define two separate groups with the granitoids showing a roughly linear trend of sharply decreasing Sr with increasing SiO_2 (Fig. 3). The arrow shows the approximate trend expected from hybridization of gabbro and relatively mafic granitoid magmas, since hybridization is most likely to occur if the compositional contrast between the two magmas is ≤10 wt% SiO_2 (Sparks and Marshall, 1986;

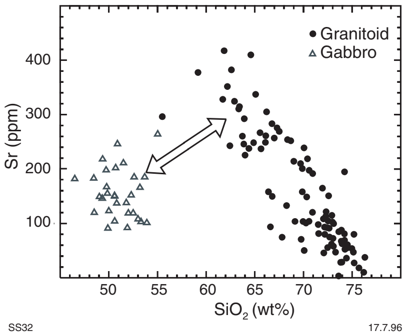

Figure 3. Harker diagram showing the compositional gap between gabbro and granitoid of the Paperbark supersuite

Frost and Mahood, 1987). The trend in the granitoids is at a high angle to that expected from hybridization with the mafic rock compositions. Only one granitoid sample, which plots midway between the two groups of rocks, is likely to be a product of hybridization.

Discussion

Several workers (Reid et al., 1983, 1993; Didier and Barbarin, 1991) have recently suggested that the compositional range in calc-alkaline batholiths is largely the result of hybridization between gabbroic and granitic magmas, rather than crystal fractionation or different degrees of partial melting of source rocks. In magmas of contrasting composition, hybridization is only possible where low melt viscosities, turbulent convection and large mass fractions of mafic magma are present.

Although intrusion of gabbro and granitoid was broadly contemporaneous in the Paperbark supersuite, they did not mix and homogenize to produce significant quantities of intermediate rock. Some of the scatter in the trends, particularly in the gabbros, could be produced by magma mingling, but hybridization is not the primary cause of compositional variation in the supersuite. The preponderance of siliceous rocks in the supersuite (and the batholith as a whole), in conjunction with an absence of cumulate rocks, indicates that the granitoids probably did not originate by fractional crystallization of mafic magma. Therefore, the primary granitoid magmas may have been quite siliceous (~70 wt% SiO_2), and thus would be unlikely to hybridize with a magma containing ~50 wt% SiO_2.

The homogeneity and restricted compositional range (typically ≤6–8 wt% SiO_2) of individual granitoid intrusions in both supersuites precludes extensive fractional crystallization in the upper crust. The fundamental controls on compositional variation in each supersuite are most likely to be variation in source rock composition and different degrees of partial melting.

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References

BLAKE, D. H., ELWELL, R. W. D., GIBSON, I. L., SKELHORN, R. R., and WALKER, G. P. L., 1965, Some relationships resulting from the intimate association of acid and basic magmas: Quarterly Journal of the Geological Society of London, v. 121, p. 31–49.

BLAKE, D. H., and HOATSON, D. M., 1993, Granite, gabbro, and migmatite field relationships in the Proterozoic Lamboo Complex of the east Kimberley region, Western Australia: AGSO Journal of Australian Geology and Geophysics, v. 14, p. 319–330.

BLUNDY, J. D., and SPARKS, R. S. J., 1992, Petrogenesis of mafic inclusions in granitoids of the Adamello Massif, Italy: Journal of Petrology, v. 33, p. 1039–1104.

DIDIER, J., and BARBARIN, B., (editors), 1991, Enclaves and granite petrology: Developments in Petrology, 13, Amsterdam, Elsevier, 601p.

D'LEMOS, R. S., 1992, Magma-mingling and melt modification between granitic pipes and host diorite, Guernsey, Channel Islands: Journal of the Geological Society, v. 149, p. 709–720.

FROST, T. R., and MAHOOD, G. A., 1987, Field, chemical and physical constraints on mafic–felsic magma interaction in the Lamarck Granodiorite, Sierra Nevada, California: Geological Society of America Bulletin, v. 99, p. 272–291.

PAGE, R. W., HOATSON, D. M., SUN, S-S., and FOUDOULIS, C., 1995, High precision geochronology of Palaeoproterozoic layered mafic–ultramafic intrusions in the East Kimberley: AGSO Research Newsletter, 22, p. 7–8.

PITCHER, W.S., 1993, The nature and origin of granite: London, Blackie Academic and Professional, 320p.

REID, J. B., EVANS, O. C., and FATES, D. G., 1983, Magma mixing in granitic rocks of the central Sierra Nevada, California: Earth and Planetary Science Letters, v. 66., p. 243–261.

REID, J. B., MURRAY, D. P., HERMES, O. D., and STEIG, E. J., 1993, Fractional crystallization in granites of the Sierra Nevada: How important is it?: Geology, v. 21, p. 587–590.

SHEPPARD, S., GRIFFIN, T. J., and TYLER, I. M., 1995, Geochemistry of felsic igneous rocks from the southern Halls Creek Orogen: Western Australia Geological Survey, Record 1995/4, 81p.

SPARKS, R.S.J., and MARSHALL, L.A., 1986, Thermal and mechanical constraints on mixing between mafic and silicic magmas: Journal of Volcanology and Geothermal Research, v. 29, p. 99–124.

TYLER, I. M., GRIFFIN, T. J., PAGE, R. W., and SHAW, R. D., 1995, Are there terranes within the Lamboo Complex of the Halls Creek Orogen?: Western Australia Geological Survey, Annual Review 1993–94, p. 37–46.

VERNON, R.H., 1983, Restite, xenoliths and microgranitoid enclaves in granites: Royal Society of New South Wales, Proceedings, v. 116, p. 77–103.

The effectiveness of potential-field data in the structural interpretation of a sedimentary basin

by R. P. Iasky, S. Shevchenko, and A. J. Mory

Abstract

The Merlinleigh Sub-basin in the onshore southern Carnarvon Basin is a frontier area for petroleum exploration, with limited seismic coverage and only two deep exploration wells. High-resolution aeromagnetic and semi-detailed heli-supported gravity surveys were conducted in 1995 to assist with the structural interpretation of the sub-basin. A regular grid of potential-field data provided structural information cheaply and an opportunity to test the relative effectiveness of gravity and magnetic data. Magnetic anomalies appear to be dominated either by near-surface sources or intra-basement sources. Gravity anomalies provided reliable definition of the structures at basement level and within the sedimentary sequence, consistent with those indicated by the seismic data, as well as lineament information that was undetected in the other datasets. Compared with the gravity data, the aeromagnetic data provided only a small contribution to the existing structural knowledge acquired from surface and seismic data. Although aeromagnetic and gravity datasets provide complementary structural information, detailed or semi-detailed evenly spaced gravity coverage is likely to provide better structural definition of a sedimentary basin than is aeromagnetic coverage. The costs of acquiring the two datasets are comparable.

KEYWORDS: aeromagnetic, gravity, Bouguer anomalies, total magnetic intensity, first vertical derivative, depth to basement, depth to magnetic basement, geological structure, structural interpretation.

The Merlinleigh Sub-basin in the onshore Carnarvon Basin (Fig. 1) is considered to be a frontier area for petroleum exploration because there has been little activity in the sub-basin apart from regional seismic coverage, twelve shallow stratigraphic wells and five exploration wells, of which only two were deep tests (Percival and Cooney, 1985; Crostella, 1995). The Geological Survey of Western Australia has embarked on a program to encourage exploration in such frontier areas. As part of this program, high-resolution aeromagnetic and semi-detailed helicopter-supported gravity data were acquired to assist with the structural interpretation of the Merlinleigh Sub-basin. The aeromagnetic survey (Fig. 1) comprised 45 305 line-kilometres and recorded data at more than 5.6 million points as readings were taken, on average, every 7.5 m along flight lines. By comparison, the helicopter gravity survey (Fig. 1) consisted of 4000 stations measured on a 2 by 3 km grid. The cost of the two surveys was comparable.

The Merlinleigh Sub-basin is an elongate depocentre of Late Carboniferous to Early Permian age that overlies Carboniferous, Devonian and Silurian rocks (Hocking et al., 1987). The succession is thickest near the centre of the sub-basin (near Kennedy Range 1), where it is estimated to reach 8000 m (Fig. 2). In general, the sub-basin is deepest to the west where it is bounded by faults and gradually shallows to the east where the pre-Permian sequences are exposed (Fig. 2). The present western boundary is defined by an en echelon fault system that separates the Gascoyne Sub-basin from the Merlinleigh Sub-basin (Fig. 2). The northern boundary is the ill-defined Marilla High and the southern boundary is along the Madeline Fault System on the southeastern side of the Carrandibby Inlier (Fig. 1). The most recent descriptions of the petroleum geology and structural setting have been made by Percival and Cooney (1985) and Crostella (1995).

Magnetic anomalies are caused by the relative intensity of magnetization of rocks, which is directly related to magnetic susceptibility. In turn, magnetic susceptibility depends upon the amount of ferrimagnetic minerals present, mainly magnetite, sometimes ilmenite or pyrrhotite (Telford et al., 1976). Since sedimentary rocks have low average susceptibility, the magnetic response of sedimentary basins is small compared with that of cratonic areas. Therefore, the magnetic response of sedimentary successions may be overwhelmed by that of the underlying basement rocks. Furthermore, the presence of

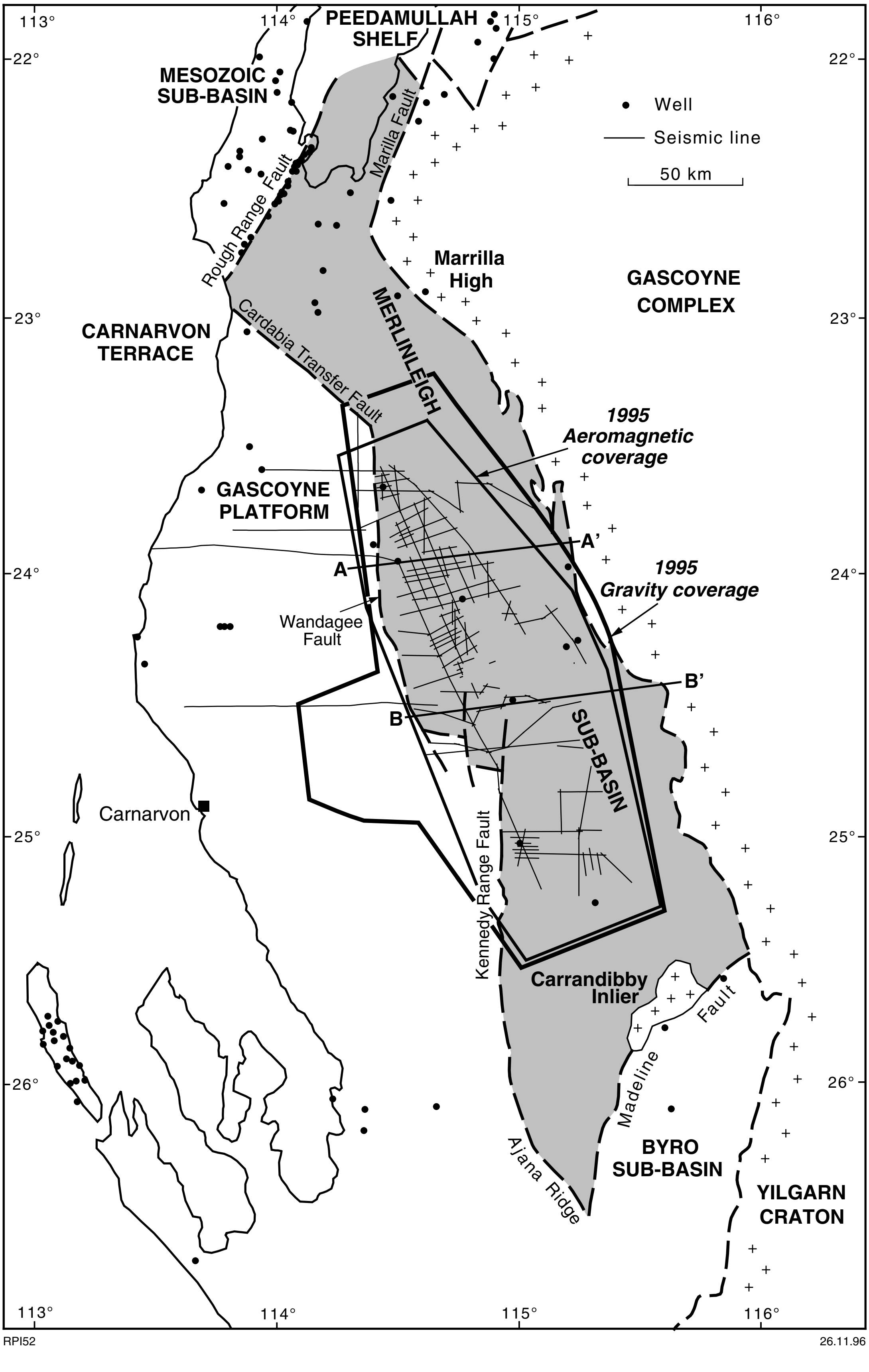

Figure 1. Location and tectonic setting of the Merlinleigh Sub-basin, areal extent of 1995 aeromagnetic and gravity surveys, and earlier seismic coverage in the sub-basin

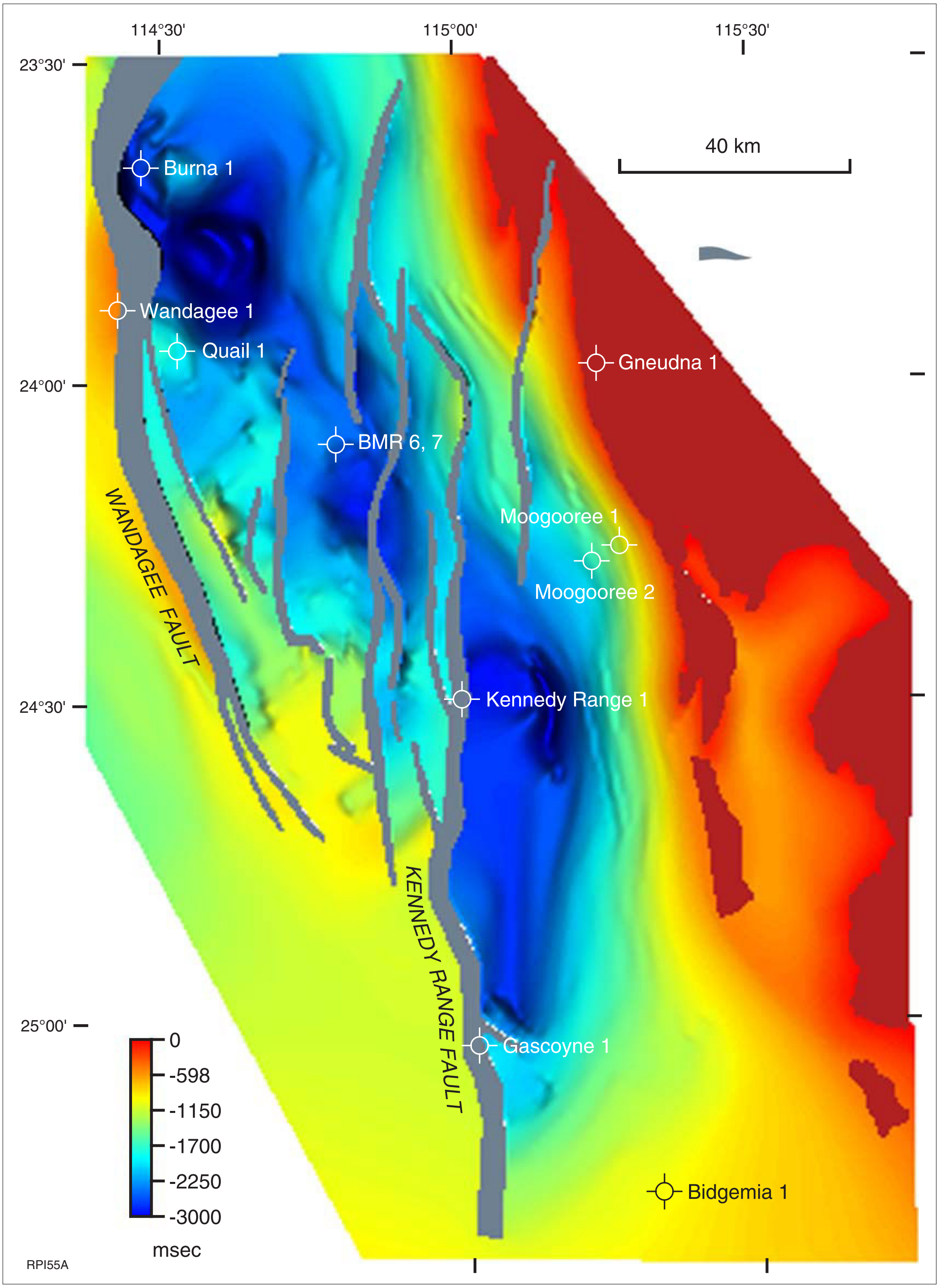

Figure 2. Image of depth to basement from seismic data

shallow volcanics or highly magnetic bodies within basement can completely overprint any signal from the sedimentary strata or, indeed, from the broader basement.

High-resolution aeromagnetic surveys have gained popularity in petroleum exploration because advances in computing, instrumentation and satellite navigation (GPS) have improved the resolution of magnetic signals. Under favourable conditions, aeromagnetic data can provide structural information both within the sedimentary sequence and at basement level. Even if the signal from a sedimentary section is poor, basement structuring can provide indirect information on structures within the overlying sediments.

Aeromagnetic surveys are more commonly conducted offshore than onshore because there are fewer cultural features affecting the magnetic signal, and it is the only efficient way of collecting potential-field data. A useful outcome of an aeromagnetic survey is the calculation of the depth to magnetic basement, which is in general taken to correspond to the depth to crystalline basement. However, depth solutions to magnetic basement may not necessarily correspond to the base of the sedimentary succession because discrete magnetic bodies may affect the depth values making depth solutions ambiguous and inaccurate.

Gravity anomalies are produced where there are density differences between various sedimentary and basement lithologies. Unlike magnetic anomalies, gravity anomalies are not affected by surface cultural effects and surficial rocks and sediments. Processed gravity images show lineaments caused by faulting as well as intra-basement structural and lithological variations in the density of the sediments. Theoretically, the gravity field is better suited to obtaining sedimentary structural information because density variations within the sedimentary succession are more measurable than changes in susceptibility. Unfortunately, a satisfactory airborne gravity system has not yet been developed, so that accurate results can only be achieved from ground measurements. In practice, because ground surveying is logistically more demanding than airborne surveying, many more data points are collected with aeromagnetic surveying than with gravity surveying. Accurate gravity measurements can be made only while stationary, unlike the automatic recording of aeromagnetic data from a moving plane. However, as with aeromagnetic surveys, onshore gravity surveys are also experiencing a resurgence because recent advances in GPS technology allow height to be determined rapidly and more accurately, thereby resulting in the more accurate definition of Bouguer anomalies.

Large parts of the Merlinleigh Sub-basin have difficult access and no seismic coverage. A systematic aeromagnetic and gravity coverage over the sub-basin provided a dataset in areas with little or no data and permitted the extrapolation of structural trends from seismic data or outcrop in these areas. Because of the scarcity of roads or tracks and the difficult terrain, a helicopter-supported gravity survey was the only way to obtain evenly spaced stations at a competitive cost while still maintaining accuracy.

Geophysical data acquisition

The high-resolution aeromagnetic and spectrometer survey over the Merlinleigh Sub-basin began on 4 March 1995 and was completed on 15 April 1995. The survey was conducted by Tesla Airborne Geoscience. A total of 45 305 line-kilometres was flown at a height of 80 m, with a traverse line spacing of 500 m and a tieline spacing of 1500 m. The traverse lines were oriented across the dip of the sub-basin at an azimuth of 067° and the tie lines were flown at an azimuth of 337°. The instruments were set to record the data every 0.1 second, which equates to a reading approximately every 7.5 m along flight lines at the average flying speed of 270 km/hr. The accuracy of the magnetometer is 0.01 nanotesla (nT), and the GPS positioning accuracy is 1 m in the horizontal control and 5 m in the vertical control. The final resolution of the survey is estimated to be better than 0.1 nT.

The semi-detailed helicopter-supported gravity survey over the Merlinleigh Sub-basin, conducted by Haines Surveys, began on 23 May 1995 and was completed on 8 August 1995. To obtain good positioning accuracy, a network of 14 permanent base stations within the survey area was established before the survey commenced and the distances between base stations were kept to a maximum of 20 km. A total of 4000 ordinary gravity stations was established over a grid of 2 by 3 km. Gravity measurements were made every 2 km on traverses oriented at 067°. The traverses were spaced 3 km apart with stations offset by 1 km on alternate traverses to provide maximum resolution of the survey across dip. The survey covered the same area as the aeromagnetic survey but was extended to include a small portion of the Gascoyne Sub-basin (Fig. 1). The additional data collected over the Gascoyne Sub-basin assisted with the interpretation by producing a greater regional coverage, and allowing a better comparison of the gravity response across sub-basins than that afforded by the existing dataset.

A Scintrex CG-3 Autograv gravimeter recorded the gravity data and two single-frequency Trimble 4000SE GPS units were used to position the gravity stations. The accuracy of the gravimeter is 0.1 micrometre/sec^2 (0.01 milligals) and the GPS positioning accuracy was 0.05 m for both horizontal and vertical control. The excellent vertical control permitted a very accurate calculation of the Bouguer anomaly, estimated to be ± 0.5 micrometre/sec^2.

Interpretation of magnetic and gravity data

The aeromagnetic and gravity data were processed and images were produced using the INTREPID and ER Mapper software. A qualitative interpretation of structural features in the Merlinleigh Sub-basin was made by identifying lineaments from magnetic and gravity images. Magnetic lineaments were interpreted from the total magnetic intensity reduced to pole (TMI-RTP), first vertical derivative of TMI-RTP and two shallower depth-slice images. Gravity lineaments were interpreted from the Bouguer anomalies and the first vertical derivative of the Bouguer anomalies images. In this review, only the TMI-RTP image (Fig. 3) and the Bouguer anomalies image (Fig. 4) are shown, the other images used in the interpretation are shown in a more comprehensive report by Iasky et al. (in prep.).

Magnetic data

The most striking feature in the TMI-RTP image is the magnetic-high on the northwestern edge of the survey area between latitudes 23° 30′S and 24° 30′S (Fig. 3). This magnetic-high corresponds to the Wandagee Ridge on the western margin of the Merlinleigh Sub-basin (Fig. 1). Seismic data show a number of down-to-the-east en echelon normal faults along the ridge. The eastern edge of the TMI-RTP image also has a high-amplitude and high-frequency magnetic response that corresponds to near-surface or outcropping basement. The magnetically low areas on the images largely correspond to areas with thicker sediments. However, a magnetic-high on the central northern part of the TMI-RTP image at 23° 50′S, 114° 35′E (Fig. 3) was mapped as an area of deep basement on the seismic data (Fig. 2), indicating the presence of a magnetic body within basement. Another magnetic-high at 24° 30′S, 114° 40′E (Fig. 3) appears to split the sedimentary trough into two parts. Seismic mapping indicates that this is an area where north–south trending faults are interrupted and the throw of faults is relayed across to other faults, suggesting that this basement high influenced the fault pattern in this area. Overall, the magnetic response of the Merlinleigh Sub-basin is very small, but three families of anomalies are present, corresponding to near-surface localized features, north-northwesterly oriented faults, and outcrop.

A number of localized high-amplitude and high-frequency anomalies can be attributed to surface or near-surface magnetization effects in the northwestern part of the image (Fig. 3, red lineaments). These anomalies correspond to kimberlite pipes mapped by Atkinson et al. (1983, 1984) and Jaques et al. (1986). Cultural features such as homesteads and the Dampier–Pinjarra gas pipeline can also be recognized within this family of localized anomalies. Some of the high-frequency anomalies follow mapped faults and may correspond to magnetized material along fault planes. One of these anomalies is present in the Kennedy Range 1 area where the anomalously high hydrocarbon-maturity values found in the well suggest that the organic matter was probably overcooked by an intrusion. The character of the magnetic anomaly over Kennedy Range 1 (Fig. 3) is also seen in another anomaly about 3 km north of the well. This latter anomaly is approximately 7 km in length and coincides with a seismically mapped fault and is also interpreted as intrusive rocks invading a fault plane.

A number of north-northwesterly oriented anomalies of high to middle frequency with varying amplitudes are found predominantly on the western margin of the image (Fig. 3, blue lineaments) and correspond to major fault systems mapped from seismic and outcrop data (Fig. 2). However, the main basin-bounding fault on the western margin (Wandagee Fault) is not imaged as a lineament, but as an area of high magnetic response. This response indicates the presence of a highly magnetic deep-seated body that interferes with smaller, shallower anomalies.

Small and frequent anomalies, represented by high-frequency, low-amplitude north-northwesterly lineaments (Fig. 3, yellow lineaments), probably correspond to near-surface magnetization along outcropping and subcropping strata.

The eastern margin of the sub-basin displays high-frequency, high-amplitude anomalies with numerous mostly north-northwesterly oriented lineaments that are associated with shallow basement rocks. On the eastern margin there are strong westerly and northwesterly lineaments between latitude 24°30′S and 25°00′S that cut across the main north-northwesterly trend. These lineaments do not extend into the trough, which suggests that the relevant structures are confined to basement.

Gravity data

As with the magnetic image, the most striking feature in the Bouguer gravity anomalies image (Fig. 4) is the gravity-high along the western margin and the gravity-low running along the central axis of the Merlinleigh Sub-basin. The shallow basement along the eastern margin of the trough is also indicated by a gravity-high. All anomalies on the gravity images can be related to larger structures within the sedimentary sequence, at basement level or deeper, as there are no high-frequency anomalies because of the 2 by 3 km data spacing. Most of the lineaments that correspond to major faults on the magnetic images are also present on the gravity images, but the gravity images illustrate a more extensive set of lineaments. Four directions of lineaments were identified from northeast and northwest illuminations of the Bouguer anomalies' first vertical derivative images: south-southwest, north-northwest, northwest and southwest (Fig. 4).

South-southwesterly oriented lineaments (Fig. 4, green lineaments, approximate azimuth of 205°) probably correspond to older basement structuring, because they appear to be displaced by the younger tectonism causing the southwesterly lineament direction (Fig. 4, yellow lineaments). An example of this type of displacement is seen at latitude 25° 10′S on the southeastern part of the gravity image.

The most prominent lineaments are oriented north-northwest (Fig. 4, blue lineaments) and may be matched with the north-northwesterly lineaments interpreted from the magnetic images (Fig. 3, blue lineaments), and to the orientation of the Merlinleigh Sub-basin. The presence of these prominent lineaments in both potential-field datasets confirms that faults of this orientation must have been generated during the formation of the sub-basin, probably in the Late Carboniferous. By comparison, the main trend of the seismically mapped faults is northerly. The difference between the main northerly trend shown by seismically mapped faults, and the prominent north-northwesterly trend of gravity lineaments lies in the wide grid of the gravity data,

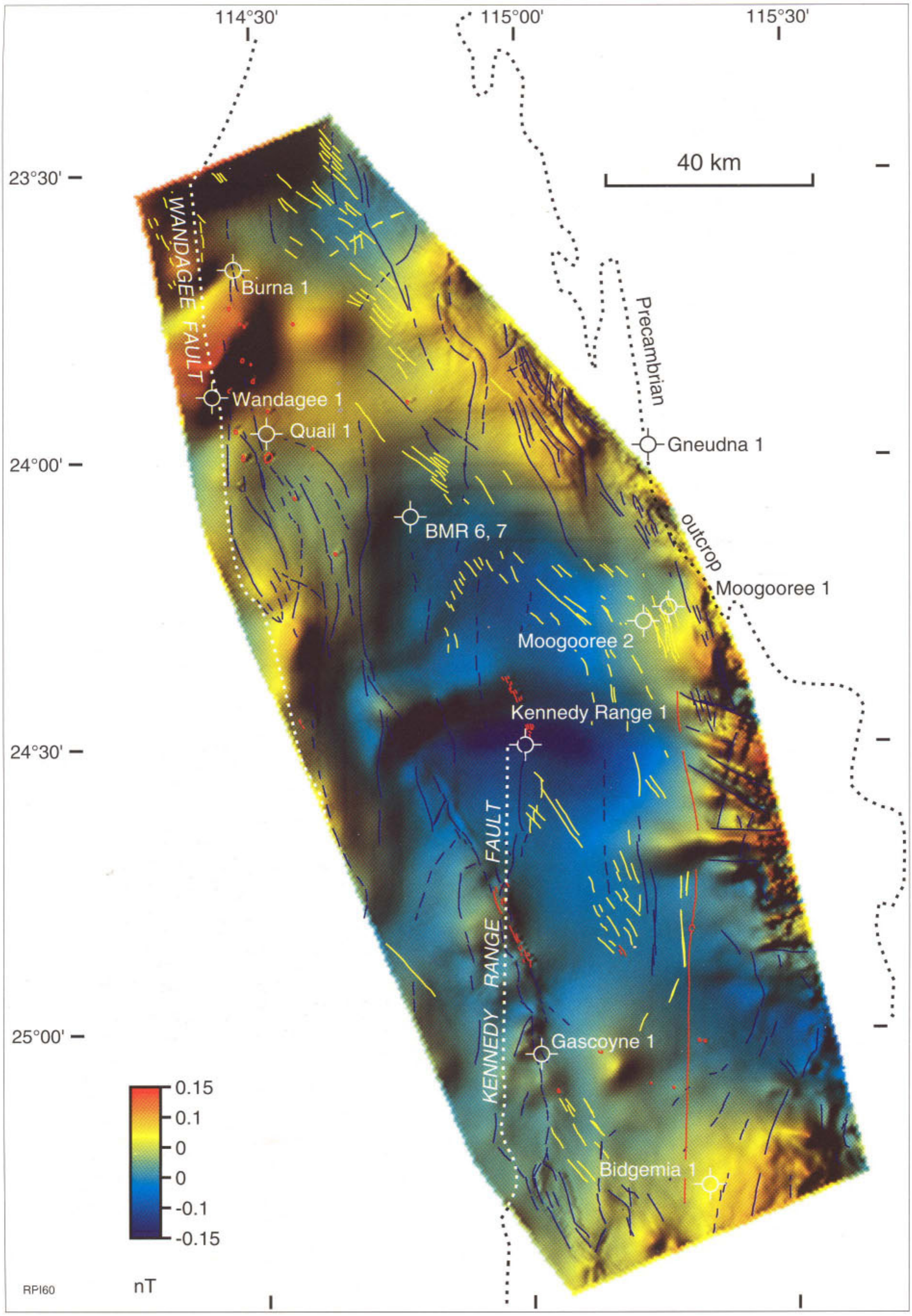

Figure 3. Image of total magnetic intensity reduced to pole (TMI-RTP) with interpreted lineaments shown

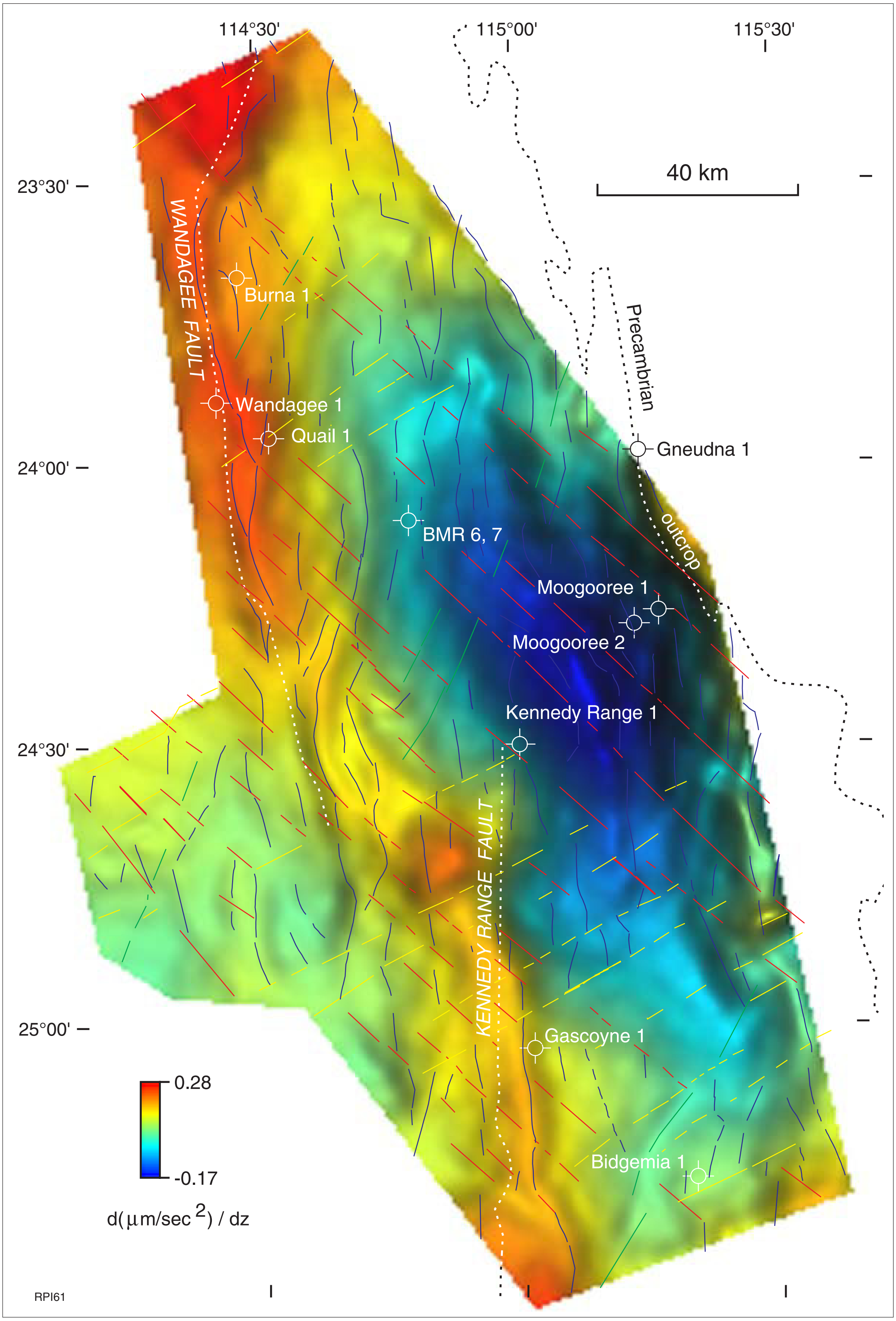

Figure 4. Image of Bouguer gravity anomalies with interpreted lineaments shown

from which only deeper structures may be resolved. The seismic data can resolve smaller and shallower faults in the sedimentary succession, suggesting that the northerly orientation of the main seismically mapped faults represents a later stage of tectonism than do the north-northwesterly trending gravity data (Crostella, 1995).

Northwesterly oriented lineaments (Fig. 4, orange lineaments, azimuth approximately 310°) displace those trending north-northwest. This relationship implies that the northwest lineaments postdate the north-northwest lineaments. These lineaments are subtle and often can be recognized only when older anomalies display a change in character or are interrupted. They have the same direction as transfer faults mapped in the Perth Basin (Mory and Iasky, 1994) and are interpreted as such in the Merlinleigh Sub-basin.

Southwesterly oriented lineaments (Fig. 4, yellow lineaments, approximate azimuth of 240°) probably correspond to strike-slip faults antithetic to the transfer faults. This relationship implies that the Merlinleigh Sub-basin underwent the same dextral transtensional stress regime as that identified by Mory and Iasky (1994) in the Perth Basin.

Of the four sets of gravity lineaments, only those trending north-northwesterly are represented on the magnetic images.

Gravity modelling of a geological cross section across the Merlinleigh Sub-basin has shown significant differences between the model and the seismically controlled cross section. There are two possible explanations: (a) there is lateral density variation within the sedimentary sequence or (b) a denser body within basement affects the gravity field (Iasky et al., in prep.). These density variations make it difficult to obtain an accurate estimation of depth to basement using gravity data.

Conclusions

In frontier areas where seismic coverage is non-existent or sparse, the acquisition of detailed and semi-detailed potential-field data can provide additional useful structural information. Both aeromagnetic and gravity surveys cost a fraction of seismic surveys and can provide valuable information on both the strike and the approximate depth of structures. However, neither method illustrates the timing of structural events, although in some instances the relative timing may be deduced.

In a regional sense, both magnetic and gravity datasets provide similar information by defining the orientation of the Merlinleigh Sub-basin, the Wandagee Ridge on the western margin of the sedimentary trough, the area of thickest sedimentary infill, and a thinning sedimentary succession towards the eastern margin. However, the delineation of lineaments from the two datasets provide contrasting structural details.

Because of the much higher density of data points, magnetic images are capable of delineating high-frequency anomalies that are generated by surface or near-surface magnetization effects, such as kimberlite pipes and volcanic intrusives (Fig. 3). Most of the lineaments seen on the western margin of the Merlinleigh Sub-basin are generated from high-frequency anomalies, suggesting a very shallow source. The larger anomalies on the images show very long wavelengths, suggesting that they are probably generated by very deep bodies within basement. The are only a few anomalies generated by sedimentary structures and at basement level, probably because in the Merlinleigh Sub-basin both the sedimentary and basement rocks have low levels of magnetic susceptibility, which generate low intensity of magnetization in the sub-basin.

The northwesterly, southwesterly and south-southwesterly lineaments from the Bouguer gravity images are interpreted as strike-slip faults that were active at different ages in the Merlinleigh Sub-basin. These lineaments are visible on the gravity image because the juxtaposition of different density rock in the sedimentary sequence causes gravity anomalies. Conversely, the lineaments are absent in the aeromagnetic images because there are no significant susceptibility changes across these faults to cause magnetic anomalies.

For the Merlinleigh Sub-basin, gravity data provide a better definition of depth to basement than magnetic data, because there are more constraints to the modelling and rock-density information is more easily accessible from well logs, well cores and outcrop. However, both lateral and vertical variations in density make it difficult to generate a detailed geological model. In the sub-basin, depth to basement determinations from magnetic data are inaccurate because magnetic bodies are present at depths other than basement level, giving spurious values in comparison with those determined independently from seismic data.

For anomalies no smaller than 1 to 2 km wavelength, the gravity data have produced a more informative structural picture of the Merlinleigh Sub-basin even though the density of the dataset is 1500 times less than that of the aeromagnetic dataset. Given that accurate gravity measurements can be made over a regular grid, gravity surveying should be given a higher priority than aeromagnetic surveying to define structural features in sedimentary basins for petroleum exploration. However, both gravity and magnetic methods provide useful and complementary datasets which can greatly assist seismic and geological interpretation.

References

ATKINSON, W. J., HUGHES, F. E., and SMITH, C. B., 1983, A review of the kimberlitic rocks of Western Australia: CRA Exploration Pty Ltd, report 130077 (unpublished).

ATKINSON, W. J., HUGHES, F. E., and SMITH, C. B., 1984, A review of the kimberlitic rocks of Western Australia, *in* Kimberlites 1: Kimberlites and related rocks *edited by* J. KORNPROBST: Amsterdam, Elselvier, p. 195–224.

CROSTELLA, A., 1995, The structural evolution and the hydrocarbon potential of the Merlinleigh and Byro Sub-basins, Carnarvon Basin, Western Australia: Western Australia Geological Survey, Report 45.

HOCKING, R. M., WILLIAMS, S. J., MOORS, H. T., and van de GRAAFF, W. J. E., 1987, The geology of the Carnarvon Basin, W.A.: Western Australia Geological Survey, Bulletin 133, 289p.

IASKY, R. P., SHEVCHENKO, S., and MORY A. J., in prep., The effectiveness of potential-field data in the structural interpretation of the Merlinleigh Sub-basin, Carnarvon Basin, W.A.: Western Australia Geological Survey, Record.

JAQUES, A. L., LEWIS, J. D., and SMITH, C. B., 1986, The kimberlites and lamproites of Western Australia: Western Australia Geological Survey, Bulletin 132, 268p.

MORY, A. J., and IASKY, R. P., 1994, Structural evolution of the onshore northern Perth Basin, Western Australia, *in* The sedimentary basins of Western Australia *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia Symposium, Perth, 1994, Proceedings.

PERCIVAL, I. G., and COONEY, P. M., 1985, Petroleum geology of the Merlinleigh Sub-basin: The APEA Journal, v. 25, p. 190–203.

TELFORD, W. M., GELDART, L. P., SHERIFF, R. E., and KEYS, D. A., 1976, Applied Geophysics: Cambridge, Cambridge University Press, p. 116–127.

Palynology in the search for Proterozoic hydrocarbons

by K. Grey and K. L. Cotter[1]

Abstract

Neoproterozoic palynomorphs from the Western Australian Officer Basin, once regarded as having little significance for correlation, are now considered to have good potential for biostratigraphic and palaeoenvironmental interpretation, and for analysis of thermal maturity. Modified preparation techniques have produced abundant, well-preserved palynomorphs from many drillcore samples, allowing the application of standard biostratigraphic methods. Palynomorphs consist mainly of spheres and filaments belonging to the cyanobacteria (blue-green bacteria) or the green algae (mainly the Prasinophytes). Many forms are long-ranging, but a few appear to have restricted ranges and are therefore useful for correlation.

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

Palynological studies form part of a major re-evaluation of the hydrocarbon potential of the Officer and Savory Basins (now incorporated in the Officer Basin as the Savory Sub-basin — Perincek, 1996a; Bagas et al., 1995) being carried out by the Interior Basins Group of the Geological Survey of Western Australia (GSWA), and the Neoproterozoic Research Group at Macquarie University. Fossils examined to date are proving useful both for correlation purposes and for thermal maturation analysis. Although work is still at an early stage, it is apparent that biostratigraphic subdivision of at least part of the Neoproterozoic may be possible, allowing enhanced correlations that will aid assessment of the hydrocarbon potential of these poorly known basins.

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In the past, studies of Australian Neoproterozoic successions have suffered from a lack of adequate radiometric dating and stratigraphic control. Considerable advances have been made recently using a combination of tools such as sequence analysis, isotope chemostratigraphy, palynology, stromatolite biostratigraphy, macropalaeontology, seismic interpretation and magnetostratigraphy (Sukanta et al., 1991; Walter, 1994; Perincek, 1996a,b). This, in turn, has led to better correlation both within, and between, the principal areas of Neoproterozoic rocks in Australia, the Centralian Superbasin and the Adelaide Geosyncline (Walter et al., 1995). Of the various tectonic units that make up the Centralian Superbasin, the Western Australian Officer Basin and, in particular, the Savory Sub-basin are still poorly understood. Outcrop is poor, and only a few holes have been drilled. One aim of the re-evaluation of these basins by GSWA is to improve stratigraphic correlation. Palynology has the potential to provide a precise tool for achieving this objective, and also supplies data about thermal maturity and palaeoenvironment.

Studies to date have involved re-assessment of about 125 previously prepared palynological slides from Officer Basin Drillholes, re-preparation of about 20 cuttings and core samples from the same drillholes, and examination of new material from drillholes in the Savory Sub-basin and adjacent areas (Fig. 1), including both diamond drillcore and rotary air blast chips. Modifications to palynological preparation techniques (Grey, in prep.) have improved yields of well-preserved palynomorphs. Many samples contain Neoproterozoic microfossil and acritarch assemblages that have potential for biostratigraphic zonation. Palynomorphs consist mainly of remains of cyanobacterial filaments and coccoids (blue-green bacteria). Other fossils belong to the acritarchs, a polyphyletic group of uncertain affinities, but probably mainly consisting of the resting cysts of prasinophyte algae, a group of planktonic green algae.

Cyanobacteria mostly grew as benthic microbial communities (BMCs) at the sediment–water interface, and are commonly facies controlled. In certain palaeoenvironments, particularly near-shore carbonate facies, BMCs constructed stromatolites, but their remains are also preserved as palynomorphs in silty marine facies. Perhaps the best examples of cyanobacteria occur in chert thin sections, but they are also common components of palynological residues.

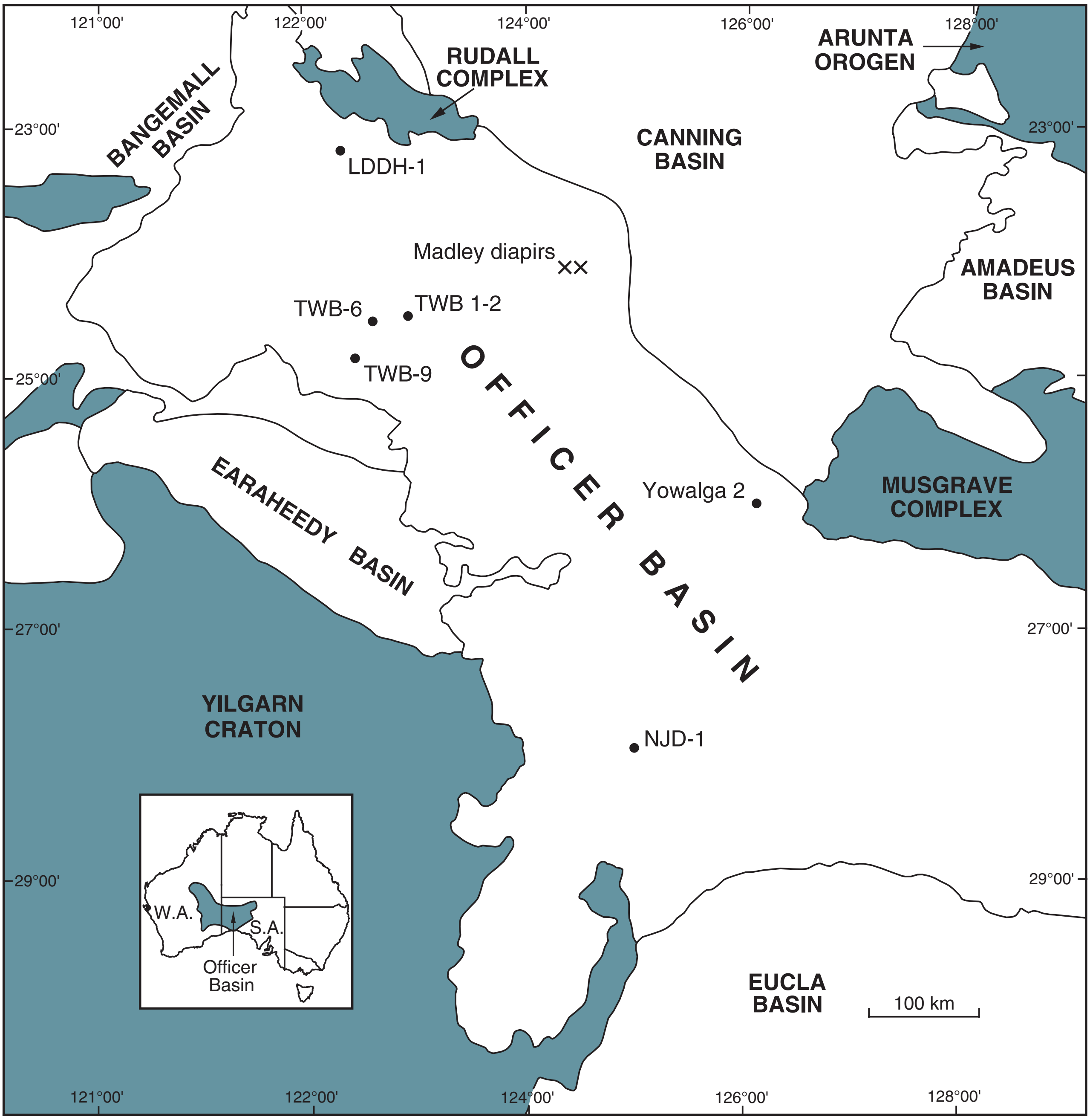


Figure 1. Officer Basin, Western Australia showing drillholes and other localities examined for palynological studies

Acritarchs are the remains of marine phytoplankton that lived mainly in the photic zone, and produced resting cysts that settled out of the water column, and became fossilized after burial. Because of their free-floating habit, phyto-plankton are less subject to (but not entirely free of) facies control. This diverse group shows rapid morphological change, a significant factor for biostratigraphic analysis. Acritarchs provide high-resolution correlation in the early Palaeozoic. Documentation of Neoproterozoic assemblages in Western Australia is still at an early stage, but continuing biostratigraphic studies indicate good potential for correlation.

Initial palynological reports on Officer Basin drillholes suggested little possibility for correlation (Grey, 1981; Hos, 1982a,b; van Niel, 1984). However, there have been considerable advances in Proterozoic palaeobiology and biostratigraphy in the decade and a half since the last of these holes was drilled, and a brief re-examination of Officer Basin preparations has indicated that some species apparently do have restricted ranges and consequently are biostrati-graphically significant. Some palaeoenvironmental control of assemblages is also evident, but the extent of this is not clear at present. Preliminary determinations of colour maturation (Traverse, 1988) indicate that at least some samples lie within the oil–gas window; for example the TAI (thermal alteration index) of samples from the Kanpa Formation in Hussar 1 ranges from 3- to 3+, which is consistent with liquid petroleum to dry gas-generation phase (Grey, 1995a). Similar levels of maturity were observed in Normandy–Poseidon's Lake Disappointment drillhole (LDDH 1) in the Tarcunyah Group (Grey, 1995b), and in a series of water bores (TWB 1, TWB 2, TWB 6 and TWB 9; Grey, 1995c) drilled in the Savory Basin by GSWA (Fig. 1).

The degree of certainty with which correlations can be made varies throughout the Neoproterozoic. Walter et al. (1995) proposed a four-fold division of the Centralian Superbasin based on a variety of methods, and based mainly on the better known successions of the Adelaide Geosyncline and the Amadeus and South Australian Officer Basins. Successions in Western Australia can be analysed using the terminology of Walter and Gorter (1994), Walter et al. (1994), and Walter et al. (1995), and correlated with acritarch assemblages from these better studied areas (Zang and Walter, 1992; Zang, 1994, 1995; Zang and McKirdy, 1994; Grey, in prep.). A generalized correlation based on Perincek (1996a) is shown in Figure 2 and a brief summary of the supersequences is given below.

- **Early Neoproterozoic.** Neoproterozoic deposition in Australia was concentrated in the Centralian Superbasin (Walter and Gorter, 1994; Walter et al., 1995) and the Adelaide Geosyncline (Preiss, 1987), although deposition also occurred in the Kimberley area, Paterson Orogen and Tasmania. Although steeply dipping rocks occur below the later Neoproterozic in Western and South Australia, their age is indeterminate and could be either Mesoproterozoic or Neoproterozoic.

  The age of depositional onset in the Centralian Superbasin and Adelaide Geosyncline is poorly constrained. The only reliable date, a concordant U–Pb date of 802 ± 10 Ma from the Rook Tuff in the Callanna Group of the Stuart Shelf in South Australia (Fanning et al., 1986) suggests that sedimentation began before 800 Ma. Fossil evidence for the age of sediments deposited prior to the formation of the Centralian Superbasin is sparse, and very little is known about the palynostratigraphy of successions older than Supersequence 1.

- **Supersequence 1.** Basal units show surprising uniformity throughout the Centralian Superbasin, and consist of arenite overlain by carbonate and siliciclastic rocks. In the western Officer Basin, Supersequence 1 comprises the Townsend Quartzite, Browne, Madley, Neale and Ilma Formations, the slightly younger Woolnough, Kanpa and Hussar Formations, and the overlying Steptoe Formation. In the Savory Basin several arenaceous units have been recognized, including the Glass Spring, Jilyili, Brassey Range and Spearhole Formations, and these are overlain by the Mundadjini and Skates Hills Formations (Williams, 1992). Although precise relationships between units are still being investigated, they appear to be equivalent to the Heavitree Quartzite and Bitter Springs Formation in the Amadeus Basin (Walter et al., 1994; Grey, 1995d). In the South Australian Officer Basin the equivalents are the Pindyin beds and the overlying Alinya Formation (Zang, 1995).

  Stromatolites, in particular *Acaciella australica*, indicate a time correlation of carbonate units throughout the superbasin (Grey, 1995d); otherwise correlation has depended mainly on lithological comparison, seismic stratigraphy, and sequence-bounding unconformities (Walter et al., 1995; Perincek, 1996a,b). However, current studies show that drillhole material contains good palynomorph assemblages. Microfossils tend to be conservative in morphology and long-ranging, but some Supersequence 1 acritarchs may be more diverse, short-ranging, distinctive and comparable with those described from material of similar age elsewhere (e.g. Zang and McKirdy, 1994; Zang, 1995; Jankauskas, 1989; Vidal, 1976; Butterfield et al., 1994). This indicates potential for biostratigraphic correlation, but their use is limited at present because stratigraphic ranges are poorly constrained. This should be resolved by more rigorous taxonomic analysis and preparation of range charts, and will provide a framework for dating successions throughout the Officer Basin and other late Neoproterozoic assemblages in the future.

- **Supersequence 2.** Australia-wide correlation of this unit is based mainly on the development of Sturtian glaciogenic sediments. The age of western Officer Basin tillites, the Turkey Hill and Lupton Formations, is uncertain. They could be Sturtian, but palaeoisopachs for Supersequence 2 (Walter and Gorter, 1994; Walter et al., 1995) suggest that this glaciation is not represented in Western Australia. Either these deposits have been removed by erosion in Western Australia, or they never extended so far west. In the Amadeus Basin, Supersequence 2 comprises the Areyonga and Aralka Formations. In the eastern South Australian Officer Basin it is represented by the Chambers Bluff Tillite and an unnamed overlying siltstone. Only a restricted palynomorph assemblage has been found so far (Grant, S., 1995, pers. comm.).

- **Supersequence 3.** The base of the supersequence is marked by the Marinoan glaciation. Tillites in the Western Australian Officer Basin tillites are probably Marinoan in age (although a Sturtian age cannot be ruled out — *see above*). The age of the Babbagoola Formation, previously assigned to supersequence 3 or younger (Water et al., 1995), is uncertain, although recent palynological investigations indicate a Supersequence 1 age for the type section and adjacent areas (Grey, 1995a). Other sediments correlated lithologically with the Babbagoola Formation may be as

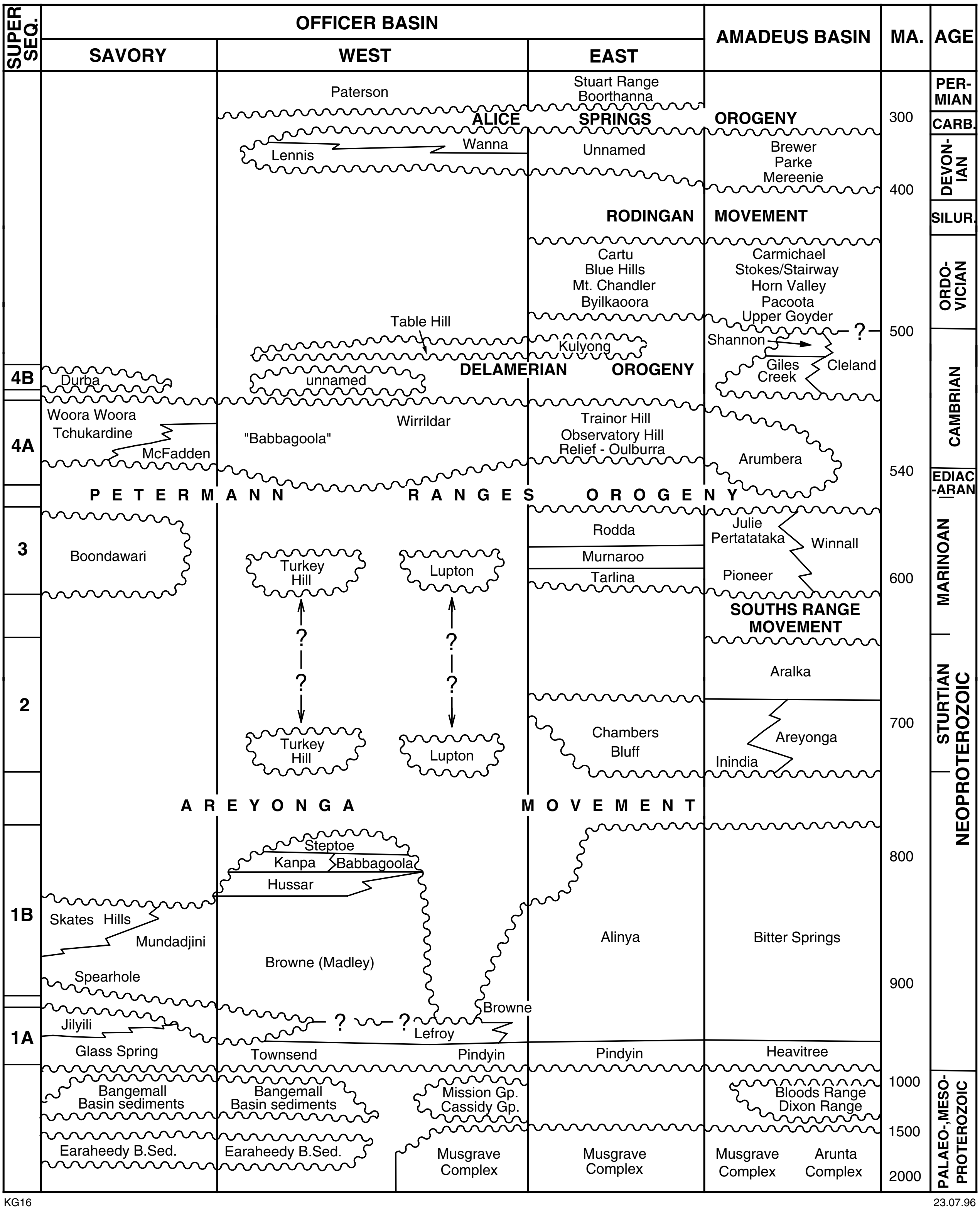


Figure 2. Proposed stratigraphic correlation of the Officer Basin and Amadeus Basin; modified after *Jackson et al. (1984), Townson (1985), Williams (1992), Walter and Gorter (1994), Gravestock and Lindsay, (1994), Moussavi-Harami and Gravestock (1994), Grey (1995), and Perincek (1996a)*

young as Cambrian (Perincek, 1996a,b).

In the Savory Sub-basin the Boondawari Formation comprises tillite, siltstone and carbonate that compare lithologically and in isotope chemostratigraphy with Supersequence 3 units elsewhere in the Centralian Superbasin (Walter et al., 1994). Surface samples from the Boondawarri Formation were prepared palynologically, but all were barren (Grey, unpublished data). The stratigraphic positions of the McFadden, Woora Woora, and Tchukardine Formations are still debatable; they could be Supersequence 3, Supersequence 4, or Cambrian (Perincek, 1996a,b).

In the Amadeus Basin this interval is represented by the Olympic Formation and Pioneer Sandstone, and overlying Pertatataka and Julie Formations, and in the South Australian Officer Basin by the Rodda beds and equivalent units. In the Adelaide Geosyncline, Supersequence 3 comprises the Nuccaleena and Brachina Formations, ABC Range Quartzite, and Bunyeroo and Wonoka Formations.

Correlations of these successions are well constrained; firstly by widespread tillites, secondly by the Acraman impact ejecta horizon, found in both the Flinders Ranges and drillholes in the Officer Basin (Gostin et al., 1986; Williams, 1986; Wallace et al., 1989), and thirdly by sequence stratigraphy (Sukanta et al., 1991; Zang, 1995; Moussavi-Harami and Gravestock, 1995). The upper part of the supersequence can be correlated by isotope chemostratigraphy (Walter et al., 1995). Stromatolites provide another, somewhat limited, means of correlation (Walter et al., 1979; Walter et al., 1994; Corkeron et al., 1996)

In addition, the Pertatataka Formation and Rodda beds contain distinctive, well-documented and well-constrained palynomorph assemblages of biostratigraphic significance (Zang and Walter, 1992; Jenkins et al., 1992; Grey, unpublished data). Much of this interval contains large, morphologically complex acritarchs that provide a basis for further subdivision (Zang and Walter, 1992; Grey, unpublished data).

Correlation of Western Australian successions with other parts of the superbasin is still uncertain. Limited isotope chemostratigraphy and similar lithology suggests correlation of the upper part of the Boondawari Formation with the Julie Formation of the Amadeus Basin and the upper Wonoka Formation of the Adelaide Geosyncline (Walter et al., 1994).

- **Supersequence 4.** The age of the McFadden, Woora Woora, and Tchukardine Formations remains unclear. From the limited evidence available they are most probably Supersequence 4, but could be uppermost Supersequence 3. Both palynological evidence and seismic interpretation have indicated that the Babbagoola Formation in Yowalga 2 (the type section) and in Yowalga 3 belong to Supersequence 1 (Grey, 1995a; Perincek, 1996a,b). The age of other sediments previously assigned to the Babbagoola Formation is still being investigated.

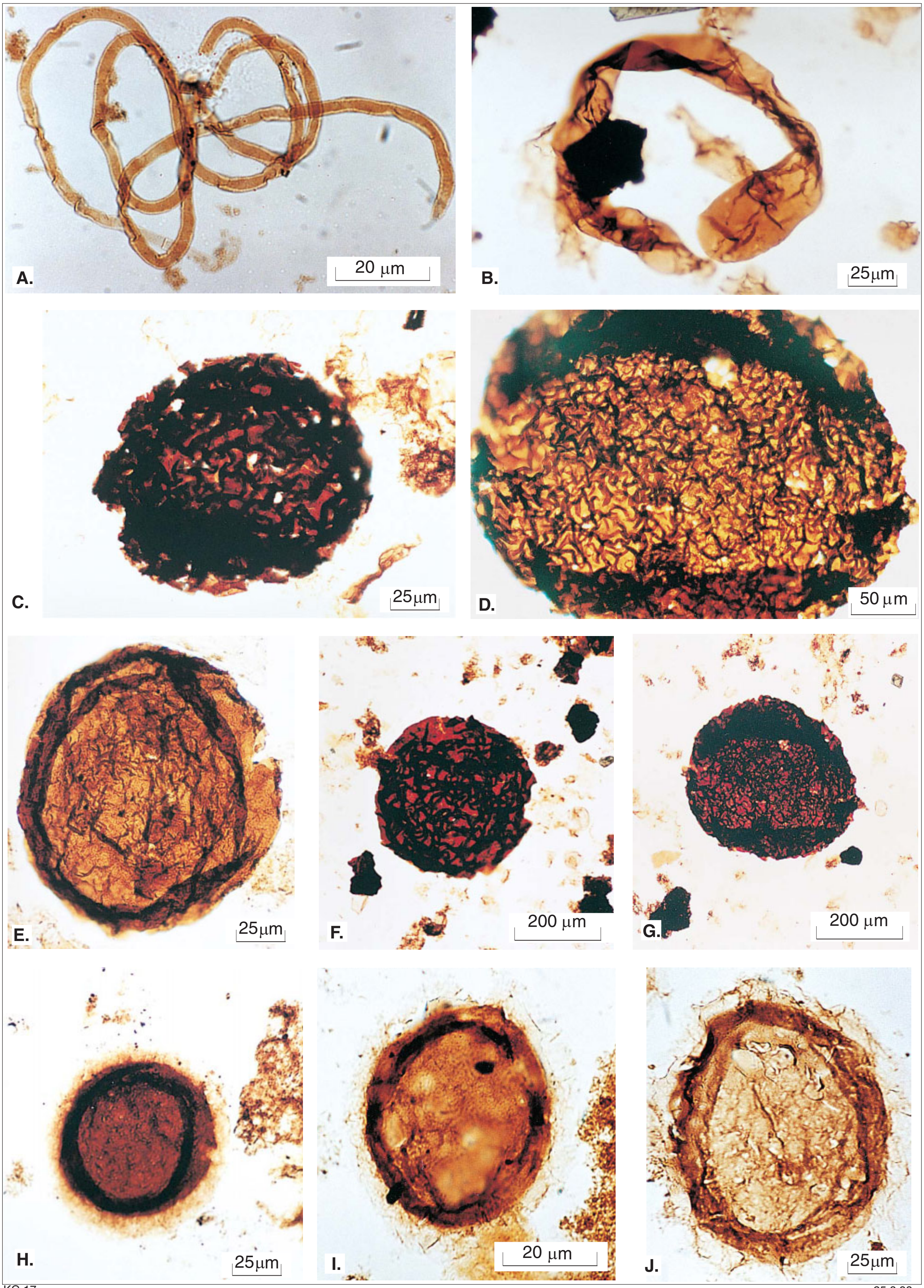
The Table Hill Volcanics is younger than the above mentioned units, and much hinges on the age of the volcanics and their northern Australian equivalents, the Antrim Plateau Volcanics, which together form a major outpouring of flood basalts. The Table Hill Volcanics has tentatively been dated at 563 ± 40 Ma (recalculated *from* Compston, 1974), an age consistent with Supersequence 4 (Walter et al., 1995), but the date is equivocal, and the formation may be as young as Cambrian (Perincek, 1996a,b).

In the Amadeus Basin, Supersequence 4 consists of the Arumbera Sandstone; in the South Australian Officer Basin it comprises the Punkerri Formation and probably the Relief Sandstone; and in the Adelaide Geosyncline, the Pound Subgroup. Outside Western Australia this interval contains metazoan body and trace fossils of the Ediacaran fauna, and is succeeded by the Tommotian small shelly fossil fauna that marks the base of the Cambrian. Possible medusoid fossils were reported from the Stirling Ranges in the southwest of Western Australia (Cruse and Harris, 1994), but no Ediacaran or Cambrian trace or body fossils have been found in the Tchukardine, Woora Woora or McFadden Formations, despite the suitability of the lithologies for the preservation of such fossils.

The palynostratigraphy of Supersequence 4 is poorly known. Limited reports from other parts of Australia and elsewhere in the world suggest that assemblages consist mainly of poorly preserved, simple forms of limited biostratigraphic potential. Large, morphologically complex species appear to have become extinct by this period. A Cambrian age was assigned to the Babbagoola Formation from what are now considered to be poorly preserved acritarchs (Jackson and Muir, 1981), and

Figure 3. Selected palynomorphs from the Western Australian Officer Basin. Identifications should be regarded as tentative pending further systematic analysis. Slides are held in the GSWA palynological relinquishment collection. England Finder coordinates are given for each specimen

(a) Siphonophycus sp. (Assemblage 2), Yowalga 2, 988.47 m/2, B-64-0
(b) Clavitrichoides rugosus (Assemblage 2), Yowalga 2, 988.47 m/2, L-62-4
(c) Cerebrosphaera sp. (Assemblage 2), Yowalga 2, 988.47 m/2, U-51-4.
(d) (g) Cerebrosphaera sp. (Assemblage 2), Hussar 1, 1275.0 m/2, U-52-4
(e) ?Chuaria circularis (Assemblage 2), Hussar 1, 1275.0 m/2, L-34-0
(f) Cerebrosphaera sp. (Assemblage 2), Hussar 1, 1275.0 m/2, H-58-1
(h) Simis annulare (Assemblage 2), Hussar 1, 1275.0 m/2, F-31-0
(i) 'Trachyhystrichosphaera vidalii' (of Zang, 1995) (Assemblage 2), Hussar 1, 1275.0 m/2, N-56-0
(j) 'Trachyhystrichosphaera vidalii' (of Zang, 1995) (Assemblage 2), Hussar 1, 1275.0 m/2, Q-53-3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current investigations have not confirmed a Cambrian age. As discussed above, at least part of the formation is of Supersequence 1 age, but palynological results from other parts of the formation have been indeterminate. This part of the succession does not appear to contain the diverse acritarch assemblage found elsewhere in Supersequence 3.

- **Cambrian** The biological explosion that occurred at the base of the Cambrian is well documented, but no sediments in Western Australia can be confidently assigned to the basal Cambrian. Acritarchs are well documented from the Proterozoic–Cambrian transition in other parts of the world. The Early Cambrian is characterized by distinctive and diverse assemblages of small spiny acritarchs, but no sediments containing these acritarchs have been reported from Western Australia to date.

Most palynological samples examined so far from Western Australia are from Supersequence 1. Supersequence 2 probably did not extend into Western Australia (Walter et al., 1995), and none of the highly diverse Supersequence 3 assemblages has been observed in Western Australia. Assemblages from rocks assigned to uppermost Supersequence 3 or Supersequence 4 are poorly preserved, and their biostratigraphic value appears limited.

Recently recognized Officer Basin and Savory Sub-basin assemblages are briefly described below, and some of the key species are illustrated in Figures 3 and 4. At this stage it is difficult to be certain of relationships between assemblages, because good stratigraphic control is lacking, and barren or poorly preserved intervals mean that the correct superposition of assemblages cannot always be determined. Some key species have yet to be rigorously defined, and because differences between species are often subtle, identification of poorly preserved specimens is difficult. In addition, there may be reworking of some of the more robust species, and there may be facies control of some distributions. Many of these problems will be resolved as knowledge of distribution patterns increases.The following (tentative) Supersequence 1 assemblages have been recognized in the Western Australian Officer Basin and Savory Sub-basin:

- ***Assemblage 1:*** Assemblage 1 contains abundant filaments, mat fragments containing either filaments and/or coccoids, clusters of spheres about 3 to 10 µm in diameter, clusters of spheres about 20 µm in diameter, and abundant leiospheres. Although the presence of mat-like fragments formed by benthic microbial communities suggests strong facies dependence, this particular assemblage seems to occur consistently in the lower part of Supersequence 1, and similar material has been recorded from the Gillen Member, the lower, evaporite-rich unit of the Bitter Springs Formation (Zang and Walter, 1992; Cotter, in prep.). The proportions of the species vary considerably, probably as a result of facies control; for example in Yowalga 3 most samples are dominated by leiospheres, whereas in other samples, filaments are the dominant elements (Cotter, in prep.). Assemblage 1 occurs in the Browne Formation in Kanpa 1A and Yowalga 3, and in the Madley Formation in Dragoon 1. This assemblage has previously been noted in NJD 1 at 260.90 m.

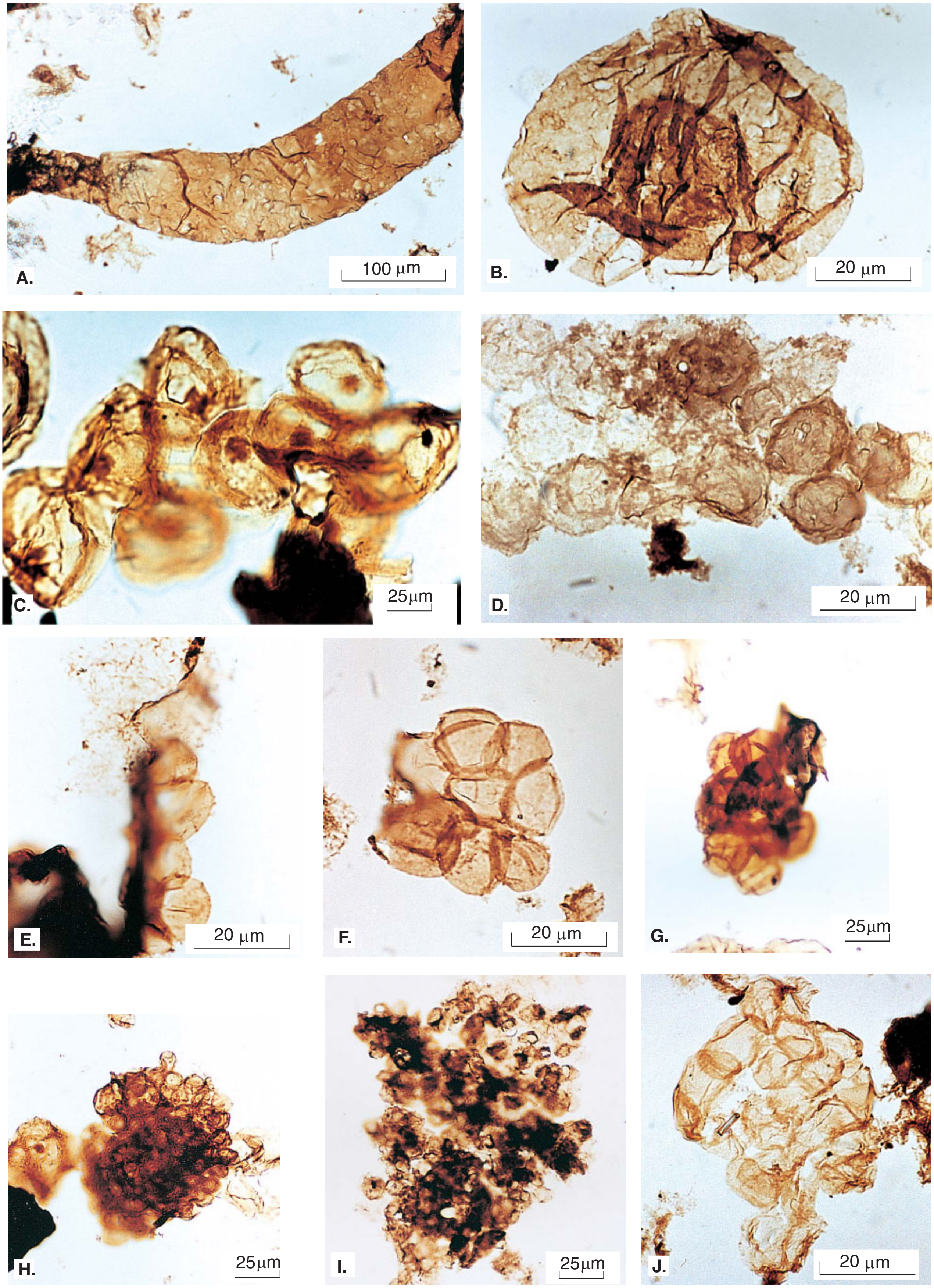
  Chert thin sections from outcrop at the Madley Diapirs comprise mainly clusters of coccoid cyanobacteria (Cotter, in prep.) and are similar to some specimens recovered in palynological preparations. Similar material has been described from the Gillen Member of the Bitter Springs Formation (Schopf, 1968; Zang and Walter, 1992).

- ***Assemblage 2:*** Assemblage 2 is dominated by a large, thick-walled acritarch with a surface covered in tight, convoluted folds. This resembles *Cerebrosphaera* Butterfield Knoll and Swett 1994, from the 700 to 800 Ma Svanbergfjellet Formation of Spitsbergen, but there are differences that suggest that it may be a new species. Coenobial aggregates, tentatively assigned to *Synsphaeridium*, are common, and a large, thick-walled leiosphere, which is either smooth or slightly wrinkled, ?*Chuaria circularis,* is fairly abundant. Smaller, thinner-walled leiospheres, *Leiosphaeridium atava* and *L. crassa* (both long-ranging forms), are also abundant. This assemblage has been recognized in the Kanpa and Hussar formations in Lungkarta 1, where it is well preserved and occurs more or less continuously from an interval of over 260 m. It is also present in the Babbagoola Formation in Yowalga 2 and Yowalga 3.

- ***Assemblage 3:*** Assemblage 3 is diverse and contains abundant specimens including *Satka colonialica*?, *Synsphaeridium, Stictosphaeridium, Simia annulare, Eoentophysalis,* ?*Leiosphaeridia exsculpta, L. atava, L. crassa, L. jacutica,* ?*Chuaria circularis.* A similar assemblage has been recorded from the South Australian Officer Basin in the Alinya Formation in Giles 1 (Zang and McKirdy, 1994; Zang, 1995). The Alinya Formation has been interpreted as a subtidal

Figure 4. Selected palynomorphs from the Western Australian Officer Basin. Identifications should be regarded as tentative pending further systematic analysis. Slides are held in the GSWA palynological relinquishment collection. England Finder coordinates are given for each specimen

(a) Large tubular filament (Assemblage 2), Yowalga 2, 988.47 m/2, Y-67-1
(b) Leiosphaeridia crassa (Assemblage 2), Hussar 1, 1275.0 m/2, T-63-4
(c) Synsphaeridium sp. (Assemblage 2), Yowalga 2, 988.47 m/2, L-62-0
(d) Synsphaeridium sp. (Assemblage 1), LDDH 1, 277.0 m/2, N-28-4
(e) Actucellularia ellipsoides (Assemblage 1), TWB 6, 49-50 m/2, P-58-3
(f) Synsphaeridium sp. (Assemblage 1), TWB 6, 49-50 m/2, G-49-4
(g) Cluster of small spheres ?Leiosphaeridia sp. (Assemblage 2), Yowalga 2, 988.47 m/2, Y-60-0
(h) Cluster of small spheres ?Myxococcoides sp. (Assemblage 2), Yowalga 2, 988.47 m/2, J-54-0
(i) Degraded coccoid mat (Assemblage 1), LDDH 1, 277.0 m/2, Q-44-0
(j) Satka colonialica? (Assemblage 1), TWB 6, 49-50 m/2, P-58-3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shelf to coastal sabkha facies, and may be equivalent to part of the Bitter Springs Formation in the Amadeus Basin, although it has not yet been observed in palynological preparations from Wallara 1 drillhole (Cotter, in prep.). Zang and McKirdy (1994) identify the Alinya Formation as a potential source rock.

In Western Australia Assemblage 3 is present in the Kanpa and Hussar Formations in Hussar 1, and possibly in the Steptoe Formation in Kanpa 1A, although this material is poorly preserved.

- ***Assemblage 4:*** The probable stratigraphic position of Assemblage 4 is uncertain. It contains abundant and well-preserved acritarchs, but consists almost entirely of simple leiospheres. The species present are long ranging and of no particular biostratigraphic significance, although similar low-diversity palynofloras have been recorded from the latest Proterozoic elsewhere in the world. Assemblage 4 is found in the Babbagoola Formation in Yowalga 3, and consists predominantly of *Leiosphaera atava* and rarer specimens of *L. crassa*. The assemblage appears to be facies controlled, and from seismic interpretation is probably part of Supersequence 1 (Perincek, 1996b).

Conclusions

Preliminary assessment of available palynological material suggests that the development of a Neoproterozoic biostratigraphic zonation for the Officer Basin and Savory Sub-basin is feasible and would aid in the evaluation of the hydrocarbon potential in Western Australia's Neoproterozoic basins. Supersequence 1 contains mainly long-ranging species of cyanobacterial origin. Nevertheless, it appears capable of further subdivision based on shorter ranging phytoplanktonic taxa. Supersequence 2 assemblages are still poorly known throughout Australia, and the supersequence does not appear to be present in Western Australia. Supersequence 3 contains a diverse, biostratigraphically significant palynomorph assemblage. The topmost Supersequence 3 and base of Supersequence 4 have not been well documented elsewhere in Australia, either because assemblages are extremely poorly preserved, or because unsuitable lithologies have prevented sampling (Grey, in prep.). The Western Australian succession is likewise poorly known.

The assemblages recorded from Western Australia are consistent with distributions in other parts of the world. Assemblages up to c. 750 Ma were dominated by long-ranging, morphologically conservative taxa, but rarer, more complex and probably short-ranged taxa are also present. After the Marinoan glaciation (equivalent to the Varanger glaciation of the northern hemisphere) the large, morphologically complex phytoplankton, typical of Supersequence 3 in Australia (Zang and Walter, 1992; Grey, unpublished data) and also reported from eastern Siberia (Moczydlowska et al., 1993), and China (Yin and Li, 1978; Yin, 1987; Awramik et al., 1985; Xing and Liu, 1982; Zhang, 1984), became dominant. Because of the diversity of the assemblage, it has good potential for biostratigraphy.

These large complex forms seem to have become extinct about the time of the first appearance of the metazoan fauna, although it is not clear precisely when, or why, they became extinct. By the latest Proterozoic (the late Vendian of Europe), assemblages again appear to be dominated by simple leiospheres.

Acritarch assemblages show considerable promise for the correlation of the various successions, not only between basins within Western Australia, but also with other basins in Australia, and on a worldwide basis. In particular, the similarities of the Western Australian assemblages to documented assemblages spanning hydrocarbon-producing successions in Siberia and China encourage continuation of this line of research.

References

AWRAMIK, S. M., McMENAMIN, D. S., YIN CHONGYU, ZHAO ZIQIANG, DING QIXIU, and ZHANG SHESEN, 1985, Prokaryotic and eukaryotic microfossils from a Proterozoic/ Phanerozoic transition in China: Nature, v. 315, p. 655–658.

BAGAS, L., GREY, K., and WILLIAMS, I. R., 1995, Reappraisal of the Paterson Orogen and Savory Basin: Western Australia Geological Survey, Annual Review 1994–95, p. 55–63.

BUTTERFIELD, N. J., KNOLL, A. H., and SWETT, K., 1994, Paleobiology of the Neoproterozoic Svanbergfjellet Formation, Spitsbergen: Fossils and Strata, no. 34, p. 1–84.

COMPSTON, W., 1974, The Table Hill Volcanics of the Officer Basin — Precambrian or Palaeozoic?: Geological Society of Australia, Journal, v. 21, p. 403–12.

CORKERON, M., GREY, K., LI, Z. X., and POWELL, C. McA., 1996, Neoproterozoic glacial episodes in the Kimberley region, northwestern Australia: Geological Society of Australia, Abstracts no. 41, 13th Australian Geological Convention, p. 97.

COTTER, K. L., in prep., Palaeobiology of Neoproterozoic chert and siliciclastics of Supersequence 1, from the western Officer Basin, Western Australia: Alcheringa.

CRUSE, T., and HARRIS, L.B., 1994, Ediacaran fossils from the Stirling Range Formation, Western Australia: Precambrian Research, v. 67, p. 1–10.

FANNING, C. M., LUDWIG, K. R., FORBES, B. G., and PREISS, W. V., 1986, Single and multiple grain U–Pb zircon analyses for the early Adelaidean Rook Tuff, Willouran Ranges, South Australia: Geological Society of Australia, Abstracts, no. 15, p. 255–304.

GOSTIN, V. A., HAINES, P. W., JENKINS, R. J. F., COMPSTON, W., and WILLIAMS, I. S., 1986, Impact ejecta horizon within late Precambrian shales, Adelaide Geosyncline, South Australia: Science, v. 233, p. 198–200.

GRAVESTOCK, D. I., and LINDSAY, J. F., 1994, Summary of 1993 seismic exploration in the Officer Basin, South Australia: PESA Journal, no. 22, p. 65–75.

GREY, K., 1981, *Acaciella* cf. *australica* and organic-walled microfossils from the Proterozoic Browne beds, Shell Yowalga 3, Officer Basin: Western Australia Geological Survey, Palaeontology Report 44/1981 (unpublished).

GREY, K., 1993, Appendix F: Acritarch biostratigraphy of the Ediacarian of the Centralian Superbasin, *in* Field guide to the Adelaide Geosyncline and Amadeus Basin, Australia *edited by* R. J. F. JENKINS, J. F. LINDSAY and M. R. WALTER: Australian Geological Survey Organisation, Record 1993/35, p. 109–118.

GREY, K., 1995a, Officer Basin drillholes — review of Neoproterozoic palynological data: Western Australia Geological Survey, Palaeontological Report 1995/11 (unpublished).

GREY, K., 1995b, Palynology of Normandy–Poseidon Lake Disappointment 1 corehole, Tarcunyah Group, Paterson Orogeny: Western Australia Geological Survey, Palaeontology Report 1995/21 (unpublished).

GREY, K., 1995c, Savory Basin drillholes TWB 1, 2, 6, 9 (Trainor water bores) palynology and thermal maturation: Western Australia Geological Survey, Palaeontology Report 1995/20 (unpublished).

GREY, K., 1995d, Neoproterozoic stromatolites from the Skates Hills Formation, Savory Basin, Western Australia, and a review of the distribution of *Acaciella australica*: Australian Journal of Earth Sciences, v. 42, p. 123–132.

GREY, K., in prep., Neoproterozoic acritarchs from the Centralian Superbasin: Macquarie University, PhD thesis (unpublished).

HOS, D. P. C., 1982a, Eagle Corporation Ltd. Dragoon No. 1 Palynological Report (unpublished).

HOS, D. P. C., 1982b, Palynological Report on Eagle Corporation Ltd. et al. Hussar No. 1 Well, Officer Basin (unpublished).

JACKSON, M. J., and MUIR, M. D., 1981, The Babbagoola Beds, Officer Basin, Western Australia: correlations, micropalaeontology, and implications for petroleum prospectivity: BMR Journal of Australian Geology and Geophysics, v. 6, no. 1, p. 81–93.

JACKSON, K. S, McKIRDY, D. M., and DECKELMAN, J. A., 1984, Hydrocarbon generation in the Amadeus Basin, Central Australia: The APEA Journal, no. 24, p. 42–65.

JANKAUSKAS, T. V., (editor), 1989, Mikrofossilii Dokembriya SSSR (Precambrian microfossils of the USSR), Trudy Institut Geologii i Geokhronologii, SSSR Akademiya Nauk, Lenningrad, 191p (in Russian).

JENKINS, R. J. F., McKIRDY, D. M., FOSTER, C. B., O'LEARY, T., and PELL, S.D., 1992, The record and stratigraphic implications of organic-walled microfossils from the Ediacaran (terminal Proterozoic) of South Australia: Geological Magazine, v. 129, p. 401–410.

MOCZYDLOWSKA, M., VIDAL, G., and RUDAVSKAYA, V. A., 1993, Neoproterozoic (Vendian) phytoplankton from the Siberian platform, Yakutia: Palaeontology, v. 36, p. 495–521.

MOUSSAVI-HARAMI, R., and GRAVESTOCK, D. I., 1995, Burial history of the eastern Officer Basin, South Australia: APEA Journal 1995, p. 307–320.

PERINCEK, D.,1996a, The age of the Neoproterozoic–Palaeozoic sediments within the Officer Basin of the Centralian Super-Basin can be constrained by major sequence-boundary unconformities: APPEA Journal, v. 36, p. 61–79.

PERINCEK, D., 1996b, The stratigraphic and structural development of the Officer Basin, Western Australia: a review: Western Australia Geological Survey, Annual Review 1995–96, p. 135–148

PREISS, W. V. (compiler), 1987, The Adelaide Geosyncline — late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics: South Australia Geological Survey, Bulletin 53, 438p.

SCHOPF, J. W., 1968, Microflora of the Bitter Springs Formation, Late Precambrian, Central Australia: Journal of Paleontology, v. 42, p. 651–688.

SUKANTA, U., THOMAS, B., von der BORCH, C. C., and GATEHOUSE, C. G., 1991, Sequence stratigraphic studies and canyon formation, South Australia: PESA Journal, v. 19, p. 68–73.

TOWNSON, W. G., 1985, The subsurface geology of the western Officer Basin — results of Shell's 1980–1984 petroleum exploration campaign: APEA Journal, no. 25, p. 34–51.

TRAVERSE, A., 1988, Paleopalynology: London, Unwin Hyman, 600p.

van NIEL, J., 1984, Palynological analysis of Lungkarta 1, Officer Basin, WA: (Permit EP 178) Shell Development (Australia) Pty Ltd SDA 652 (unpublished).

VIDAL, G., 1976, Late Precambrian microfossils from the Visingso Beds in southern Sweden: Fossils and Strata, no. 9, 57p.

WALLACE, M. W., GOSTIN, V. A., and KEAYS, R. R., 1989, Discovery of the Acraman impact ejecta blanket in the Officer Basin and its stratigraphic significance: Australian Journal of Earth Sciences, v. 36, p. 585–587.

WALTER, M. R., 1994, A revolution in exploration of Proterozoic Basins: Australasian Institute of Mining and Metallurgy, Bulletin no. 6, p. 68–69.

WALTER, M. R., and GORTER, J. D., 1994, The Neoproterozoic Centralian Superbasin in Western Australia: the Savory and Officer Basins, *in* The sedimentary basins of Western Australia *edited by* P. G. PURCELL and R. R. PURCELL: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth 1994, p. 851–864.

WALTER, M. R., GREY, K, WILLIAMS, I. R., and CALVER, C. R., 1994, Stratigraphy of the Neoproterozoic to Early Palaeozoic Savory Basin, Western Australia, and correlation with the Amadeus and Officer Basins: Australian Journal of Earth Sciences, v. 41, p. 533–546.

WALTER, M. R., KRYLOV, I. N., and PREISS, W. V., 1979, Stromatolites from Adelaidean (Late Proterozoic) sequences in central and South Australia: *Alcheringa*, v. 3, p. 287–305.

WALTER, M. R., VEEVERS, J. J., CALVER, C. R., and GREY, K., 1995, Neoproterozoic stratigraphy of the Centralian Superbasin, Australia: Precambrian Research, v. 73, p. 173–195.

WILLIAMS, G. E., 1986, The Acraman impact structure: source of ejecta in late Precambrian shales, South Australia: Science, v. 233, p. 200–203.

WILLIAMS, I. R., 1992, Geology of the Savory Basin, Western Australia: Western Australia Geological Survey, Bulletin 141, 115p.

XING YUSHENG, and LIU KUIZHI, 1982, Late Precambrian microflora of China and its stratigraphical significance. Bulletin of Chinese Academy of Geological Science, no. 4, p. 55–64 (in Chinese with English summary).

YIN LEIMING, 1987, New data of microfossils from Precambrian–Cambrian cherts in Ningqiang, southern Shaanxi: Acta Palaeontologica Sinica, v. 26, p. 187–195 (in Chinese with English summary).

YIN LEIMING, and LI ZAIPING, 1978, Precambrian microfloras of Southwest China, with reference to their stratigraphic significance: Memoirs of the Nanjing Institute of Geology and Palaeontology, Academia Sinica, v. 10, p. 41–102 (in Chinese with English summary).

ZANG, W., 1994, Review of Neoproterozoic and Early Palaeozoic acritarch biostratigraphy in Australia: PESA Journal no. 22, p. 101–106.

ZANG, W., 1995, Early Neoproterozoic sequence stratigraphy and acritarch biostratigraphy, eastern Officer Basin, South Australia: Precambrian Research, v. 74, p. 119–175.

ZANG, W., and McKIRDY, D. M., 1994, Microfossils and molecular fossils from the Neoproterozoic Alinya Formation — a possible new source rock in the eastern Officer Basin. PESA Journal no. 22, p. 89–90.

ZANG, W., and WALTER, M. R., 1992, Late Proterozoic and Early Cambrian microfossils and biostratigraphy, Amadeus Basin, central Australia: Association of Australasian Palaeontologists, Memoir 12.

ZHANG ZHONGYING, 1984, A new microphytoplankton species from the Sinian of Western Hubei Province: Acta Botanica Sinica, v. 26, p. 94–98 (in Chinese with English summary).

A reappraisal of the stratigraphy of the Glengarry Basin, Western Australia

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Abstract

Recent detailed mapping of the area previously defined as the Palaeoproterozoic Glengarry Basin has resulted in a greater understanding of the stratigraphy and tectonic setting of the area. The former Glengarry Basin of Gee and Grey (1993) has been redefined and subdivided into three basins : Yerrida and Bryah Basins (containing the Yerrida and Bryah Groups), and Padbury Basin (containing the Padbury Group). The Yerrida Group comprises a sag-basin succession (Windplain Subgroup) and a rift-basin succession (Mooloogool Subgroup). The Bryah Group comprises a rift-basin succession dominated by mafic and ultramafic volcanics. Contacts between the Bryah and Yerrida Groups are faults. The Padbury Group is interpreted as a peripheral foreland basin succession developed on the Bryah Group.

KEYWORDS: Yerrida Basin, Bryah Basin, Padbury Basin, Glengarry Basin, Mooloogool Subgroup, Windplain Subgroup, regional geology, geochronology, stratigraphy.

The Palaeoproterozoic Glengarry Group was originally regarded as the western part of the much larger Nabberu Basin (Hall and Goode, 1978; Gee, 1987; Bunting et al., 1977), but was elevated to separate basin status as the Glengarry Basin by Gee and Grey (1993).

Data obtained from detailed geological mapping, petrological, and geochemical studies, integrated with Landsat and aeromagnetic image interpretations of the Glengarry Basin since 1994, have been presented in a series of preliminary maps (Adamides, 1995; Dawes and Le Blanc Smith, 1995; Pirajno and Occhipinti, 1995a) and interim contributions (Pirajno et al., 1995a,b; Pirajno and Occhipinti, 1995b; Pirajno and Davy, 1996). This and other information currently being assessed (e.g. Bagas, in prep.; Occhipinti et al., in prep.b) have led to a reappraisal of the tectono-stratigraphic framework of the basin. The new evidence suggests that the Glengarry Basin, as originally defined by Gee and Grey (1993), can be divided into three distinct units called the Yerrida (new name after Yerrida Spring on THADUNA*; formally part of the Glengarry Group), Bryah, and Padbury Groups (Pirajno et al., 1995b). These groups are now recognized as three separate basins.

Previously, the area now defined by the Yerrida, Bryah and Padbury Groups (Glengarry Basin) was considered to be united by a common tectonic history (Gee and Grey, 1993). Recent mapping on BRYAH, PADBURY and MILGUN has recognized the unconformable and structural relationships between the Padbury Group and the underlying Bryah Group (Windh, 1992; Martin, 1994; Occhipinti, 1996) and that the Yerrida and Bryah Groups are separated by a major fault. As a result of these studies, the Padbury, Bryah and Yerrida Groups are now considered as separate entities and have each been assigned basin status. The former Glengarry Group is now redundant, but for the sake of convenience, these three basins are collectively referred to as Glengarry basins. The former Peak Hill Metamorphics, which was included in the Glengarry Group by Gee (1987), is now considered part of the Archaean Marymia Inlier and is assigned the name of Peak Hill Schist.

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

Regional geological setting

The Palaeoproterozoic Glengarry basins are situated along the northern margin of the Archaean Yilgarn Craton, and are unconformably overlain to the north by the Bangemall Basin. The Glengarry basins, together with the Earaheedy Basin, Ashburton Basin, Gascoyne Complex and the northern part of the Narryer Terrane, are included in the Capricorn Orogen. The Orogen constitutes a 300 km-wide belt of Palaeoproterozoic volcano-sedimentary deposition, deformation and metamorphism, igneous intrusions and basement reworking, that formed between c. 2200 and 1650 Ma (Gee, 1979, 1990; Tyler and Thorne, 1990; Myers, 1993).

Some workers have suggested that the Pilbara and Yilgarn Cratons are interconnected and continuous beneath geosynclinal deposits of the Capricorn Orogen, and hence interpreted the orogen as ensialic or intracontinental (Gee, 1979; Windh, 1992). Others have suggested that the Capricorn Orogen was formed as a result of convergence, collision and post-collisional movements between the Pilbara and Yilgarn Cratons (Muhling, 1988; Tyler and Thorne, 1990; Myers, 1990, 1993; Martin, 1994; Tyler et al., in press).

Tectonic models for the combined Glengarry basins include: development as an ensialic or intracontinental basin (Gee, 1979; Hynes and Gee, 1986; Windh, 1992); in part as a back-arc basin above a subduction zone dipping southward beneath the Yilgarn Craton (Tyler and Thorne, 1990; Myers, 1993); and as a pull-apart basin, along the northern Yilgarn Craton, during sinistral transpression resulting from the oblique convergence and collision between the Yilgarn and Pilbara Cratons (Pirajno et al., 1995b). Martin (1994) interpreted the Padbury Group as a peripheral foreland basin, developed during the early stages of basin closure of the Yerrida and Bryah Groups, after collision of the Yilgarn and Pilbara Cratons. He suggested that the Padbury Basin developed on top of the Bryah Group by tectonic loading and crustal flexure when a northern continent was thrust over the Yilgarn Craton from north to south.

As the Bangemall Basin was formed on a basement of the deformed, uplifted, and eroded rocks of the Capricorn Orogen after c. 1650 Ma (Muhling and Brakel, 1985; Myers, 1993; Nelson, 1995), and sedimentation probably continued well into the Mesoproterozoic, this basin is not included in the orogen. The development of the Bangemall Basin, however, illustrates the continuing weakness of the Capricorn Orogenic zone well into the Mesoproterozoic. This continued weakness is also illustrated by late strike-slip movement along the reactivated Jenkin Fault that has displaced the Bangemall Group in northeastern MARYMIA (Bagas, in prep.).

In the east the Glengarry Basin is unconformably overlain by the Earaheedy Group, outliers of which can be seen as far west as BRYAH.

Yerrida, Bryah and Padbury Basins

The original Glengarry Basin (Gee and Grey, 1993) is now subdivided into three groups and two subgroups that are interpreted to represent successions deposited in sag, rift, and foreland basins. Details of these successions and of the new stratigraphy are given in Table 1 and discussed below.

The Yerrida Group is present in the central and eastern parts of the former Glengarry Basin and is subdivided into the Windplain and overlying Mooloogool Subgroups (Table 1).

The Windplain Subgroup consists of the Juderina and Johnson Cairn Formations, which are considered to represent a sag-basin succession deposited in a predominantly shallow-water to evaporitic environment. The Juderina Formation unconformably overlies, or is in fault contact with, the Archaean granite–greenstone basement. The formation consists of shallow-water arenite (including the Finlayson member), rarely seen fetid carbonate units, and silicified evaporitic rocks and stromatolitic carbonate (Bubble Well member). The Bubble Well member contains silicified evaporitic rocks and stromatolitic carbonate. The Johnson Cairn Formation transitionally overlies the Juderina Formation, and is interpreted to represent a relatively deeper water facies of the sag-basin succession (Bagas, in prep.; Pirajno and Adamides, in prep.).

The Mooloogool Subgroup (Pirajno et al., 1995b; Occhipinti et al., in prep.a) has been redefined to exclude the Johnson Cairn Formation. The subgroup represents a significant change in depositional environment from a sag-basin (Windplain Subgroup) to a rift-basin setting (Pirajno et al., 1995b; Occhipinti et al., in prep. a). The contact between the two subgroups is transitional on MARYMIA (Bagas, in prep.).

The Mooloogool Subgroup contains four formations (Table 1), which represent two distinct depositional domains. One domain includes the predominantly turbiditic units of the Thaduna and Doolgunna Formations, and occur as a northeasterly trending zone centred around the Goodin Inlier (Fig. 1). The other domain includes the Killara and Maraloou Formations (Table 1). The Killara Formation is a sequence of aphyric lavas and microgabbro sills, characterized by low REE abundances with positive Eu anomalies and trace-element chemistry suggestive of an intracontinental tectonic setting (Pirajno and Davy, 1996). The Maraloou Formation is a sequence of black shale, siltstone and calcareous units, overlying the Killara mafic rocks (Pirajno et al., 1995a). In the southeastern part of the basin, the Thaduna and Doolgunna Formations are intercalated with tholeiitic lavas and sills of the Killara Formation. In addition, the presence of tabular blocks from the Killara tholeiites in turbidites of the Thaduna Formation suggests penecontemporaneous deposition of the two formations.

The Bryah Group is everywhere in fault contact with rocks of the Yerrida Group (Occhipinti et al., in prep.a). A major northeasterly-trending thrust-fault zone (Goodin Fault) marks the boundary between the two groups in the central part of the basin (Fig. 1). The Bryah Group (Table 1) comprises a sequence of greywacke and conglomerate (Karalundi Formation), mafic–ultramafic volcanic rocks (Narracoota Formation), turbiditic sedimentary rocks (Ravelstone Formation), and chemical and fine-grained clastic units (Horseshoe Formation). The Narracoota Formation is especially important in constraining the tectonic setting of the Bryah Group. The Narracoota mafic–ultramafic rocks are of subalkaline affinity characterized by low REE abundances and flat chondrite-normalized patterns. Trace- and major-element data suggest mixed MORB to oceanic-island chemical signatures (Pirajno and Davy, 1996).

The Padbury Group clastic succession has no volcanic component. The group unconformably overlies, or is in faulted contact with, the Bryah Group (Windh, 1992; Martin, 1994; Occhipinti, 1966), and represents a peripheral foreland basin sequence (Martin, 1994). Details of the Padbury stratigraphy are given by Occhipinti (1996).

Table 1. New stratigraphy of the Yerrida, Bryah and Padbury Basins

Basin/group	*Subgroup*	*Formation*	*Rock type*
PADBURY (peripheral foreland basin) **Padbury Group**		Millidie	sericitic siltstone, chloritic siltstone, BIF, dolomitic arenite
		Robinson Range	ferruginous shale, BIF
		Wilthorpe (Beatty Park and Heines members)	quartz-pebble conglomerate, (mafic wacke, and polymictic conglomerate, respectively)
		Labouchere	turbidite sequence (quartz wacke, siltstone)
~ ~ ~ ~ *Unconformity* ~ ~ ~ ~			
GLENGARRY **Bryah Group** (rift succession)		Horseshoe	BIF, wacke, shale
		Ravelstone	quartz-lithic wacke
		Narracoota	mafic–ultramafic volcanics and dykes, tuffs and intercalated sedimentary rocks
		Karalundi	conglomerate, quartz wacke
~ ~ ~ ~ ***Major tectonic break*** ~ ~ ~ ~			
Yerrida Group	Mooloogool Subgroup (rift-basin succession)	Maraloou	black shale, siltstone, carbonate
		Killara	aphyric mafic lavas and intrusives
	Intercalated	Doolgunna	arkosic sandstone, siltstone, shale, quartz wacke
		Thaduna	lithic wacke, siltstone, shale, minor arkose
	Windplain Subgroup (sag-basin succession)	Johnson Cairn	siltstone, shale, carbonate, minor lithic wacke
		Juderina (Bubble Well and Finlayson members)	arenite, conglomerate, minor carbonate (silicified carbonate with evaporites, and arenite, respectively)
~ ~ ~ ~ *Unconformity on Yilgarn Craton* ~ ~ ~ ~			

Geochronological constraints

Geochronological constraints on the deposition and deformation of the Glengarry and Padbury Basins are poorly defined. At the time of writing a number of samples are being processed for zircon dating and further sampling of key units is underway. The currently available geochronological data are summarized in Table 2.

Gee (1990) inferred that the Palaeoproterozoic basin material was deposited and deformed on the northern margin of the Yilgarn Craton between 2000 and 1650 Ma. Windh (1992) proposed a narrower interval with sedimentation in the Bryah Group occurring around 1920 Ma and deformation between 1.9 and 1.8 Ga. This age range is based on a Pb–Pb model age of 1920 ± 35 Ma for a presumed syngenetic pyrite from the Narracoota Formation. Windh (1992) also inferred a maximum depositional age of 2.0–1.9 Ga for the regional quartz-arenite marker in the Labouchere Formation of the Padbury Group, based on the youngest age of detrital zircons. Russell et al. (1994) reported a Pb–Pb isochron of 2258 ± 180 Ma for stromatolitic carbonate in the basal Juderina Formation of the Yerrida Group.

A Pb–Pb model age of 1.7 Ga was obtained on pyrite formed during late-stage gold mineralization at Mikhabura mine in the Bryah Group on BRYAH (Blockley J., 1996, pers. comm.), whereas Windh (1992) obtained Pb–Pb ages of 1.9–1.8 Ga for pyrite and galena associated with late stage gold deposition at the Nathan mine in the Padbury Group on MILGUN (Swager and Myers, in prep.).

Age constraints on regional deformation (and hence minimum-age constraints on deposition) are provided by Palaeoproterozoic granites in the Narryer Terrane. The granites are interpreted to be

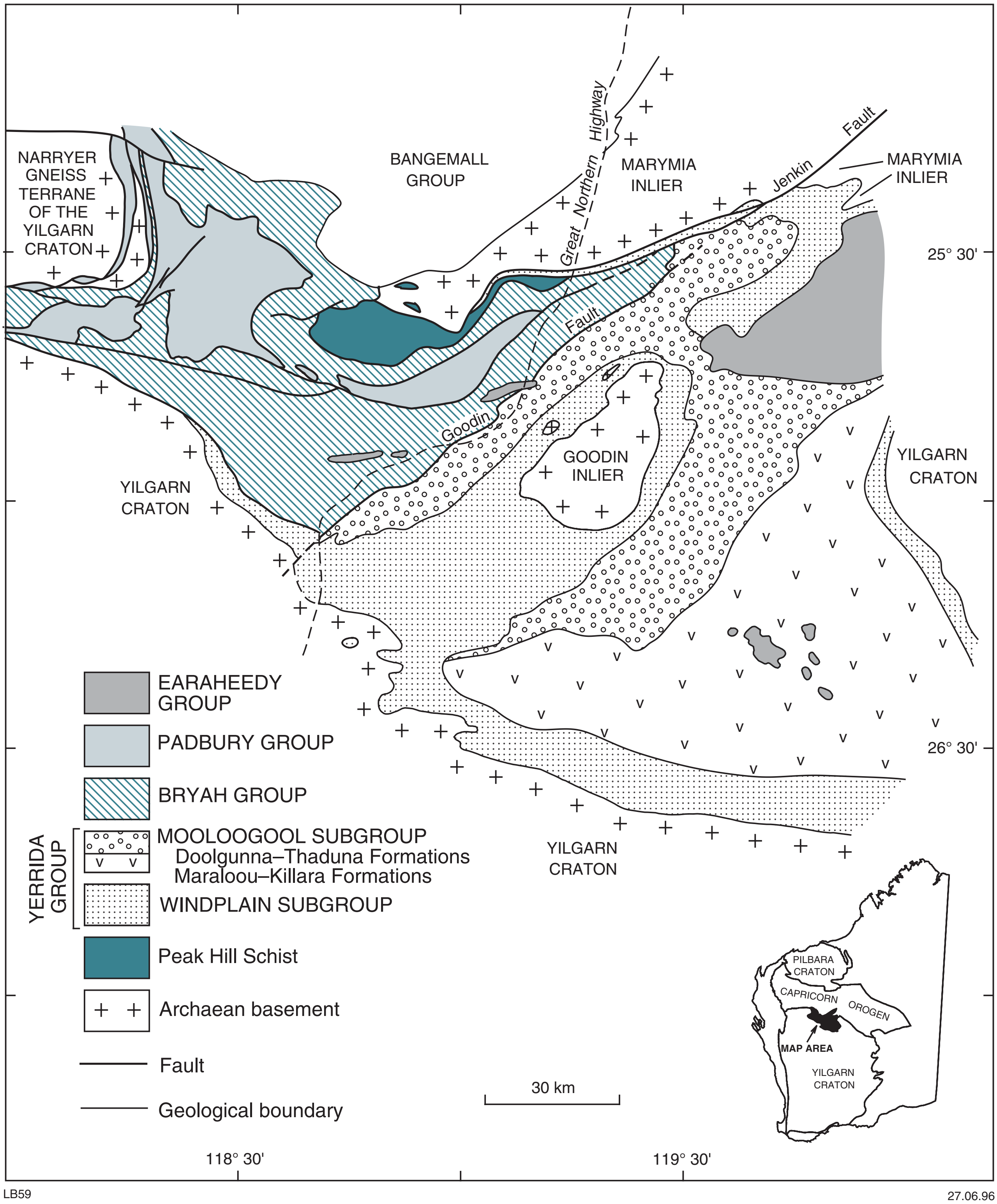

Figure 1. ***Simplified geological map of the Yerrida, Bryah and Padbury Basins (modified*** after ***Pirajno et al., 1995b).***

Table 2. Current geochronology of the Yerrida, Bryah and Padbury Groups

Age	*Group/Formation*	*Dating method, and reference*	*Interpretation*
2258 ± 180 Ma	YERRIDA GROUP Juderina Formation	Pb–Pb isochron (Russell et al., 1994)	Depositional age (of the Yerrida Group)
1920 ± 35 Ma	BRYAH GROUP Narracoota Formation	Pb–Pb model age (Windh, 1992)	Age of syngenetic pyrite, age of the Bryah Group
2.0–1.9 Ga	PADBURY GROUP Labouchere Formation	SHRIMP U–Pb zircon age (A. P. Nutman quoted *in* Windh, 1992)	Maximum age of the Padbury Group based on the minimum age of the detrital zircons
c. 1.9–1.8 Ga	Granite intruding Narryer Terrane	SHRIMP U–Pb zircon age (Nutman et al., 1991)	Syntectonic granite emplaced during the Capricorn Orogeny
1638 ± 14 Ma	BANGEMALL GROUP Coobarra Formation	SHRIMP U–Pb zircon age (Nelson, 1995)	Age of porphyritic rhyolite emplacement in the lower Bangemall Group

synchronous with tectonic movements responsible for the strong north–south foliation in the Padbury and Bryah Groups on MILGUN (e.g. Williams, 1986; Muhling, 1988). Age estimates for the granites include c. 1.9 Ga (Nutman et al., 1991), c. 1.8 Ga (Windh, 1992), c. 1.8–1.5 Ga (Muhling, 1988), and 1550 Ma (Williams, 1986). The younger ages can be discounted in view of the 1638 ± 14 Ma age for felsic volcanic rocks in the lower Bangemall Group (Nelson, 1995).

Discussion and conclusions

There is complex faulting between the Yerrida and Bryah Basins. The Bryah Group is thrust over the Yerrida Group along the northeasterly trending Goodin Fault, which separates them (Fig. 1). The Bryah and Padbury Basins have faulted contacts with the Archaean Narryer Terrane in the west, and the Marymia Inlier in the north (Pirajno et al., 1995). The Archaean and Palaeoproterozoic rocks in the west are complexly interleaved and have thrust-fault contacts, which formed during several tectonic events related to the Capricorn Orogeny (Occhipinti et al., in prep.b, 1996). The faulted contact between the Yerrida Basin and Marymia Inlier has been reactivated over a long period of time, and includes post-Bangemall Group strike-slip faulting with sinistral movement on northwest MARYMIA (Bagas, in prep.). The Goodin Inlier of Archaean rocks (in the Yerrida Basin) is unconformably overlain or in faulted contact with the Yerrida Group.

The available geochronological data and field observations suggest that the Windplain Subgroup is the oldest part of the Yerrida Basin, and was deposited around 2.2 Ga in a sag-basin setting. The Windplain Subgroup is locally transitionally overlain by turbidites and volcanics of the Mooloogool Subgroup, which was deposited in a rift-basin setting. The volcano-sedimentary succession of the Bryah Group is in thrust contact with the Yerrida Group, and its depositional relationship with the Yerrida Group has not been observed. The Bryah Group may have been deposited around 1920 Ma. The predominantly clastic Padbury Group unconformably overlies the Bryah Group, and was possibly deposited at c. 1.9 Ga.

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References

ADAMIDES, N. G., 1995, Doolgunna, W.A. (preliminary edition): Western Australia Geological Survey, 1:100 000 Geological Series.

BAGAS, L., in prep., Geology of the Marymia 1:100 000 Sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

BUNTING, J. A., COMMANDER, D. P., and GEE, R. D., 1977, Preliminary synthesis of Lower Proterozoic stratigraphy and structure adjacent to the northern margin of the Yilgarn Block: Western Australia Geological Survey, Annual Report 1976, p. 43–48.

DAWES, P., and LE BLANC SMITH, G., 1995, Mount Bartle, W.A. (preliminary edition): Western Australia Geological Survey, 1:100 000 Geological Series.

GEE, R. D., 1979, The geology of the Peak Hill area: Western Australia Geological Survey, Annual Report 1978, p. 55–62.

GEE, R. D., 1987, Peak Hill, W.A. (2nd edition): Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

GEE, R. D., 1990, Nabberu Basin, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 202–210.

GEE, R. D., and GREY, K., 1993, Proterozoic rocks on the Glengarry 1:250 000 sheet: stratigraphy, structure, and stromatolite biostratigraphy: Western Australia Geological Survey, Report 41, 30p.

HALL, W. D. M., and GOODE, A. D. T., 1978, The Early Proterozoic Nabberu Basin and associated iron formations of Western Australia: Precambrian Research, v. 7, p. 129–184.

HYNES, A., and GEE, R. D., 1986, Geological setting and petrochemistry of the Narracoota Volcanics, Capricorn Orogen, Western Australia: Precambrian Research, v. 31, p. 107–132.

MARTIN, D. M., 1994, Sedimentology, sequence stratigraphy, and tectonic setting of a Palaeoproterozoic turbidite complex, Lower Padbury Group, Western Australia: University of Western Australia, PhD thesis (unpublished).

MUHLING, J. R., 1988, The nature of Proterozoic reworking of Early Archaean gneisses, Mukalo Creek area, southern Gascoyne Province, Western Australia: Precambrian Research, v. 40/41, p. 341–362.

MUHLING, P.C., and BRAKEL, A.T., 1985, Geology of the Bangemall Group — the evolution of an intracratonic Proterozoic basin: Western Australia Geological Survey, Bulletin 128, 266p.

MYERS, J. S., 1990, Capricorn Orogen, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 197–198.

MYERS, J. S., 1993, Precambrian history of the West Australian Craton and adjacent orogens: Annual Review of Earth and Planetary Sciences, v. 21, p. 453–485.

NELSON, D. R., 1995, Compilation of SHRIMP U–Pb zircon geochronology data, 1994: Western Australia Geological Survey, Record 1995/3, 244p.

NUTMAN, A. P., KINNY, P. D., COMPSTON, W., and WILLIAMS, 1. S., 1991, SHRIMP U–Pb zircon geochronology of the Narryer Gneiss Complex, Western Australia: Precambrian Research, v. 52, p. 275–300.

OCCHIPINTI, S.A., GREY K., ADAMIDES, N.G., BAGAS, L., PIRAJNO, F., DAWES, P., and SWAGER, C.P., in prep. a, Stratigraphic revision of the Palaeoproterozoic rocks on the Robinson Range, Peak Hill, Glengarry, and Wiluna 1:250 000 sheets: Western Australia Geological Survey, Record.

OCCHIPINTI, S. A., SWAGER, C. P., and MYERS, J. S., in prep. b, Geology of the Padbury 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

OCCHIPINTI, S.A., SWAGER, C.P., and PIRAJNO, F., 1996, Structural and stratigraphic relationships of the Padbury Group, Western Australia — implications for tectonic history: Western Australia Geological Survey, Annual Review 1995–96, p. 88–95.

PIRAJNO, F., 1996, Models for the geodynamic evolution of the Palaeoproterozoic Glengarry Basin, Western Australia: Western Australia Geological Survey, Annual Review 1995–96. p. 96–103.

PIRAJNO, F., and ADAMIDES, N. G., in prep., Geology of the Thaduna 1:100 000 sheet: Western Australia Geological Survey 1:100 000 Geological Series Explanatory Notes.

PIRAJNO, F., ADAMIDES, N. G., OCCHIPINTI, S. A., SWAGER, C. P., and BAGAS, L., 1995b, Geology and tectonic evolution of the Early Proterozoic Glengarry Basin, Western Australia: Western Australia Geological Survey, Annual Review 1994–95, p. 71–80.

PIRAJNO, F., and DAVY, R., 1996, Mafic volcanism in the Palaeoproterozoic Glengarry Basin, Western Australia, and implications for its tectonic evolution: Geological Society of Australia, Abstracts, v. 41, p. 343.

PIRAJNO, F., and OCCHIPINTI, S. A., 1995a, Bryah, W.A. (preliminary edition): Western Australia Geological Survey, 1:100 000 Geological Series.

PIRAJNO, F., and OCCHIPINTI, S., 1995b, Base metal potential of the Palaeoproterozoic Glengarry and Bryah basins, Western Australia: Australian Institute of Geoscientists, Bulletin 16, p. 51–56.

PIRAJNO, F., OCCHIPINTI, S. A., LE BLANC SMITH, G., and ADAMIDES, N. G., 1995a, Pillow lavas in the Peak Hill and Glengarry terranes: Western Australia Geological Survey, Annual Review 1993–94, p. 63–66.

RUSSELL, J., GREY, K., WHITEHOUSE, M., and MOORBATH, S., 1994, Direct Pb/Pb age determination of Proterozoic stromatolites from the Ashburton and Nabberu basins, Western Australia: Abstracts, International Conference on Geochronology, Geochemistry and Cosmochemistry, v. 8.

SWAGER, C. P., and MYERS, J. S., in prep., Geology of the Milgun 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

TYLER, I. M., and THORNE, A. M., 1990, Structural evolution of the northern margin, *in* Geology and Mineral Resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 223–232.

TYLER, I. M., PIRAJNO, F., BAGAS, L., MYERS, J. S., and PRESTON, W., in press, The geology and mineral deposits of the Proterozoic in Western Australia: AGSO Journal of Australian Geology and Geophysics, v. 17.

WINDH, J., 1992, Tectonic evolution and metallogenesis of the Early Proterozoic Glengarry Basin, Western Australia: University of Western Australia, PhD thesis (unpublished).

WILLIAMS, S. J., 1986, Geology of the Gascoyne Province, Western Australia: Western Australia Geological Survey, Report 15, 85p.

Structural and stratigraphic relationships of the Padbury Group, Western Australia — implications for tectonic history

by S. A. Occhipinti, C. P. Swager, and F. Pirajno

Abstract

The Palaeoproterozoic Padbury Group was deposited in a syntectonic basin (Padbury Basin), in the southern part of the Capricorn Orogen. The Padbury Group comprises clastic and chemical sedimentary rocks. This group was deposited on the clastic and chemical sedimentary rocks and mafic–ultramafic volcanic rocks of the Bryah Group, and was deformed and displaced synchronously with this group during its development.

KEYWORDS: Capricorn Orogen, Palaeoproterozoic, Padbury foreland basin, Bryah Group.

Regional geology

The Palaeoproterozoic rocks described constitute the southern part of the Capricorn Orogen, a major zone of deformed, low- to high-grade metamorphic rocks and granitoid intrusions formed during continental crustal collision between the Pilbara and Yilgarn Cratons at about 2000–1700 Ma (Tyler and Thorne, 1990; Myers, 1993). The Padbury Group was formerly included with the Glengarry Group as a component of the Glengarry Basin. However, recent mapping suggests that the Glengarry Basin and the Glengarry Group, as originally defined by Gee and Grey (1993) and Gee (1979), can be subdivided into the Bryah and Yerrida Basins, with different stratigraphic and structural histories (Pirajno, 1996), and within which volcano-sedimentary successions were deposited. These two groups are called the Bryah and Yerrida Groups respectively, and the names Glengarry Group and Glengarry Basin are abandoned (Pirajno et al., 1996) (Fig. 1). The Bryah Group lies in the northwestern part of the former Glengarry Basin and includes the area that abuts both the Narryer Terrane and the southern part of the Marymia Inlier, an Archaean granite–greenstone terrane.

Both the Yerrida and Bryah Groups contain abundant mafic–ultramafic volcanic rocks (Killara and Narracoota Formations, respectively). These mafic–ultramafic igneous rocks have been divided on the basis of geochemical character into two units, indicative of oceanic (Narracoota Formation) and mixed continental–oceanic (Killara Formation) origins. Clastic units within the Bryah and the Yerrida Groups are also dissimilar. For example, the basal unit of the Yerrida Group is a quartz arenite (Finlayson Member), whereas the basal unit of the Bryah Group includes lithic wacke, sublitharenite, and shale (Karalundi Formation) (Fig. 2). Pirajno et al. (1996) speculate that the Bryah and Yerrida Groups were probably deposited at the same time, in adjacent areas, within the Bryah and Yerrida Basins.

The Padbury Group rests unconformably on the Horseshoe Formation of the Bryah Group, but is also extensively disrupted by faulting. The Padbury Group was originally defined by Barnett (1975) as a sequence of banded iron-formation (BIF), hematitic shale, wacke, siltstone conglomerate, and dolomite. Herein it is redefined to include also mafic clastic rocks. Martin (1994) interpreted the Padbury Group as a foreland basin deposit that developed on top of the Bryah Group. This foreland basin is called the Padbury Basin. The Padbury Group is in fault contact with the Narracoota Formation, and in places the Horseshoe Formation of the Bryah Group and the Narryer Terrane.

Padbury Group

The Padbury Group is subdivided, in ascending chronological order, into the Labouchere, Wilthorpe, Robinson Range, and Millidie Creek Formations (Fig. 2). The Labouchere Formation contains regularly layered quartz wacke and siltstone, and includes a regionally extensive quartzarenite marker bed. The Wilthorpe Formation contains abundant quartz-pebble conglomerate and includes the Heines and Beatty Park Members that comprise conglomerate, sandstone, and shale (Pirajno and Occhipinti, in prep.; Occhipinti et al., in prep.). These members both occur at the same stratigraphic level in the dominant quartz-pebble conglomerate of the Wilthorpe Formation but outcrop in different areas, thus reflecting different source rocks during the same time of deposition. The Heines Member outcrops only on BRYAH and contains a polymictic conglomerate, quartz sandstone and shale; the Beatty Park

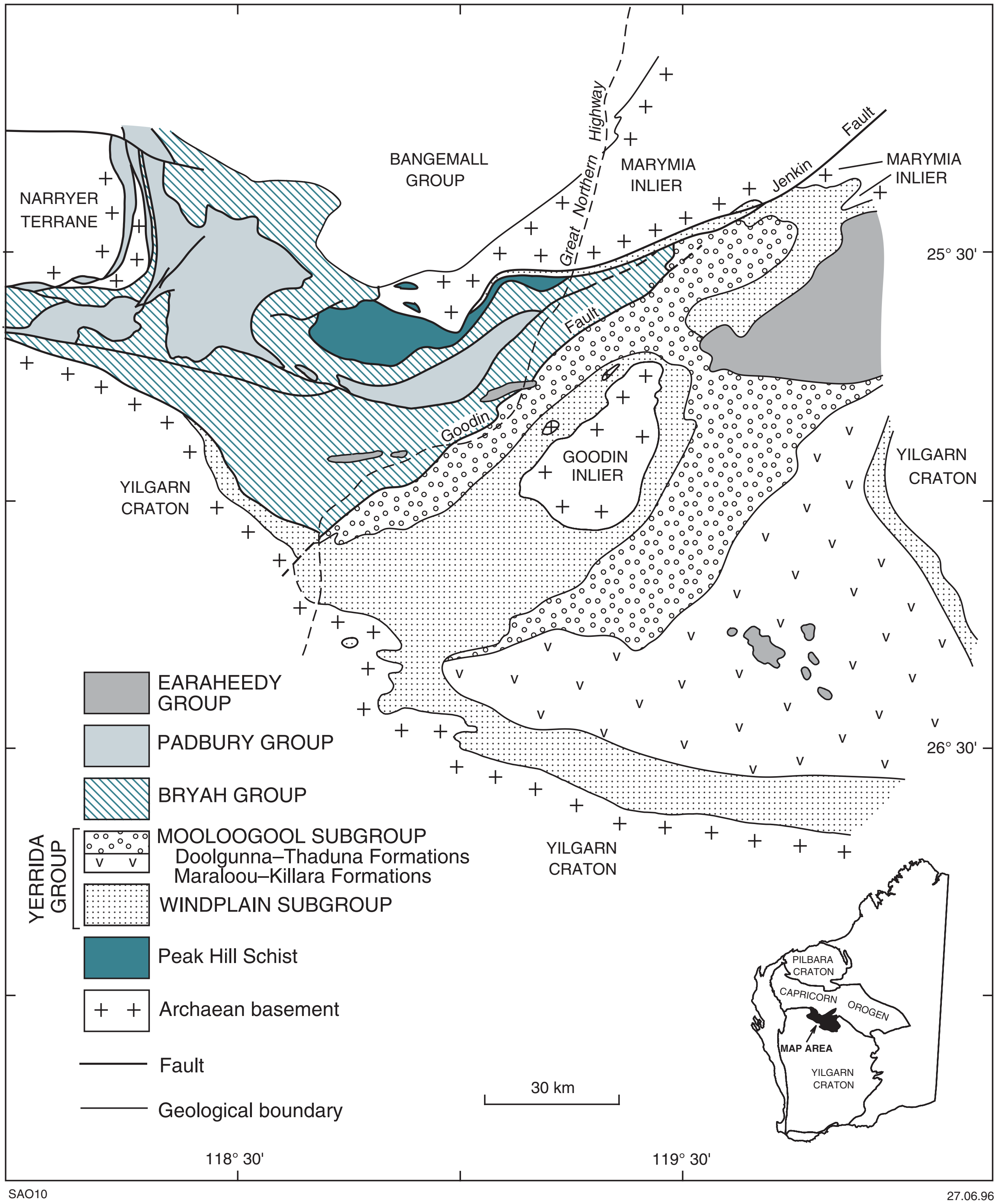
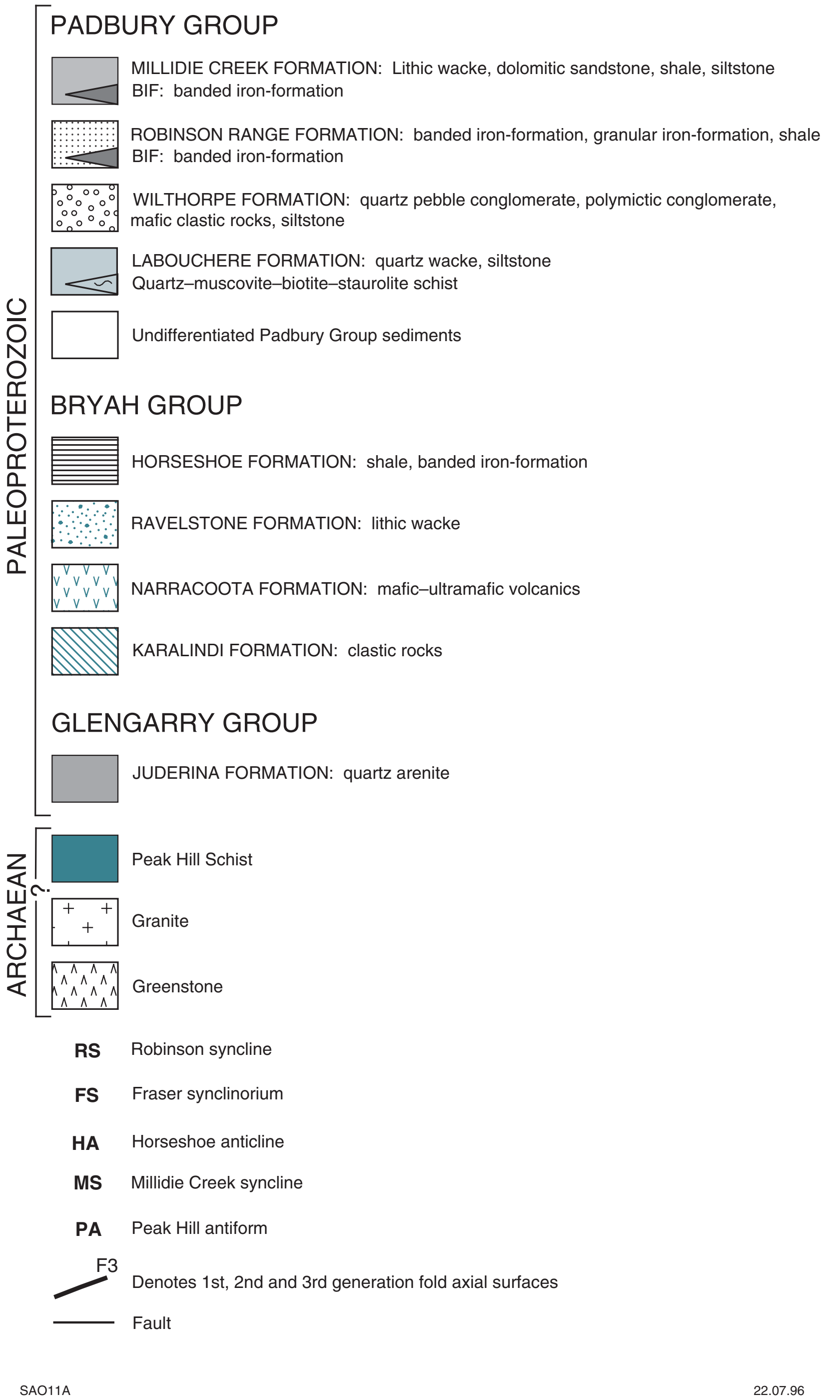


Figure 1. Map outlining the main geological features of the Padbury, Bryah and Yerrida Basins



Member (on PADBURY*) consists of volcanic-derived mafic clastic rocks intercalated with white chert beds towards the top. Martin (1994) noted that on MILGUN two intervals of polymictic conglomerate are present within the Wilthorpe Formation. These are correlated with the Heines Member. The Heines Member is conformably overlain by the Robinson Range Formation, but its base has been observed only in faulted contact with only the Narracoota Formation (Bryah Group). The Beatty Park Member has an apparently conformable contact with the underlying Labouchere Formation and grades upward into the Robinson Range Formation. The fine-grained mafic clastic rocks of the Beatty Park Member are intercalated with chert, minor BIF, and sericitic shale typical of the Robinson Range Formation. The Wilthorpe Formation has gradational contacts with the underlying Labouchere Formation and overlying Robinson Range Formation. The Millidie Creek Formation consists of iron-rich shale and siltstone, irregularly banded manganiferous iron-formation, dolomitic sandstone, quartz wacke, and chloritic siltstone, and conformably overlies the Robinson Range Formation.

Previous workers recognized that the Padbury Group consists of both siliciclastic (Labouchere and Wilthorpe Formations) and chemical sedimentary rocks (Robinson Range and Millidie Creek Formations). The new mapping has recognized coarse- and fine-grained mafic epiclastic rocks within the Beatty Park Member, polymictic conglomerate within the Heines Member and chloritic siltstone within the Millidie Creek Formation.

Rare-earth element (REE) geochemical analyses of chloritic siltstone from the Beatty Park Member were completed in order to determine their possible provenance. These samples had a SiO_2 range of between 61 and 69 wt% (Fig. 3). The REE patterns show slight enrichment in light REE and are similar to the REE patterns of the Narracoota Formation presented by Pirajno et al. (1995). This suggests that the mafic epiclastics may reflect local derivation from a nearby, uplifted fault block of mafic igneous rocks of the Narracoota Formation.

Martin (1994) suggested that the Padbury Group was deposited in a foreland basin that developed on the northern margin of the Yilgarn Craton (Fig. 4). A foreland basin is an asymmetric subsiding trough that forms adjacent to active fold-and-thrust belts (Flemings and Jordan, 1990). The style of deposition within such a basin is dependent on a number of factors, including the relief of the developing mountain belt that, in part, supplies the sediment, and whether or not the thrust belt is active. Price (1973) first recognized that foreland basins resulted from flexuring of the lithosphere in response to loading by thrust sheets. A foreland basin is loaded on one

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

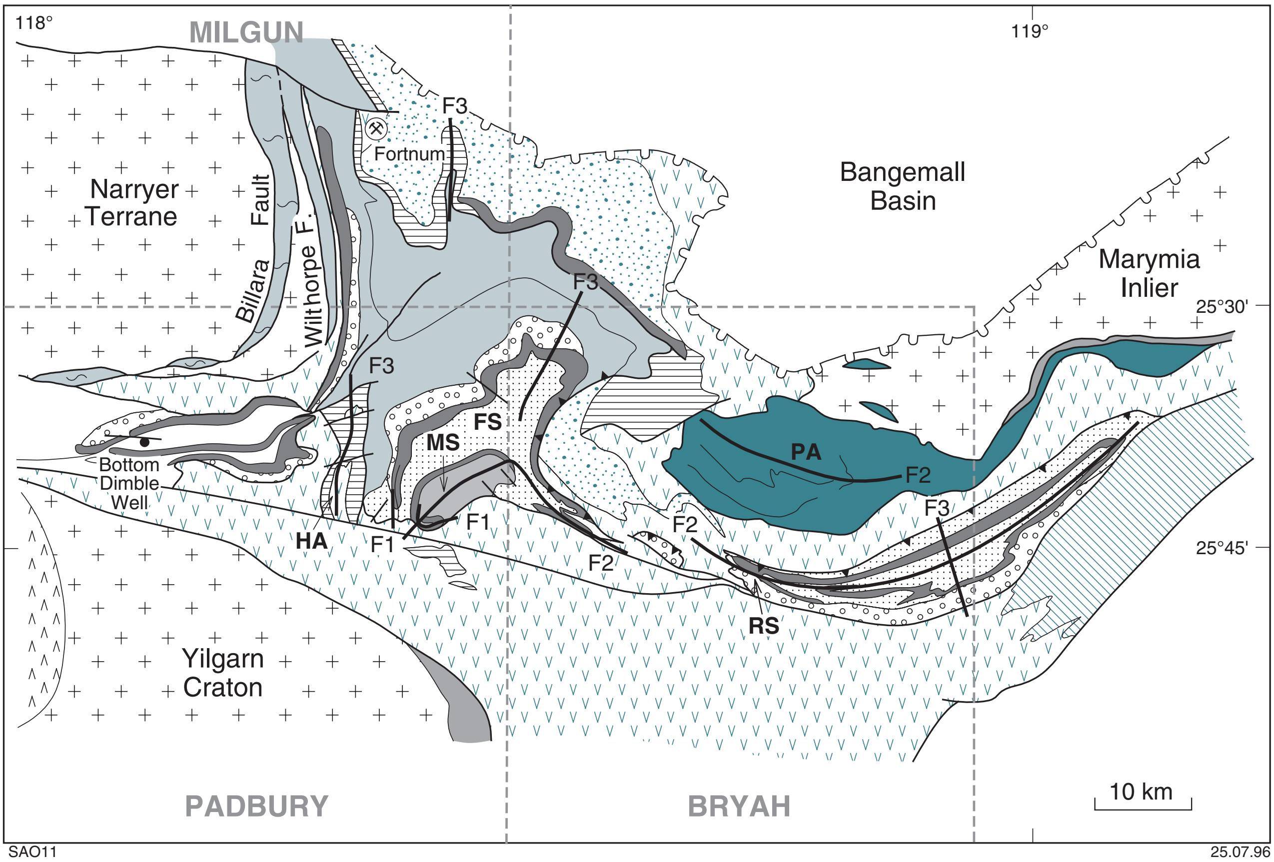


Figure 2. Simplified solid geology map of the Padbury and Bryah Groups. This map was compiled using field data, landsat thematic mapper and aeromagnetic data. Legend on opposite page

side by a fold-and-thrust belt and by a peripheral arch (forebulge) on the other side adjacent to an unflexed foreland (Martin, 1994, p. 163). In Martin's model, the foreland basin developed between a fold-and-thrust belt in the north and a forebulge on the Yilgarn Craton to the south. Through time, continued convergence of the fold-and-thrust belt and the foreland basin led to the development of large-scale isoclinal folds.

Recent work has recognized mafic volcanics interleaved with the Padbury Group. Windh (1992) interpreted this as an original depositional feature, but Martin (1994), Swager and Myers (in prep.), and Occhipinti et al. (in prep.) suggest that the interleaving was tectonic.

Throughout the northern part of PADBURY, percussion drilling on the flat landscape adjacent to the hills of the Robinson Range Formation detected mafic and ultramafic schist. This suggests that the Padbury Group directly overlies units of the lower Bryah Group. Tectonic interleaving between the two groups is observed on MILGUN in the vicinity, and particularly to the east, of the Fortnum mine. In one instance a shear zone containing mafic schist separates the north-striking, steeply dipping beds of the Robinson Range and Labouchere Formations. Aeromagnetic data indicate that this shear zone may be traced into the northern part of PADBURY, where it bends around to the west and appears to be cut off by an approximately east–west trending fault (Fig. 2). North of this fault is the Dimble Belt (Elias and Williams, 1980), a zone of mafic igneous rocks that were interpreted by Hynes and Gee (1986) to be part of the Narracoota Formation, based on chemical similarities to the Narracoota Formation mafic volcanic rocks that outcrop on BRYAH. Further work has indicated that the REE and major-element geochemical characteristics of the Dimble mafic volcanic rocks are similar to those reported by Pirajno et al., (1995) from the Narracoota Formation (Occhipinti et al., in prep.). These geochemical results are illustrated in Figure 3.

In addition, on central PADBURY, the Horseshoe anticlinal block (Fig. 2) provides a window into the Bryah Group. This block contains rocks of the Horseshoe and Narracoota formations (Bryah Group) that are folded into an anticlinal structure. The Horseshoe anticlinal block is fault bounded on all sides and is in contact with the Padbury Group on its northern and northeastern sides, and with the Narracoota Formation (Bryah Group) on its western and southern sides. Tectonic interleaving within the Bryah Group is also observed within the Horseshoe anticlinal block. Rocks previously thought to be carbonate intrusions into the core of the anticline (Lewis, 1971; Lewis and Williams, 1970; Elias et al., 1980) are now interpreted as carbonated or

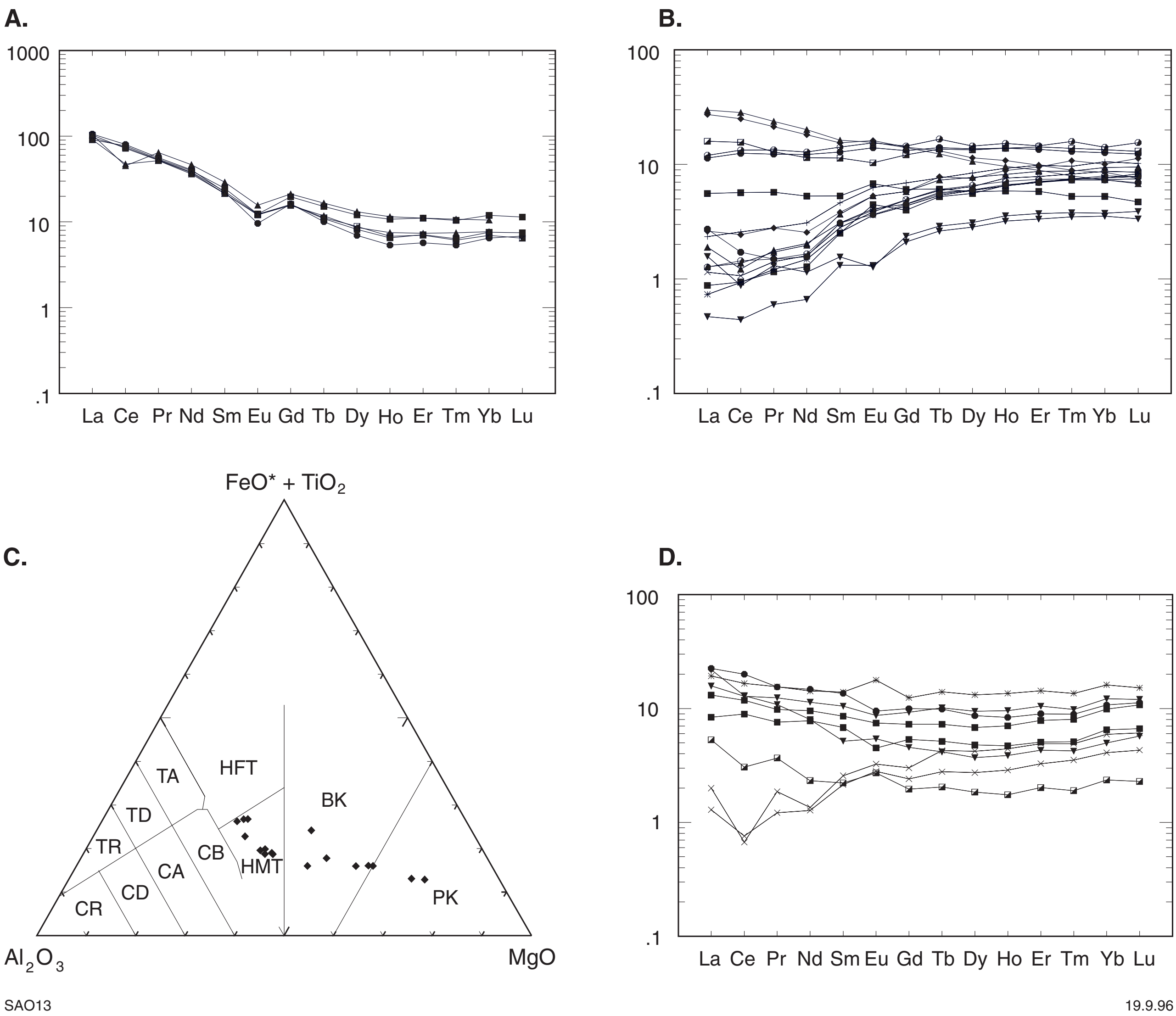


Figure 3. *A. Chondrite-normalized REE plot for the Beatty Park Member mafic epiclastic rocks (normalizing factors* after *Sun, 1982)*

B. Chondrite-normalized REE plot for the Narracoota Formation mafic–ultramafic rocks from the Dimble belt (normalizing factors after *Sun, 1982)*

C. Jensen (1976) cationic plot for mafic–ultramafic Narracoota Formation rocks from the Dimble belt. PK: peridotitic komatiite, BK: basaltic komatiite, HMT: high-magnesium tholeiite, HFT: high-iron tholeiite, CB: calc-alkaline basalt, CA: calc-alkaline andesite, CD: calc-alkaline dacite, CR: calc-alkaline rhyolite, TA: tholeiitic andesite, TD: tholeiitic dacite, TR: tholeiitic rhyolite

D. Chondrite-normalized REE plot for the carbonated and silicified mafic rocks of the Narracoota Formation (normalizing factors after *Sun, 1982)*

silicified mafic rocks. High chromium and nickel contents, and relatively low REE abundances, and slight light REE enrichment suggest that these altered mafic rocks can be correlated with the Narracoota Formation (Fig. 3). In addition, the clastic sedimentary rocks of the Ravelstone Formation, which conformably underlie the Horseshoe Formation (Pirajno and Occhipinti, in prep.), are not present within this structure. This also suggests that here the contact relationship between the Narracoota and the Horseshoe Formations may be a fault.

West of PADBURY on MOORARIE is the Trillbar Belt, which includes metamorphosed mafic igneous rocks, ferruginous phyllite and pelitic schist and metamorphosed banded iron-formation (Williams, 1986, p. 31). Williams (1986) suggested that as the mafic rocks within the Trillbar Belt are 'virtually continuous' with the Narracoota Formation, they may be the higher grade equivalents. If this assumption is correct, then the Trillbar Belt would be the metamorphosed equivalent of units contained within the Bryah Group. Further work is required to confirm this.

The rocks of the Trillbar Belt were reinterpreted by Myers (1989) as heterogeneously deformed metagabbroic and ultramafic rocks. They were correlated with

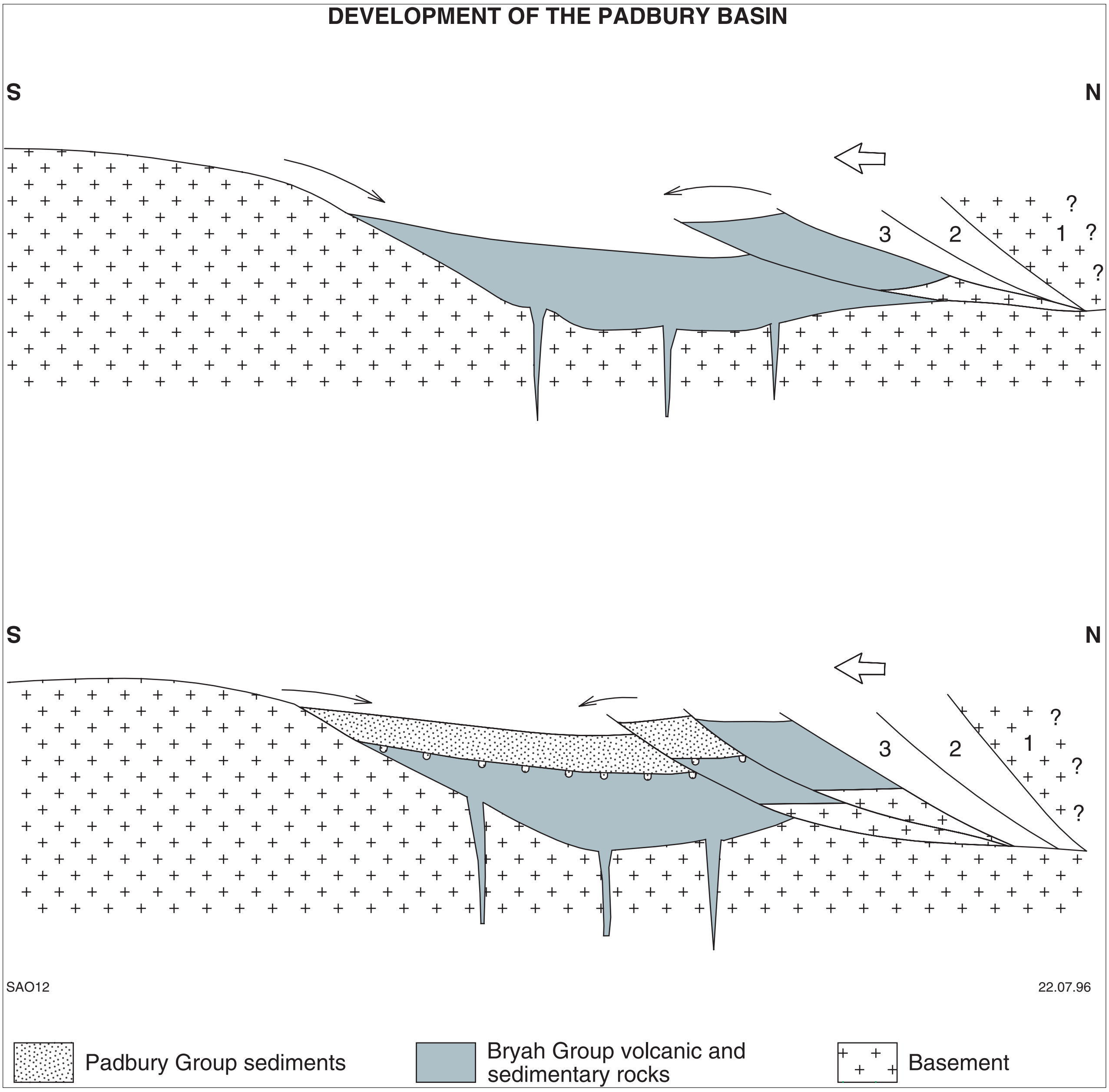


Figure 4. Diagrammatic cross section illustrating the development of the Padbury foreland basin (modified after *Martin, 1994). The denudation rate is increased in areas of higher relief and when the thrust belt is active (Flemings and Jordan, 1990)*

mafic schists in the Dimble Belt (25°36'S, 118°12'E — part of the Narracoota Formation) and together named the Trillbar Complex.

The continued convergence of the fold-and-thrust belt and forebulge may have led to both the closing of the basin and the formation of the early formed east–west striking structures observed in the region (Figs 2 and 4). The presence of Padbury Group rocks directly overlying the lower Bryah Group (Narracoota Formation) suggests that the Padbury Basin may have developed on top of the Bryah Group. Observations suggesting large-scale interleaving of the Padbury and Bryah Groups could be the result of active folding and thrusting. Thus deformation and interleaving of rocks of the Padbury and Bryah Groups may have been synchronous with the deposition of the Padbury Group (*see* Windh, 1992).

Structure

Diverse styles of structures are observed on Bryah, Padbury, and Milgun. On Bryah, in the hinge zone of the Robinson Syncline, an upright, steeply dipping isoclinal syncline that strikes easterly, and has a shallow plunge, is characterized by refolded folds (Fig. 2). These refolded folds are early structures that have been deformed by the steeply dipping east-trending syncline. The early folds also strike easterly, but are interpreted to have originally been subhorizontal or recumbent folds. In the Millidie Creek Syncline on PADBURY, isoclinal shallowly plunging folds with axial surfaces that are sub-parallel to bedding can be seen within the banded iron-formation beds. Aeromagnetic images indicate that the Millidie Creek Syncline is a refolded fold structure. Similar folds are observed in the Fraser Synclinorium which, on the aeromagnetic image, appears to be a refolded fold. Similar structures also occur in the Beatty Park Bore (25°40'13"S, 118°17'36"E) area, in the banded iron-formation of the Robinson Range Formation, and in the Horseshoe Formation anticlinal fault block. North–south compression, may have led to the formation of the early formed subhorizontal folds, and the steeply dipping east-trending folds in the region. This north–south compression may have been accommodated by the movement of a fold-and-thrust belt as suggested by Martin (1994) in his foreland-basin model. Large-scale tectonic interleaving of the Padbury and Bryah Groups, within the Bryah Group (Horseshoe anticlinal block), and between the Padbury Group and the Narryer Terrane, may have taken place during the north–south convergence.

North-trending folds in the region have overprinted the steeply dipping tight to isoclinal, east-trending folds. This relationship is observed on BRYAH, where open, north-trending folds have gently refolded structures such as the Peak Hill Antiform and the Robinson Range Syncline. This overprinting relationship is not as obvious on PADBURY and MILGUN; however, north-trending folds are present. These folds are tight to isoclinal, and are disharmonic on MILGUN. It is possible that the PADBURY and MILGUN areas represent higher strain zones of an east–west compression event. The east–west compression post-dates the foreland-basin closure, and may have included further tectonic interleaving between the Padbury Group and the Narryer Terrane. This would explain the development of tight north–south trending structures in the west and gentle north–south trending structures in the east of the domain characterized by the Padbury and Bryah Groups.

Elias et al. (1980) suggested that a major refolded syncline was present in the area extending east from Bottom Dimble Well through to Mount Padbury (25°38'S, 118°16'E), and then north up to Carlyons Rockhole (25°24'S, 118°18'E). They called this the ‘Padbury Syncline’ and suggested that it had been refolded by the northwest-trending ‘Fraser Antiform’ (Elias et al., 1980; Fig. 2). The recent mapping suggests that the Padbury Syncline is not a simple synclinal structure, and that it has been cross-cut in many places by faults and shear zones. The unusual orientation of the ‘Padbury Syncline’ suggests that this has been modified by shearing and faulting. Furthermore, the Fraser Antiform, as outlined by Elias et al. (1980), is a more complex structure, involving at least three episodes of folding.

Some early faults observed within the Padbury and Bryah Groups are interpreted to be associated with the initial stages of the deformation history, and in some cases may have been coeval with deposition of the clastic Padbury Group rocks onto the volcano-sedimentary rocks of the Bryah Group. The early structures may have developed either in discrete deformation events possibly caused by episodic convergence of the Yilgarn and Pilbara Cratons, or in a progressive deformation event during which early shallow-dipping structures were re-oriented and refolded into steeper dipping structures. Both models can account for the coaxial nature of the fold axial surfaces. Recognition of original flat-lying structures may explain the large-scale tectonic interleaving of the Padbury and Bryah Groups and the Narryer Terrane. The disharmonic shape of some of the folds in the Padbury Group may be explained by either fold interference patterns, or by complex basement-cover structural relationships.

References

BARNETT, J. C., 1975, Some probable Lower Proterozoic sediments in the Mount Padbury area: Western Australia Geological Survey, Annual Report 1974, p. 52–54.

ELIAS, M., and WILLIAMS, S. J., 1980, Explanatory notes on the Robinson Range 1:250 000 geological sheet, Western Australia: Western Australia Geological Survey, Record 1977/6.

ELIAS, M., BARNETT, J. C., and WILLIAMS, S. J., 1980, Robinson Range W.A.: Western Australia Geological Survey, 1:250 000 Geological Series.

FLEMINGS, P., and JORDAN, T. E., 1990, Stratigraphic modeling of foreland basins: interpreting thrust deformation and lithosphere rheology: Geology, v. 18, p. 430–434.

GEE, R. D., and GREY, K., 1993, Proterozoic rocks on the Glengarry 1:250 000 sheet —stratigraphy, structure and stromatolite biostratigraphy: Western Australia Geological Survey, Report 41, 30p.

HYNES, A., and GEE, R. D., 1986, Geological setting and petrochemistry of the Narracoota Volcanics, Capricorn Orogen, Western Australia: Precambrian Research, v. 31, p. 107–132.

JENSEN, L. S., 1976, A new cation plot for classifying subalkalic volcanic rocks: Ontario Division of Mines, MP66, 22p.

LEWIS, J. D., 1971, The geology of some carbonate intrusions in the Mount Fraser area, Peak Hill Goldfield, Western Australia: Western Australian Geological Survey, Annual Report 1970, p. 50–56.

LEWIS, J. D., and WILLIAMS, X. K., 1970, The geology and geochemistry of some carbonate intrusions in the Mount Fraser area, Peak Hill Goldfield: Western Australian Geological Survey, Record 1970/8.

MARTIN, D. M., 1994, Sedimentology, sequence stratigraphy, and tectonic setting of a Palaeoproterozoic turbidite complex, Lower Padbury Group, Western Australia: The University of Western Australia, PhD thesis (unpublished).

MYERS, J. A., 1989, Thrust sheets on the southern foreland of the Capricorn Orogen, Robinson Range, Western Australia: Western Australia Geological Survey, Report 26, Professional Papers, p. 127–130.

MYERS, J. S., 1993, Precambrian history of the west Australian craton and adjacent orogens: Annual Reviews in Earth and Planetary Science, v. 21, p. 453–485.

OCCHIPINTI, S. A., SWAGER, C. P., and MYERS, J., in prep., Geology of the Padbury 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

PIRAJNO, F., BAGAS, L., SWAGER, C. P., OCCHIPINTI, S. A., and ADAMIDES, N. G., 1996, A reappraisal of the stratigraphy of the Glengarry Basin: Western Australia Geological Survey, Annual Review 1995–96, p. 81–87.

PIRAJNO, F., 1996, Models for the geodynamic evolution of the Palaeoproterozoic Glengarry basin, Western Australia: Western Australia Geological Survey, Annual Review 1995–96, p. 96–103.

PIRAJNO, F., ADAMIDES, N. G., OCCHIPINTI, S., SWAGER, C. P., and BAGAS, L., 1995, Geology and tectonic evolution of the Early Proterozoic Glengarry Basin, Western Australia: Western Australia Geological Survey, Annual Review 1994–95, p. 71–80.

PIRAJNO, F., and OCCHIPINTI, S. A., in prep., Geology of the Bryah 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

PRICE, R. A., 1973, Large-scale gravitational flow of supracrustal rocks, southern Canadian Rockies, *in* Gravity and tectonics *edited by* K. A. DE JONG and R. SCHOLTEN: New York, John Wiley, p. 491–502.

SUN, S. S., 1982, Chemical composition and origin of the Earth’s primitive mantle: Geochimica et Cosmochimica Acta, v. 46, p. 179–192.

SWAGER, C. P., and MYERS, J., in prep., Geology of the Milgun 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

TYLER, I. M., and THORNE, A. M., 1990, The northern margin of the Capricorn Orogen, Western Australia — an example of an early Proterozoic collision zone: Journal of Structural Geology, v. 12, p. 685–701.

WILLIAMS, S. J., 1986, Geology of the Gascoyne Province, Western Australia: Western Australia Geological Survey, Report 15, 85p.

WINDH, J., 1992, Tectonic evolution and metallogenesis of the early Proterozoic Glengarry basin, Western Australia: University of Western Australia, PhD thesis (unpublished).

Models for the geodynamic evolution of the Palaeoproterozoic Glengarry Basin, Western Australia

by F. Pirajno

Abstract

The origin and tectonic development of the Glengarry basins are modelled in the light of recent detailed geological mapping. The Glengarry basins comprise three lithostratigraphic successions, namely: Bryah, Padbury and Yerrida Groups. Field, structural and geochemical evidence suggests that the Bryah and Yerrida Groups may have formed either in a back-arc setting or as a series of pull-apart openings related to the convergence of the Pilbara and Yilgarn Cratons.

KEYWORDS: Palaeoproterozoic pull-apart basin, back-arc rifting, mafic volcanism

The Palaeoproterozoic Glengarry Basin, as originally defined by Gee and Grey (1993) is situated along the northern margin of the Yilgarn Craton, within the southern part of the Capricorn Orogen (2200–1800 Ma). On the basis of recent detailed geological mapping, three lithostratigraphic domains are now recognized to constitute the former Glengarry Basin. They are: Bryah and Padbury Groups in the west and Yerrida Group in the east (Pirajno et al., 1996; Fig.1). Pirajno et al. (1995) further subdivided the Yerrida Group into the Windplain and the Mooloogool Subgroups, which in terms of their sedimentological features are interpreted to represent an early sag basin and a subsequent rift basin respectively. The lithologies of the Bryah, Padbury and Yerrida Groups have distinctive stratigraphic, structural and metamorphic characteristics and are now recognized as three separate basins (Pirajno et al., 1996). The structural contrast between the Bryah–Padbury area in the west and the Yerrida area in the east is well illustrated in aeromagnetic images of the region.

The contacts between the Bryah and Padbury Groups are generally tectonic (Occhipinti et al., 1996), but depositional (unconformable) contacts have also been reported (Martin 1994; Occhipinti et al., 1996). The boundary between the Bryah and Yerrida Groups is tectonic and trends northeast (Goodin Fault, Fig. 1). This boundary appears to be located along a pre-existing deep-seated structure which is part of a lineament that can be traced to the southwest into the Yilgarn Craton and to the northeast across the Bangemall and Savory Basins. A graben structure, informally called the Doolgunna graben, is located southeast of the Goodin Fault (Fig. 1).

The purpose of this paper is to explore and model the geodynamic evolution of the Yerrida and Bryah Basins. The Padbury Basin is considered a foreland basin that developed on top of the Bryah Group (Occhipinti et al., 1996) and is not discussed in this contribution.

Interim reports on the geology and tectonic evolution of the Glengarry Basins have been given by Pirajno et al. (1995) and Pirajno and Occhipinti (1995). The simplified geology of the Yerrida and Bryah Basins is shown in Figure 1.

Field and geochemical evidence gained to-date suggests that the Yerrida and Bryah Basins may have formed either as 1) a back-arc structure (i.e. behind a north-facing magmatic arc, during the convergence of the Pilbara and Yilgarn Cratons), or 2) a series of pull-apart sub-basins during transpressive east–west movements linked to the oblique collision of the Pilbara and Yilgarn Cratons. The first hypothesis is based on regional models by Myers (1993) and Tyler and Thorne (1990). The second hypothesis has previously been considered by Pirajno et al. (1995).

Regional tectonic setting

The former Glengarry Basin, together with the Earaheedy Basin, Ashburton Basin and the Gascoyne Complex, are part of the Capricorn Orogen (2200–1800 Ma). The Capricorn Orogen is traceable for more than 900 km with northwesterly to westerly trends, between the Pilbara and Yilgarn Cratons (inset in Fig. 1). The Capricorn Orogeny resulted from a continent–continent collision, between the Pilbara and Yilgarn Cratons and the closure of an intervening ocean, back-arc basin and accretion of a microcontinent (Myers, 1993; pers. comm. 1996; Tyler and Thorne, 1990; Tyler et al., in press). Convergence was essentially oblique, and also resulted in the development of east–west strike-slip movements,

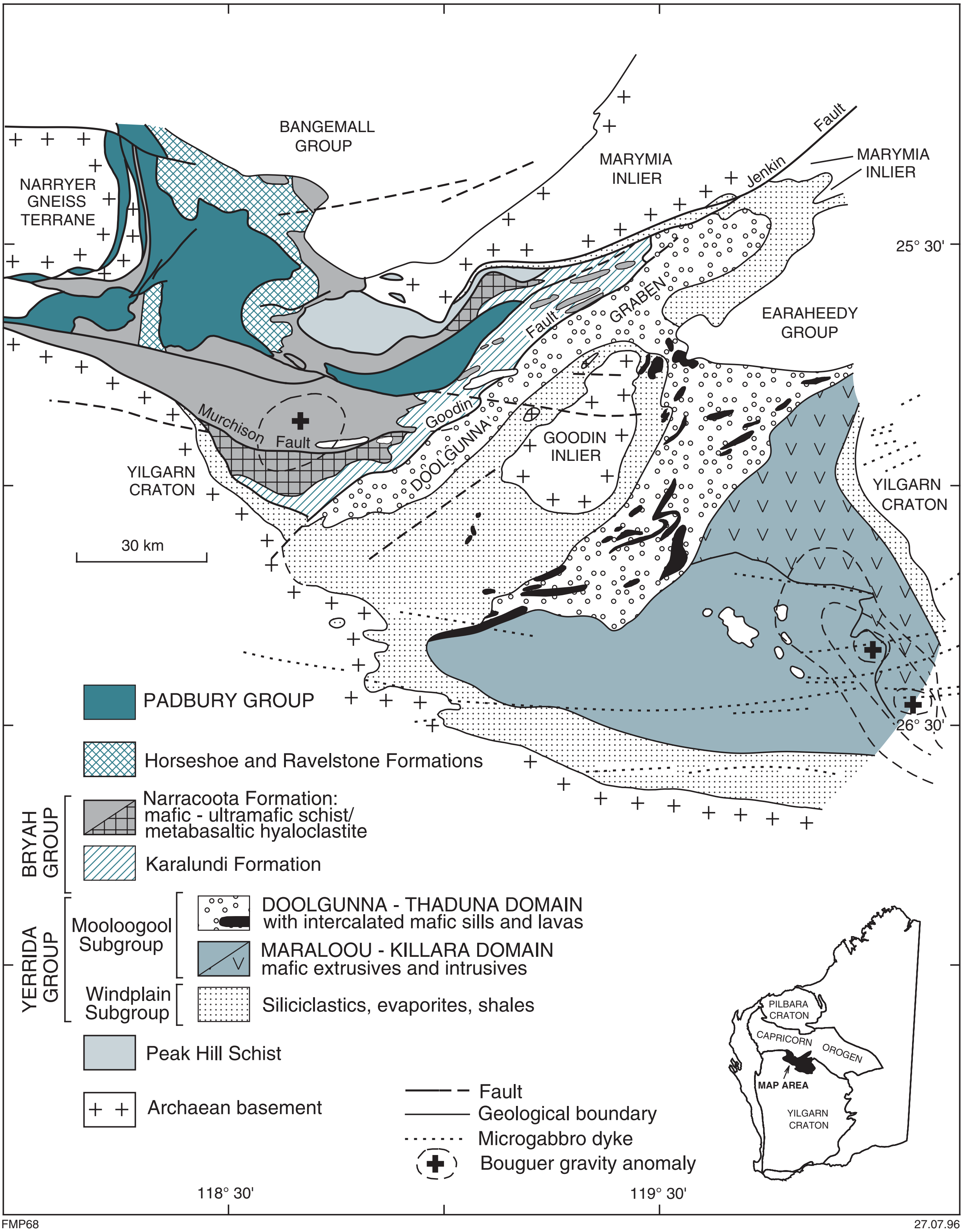


Figure 1. Simplified geological map of the Yerrida, Bryah and Padbury Basins, showing chief structural elements

which included regional sinistral faults.

Models of Yerrida and Bryah Basin development

The volcano-sedimentary successions of the Bryah and Yerrida Groups are characterized by diverse stratigraphic, metamorphic and structural histories. This, and the nature of the associated mafic magmatism (oceanic in the Bryah Group and continental in the Yerrida Group), are major features that must be considered in attempting to model the geodynamic evolution of these basins. Collectively, these features indicate that the Bryah and Yerrida Groups were deposited in separate rift-basin structures (*see* Pirajno et al., 1996).

Products of mafic volcanism (Narrracoota Formation) infilled much of the Bryah Basin. The Narracoota Formation consists of ultramafic and mafic schist, basaltic hyaloclastite and metabasalts of subalkaline Mg-rich tholeiitic affinity, with a range of MORB to oceanic island chemical signature (Pirajno and Davy, 1996). In at least one place there is evidence of a major central-type volcanic structure. Mafic pyroclastics are relatively common. In the Bryah Basin, the Narracoota Formation is locally intercalated with a basal clastic sequence (Karalundi Formation) and is overlain by chemical and clastic metasedimentary rocks. There is field and geochemical evidence that the Narracoota Formation extends farther to the west, perhaps as far as the ultramafic Trillbar Complex (Myers, 1990) and also to the northwest (Swager, C., and Occhipinti, S., 1996, pers. comm.). Except at the Horseshoe Lights volcanogenic Cu–Au deposit, no felsic members have been recognized in the Narracoota Formation.

The Yerrida Basin can be subdivided into two domains (Fig. 1): a) a northeasterly trending Doolgunna–Thaduna domain centred around the Goodin Inlier, and b) the Maraloou–Killara domain in the southeast (Mooloogool rift *of* Pirajno et al., 1995). The former is characterized by predominant turbiditic sedimentary rocks. Along the southern margins of this domain the turbidite rocks are intercalated with mafic igneous rocks of the Killara Formation along a broad northeast-trending belt (Fig. 1). Thus, the sediments of the Doolgunna–Thaduna domain were possibly shed from the Goodin Inlier and the Marymia Inlier, or equivalent basement highs (Fig. 1) in the northwest, whilst at the same time basaltic lavas (Killara Formation) were being erupted in the Maraloou–Killara domain. Continuing tectonic activity in these areas is indicated by the inclusion of tabular blocks of lavas in turbidite units on the southeastern side of the Goodin Inlier.

Field and geochemical data suggest that the Killara lavas have affinities to continental flood basalts (Pirajno and Davy, 1996). Here too there are no felsic volcanics and no evidence of central-type volcanoes or pyroclastic products. The basaltic lavas in the Mooloogool rift eventually were succeeded by the accumulation of argillaceous and silty sediments of the Maraloou Formation in the Maraloou–Killara domain. A zone of intercalated mafic lavas and black shales marks the transition from rift volcanism to rift-facies sedimentation. Peperite margins in sills indicate that mafic melts intruded wet unconsolidated sediments (Pirajno et al., 1994).

The back-arc model

A back-arc model for the Yerrida and Bryah Basins is based on a regional tectonic model for the Capricorn Orogeny by Myers (1993) and Tyler and Thorne (1990). The regional model proposed by Myers (1993; pers. comm., 1996) suggests that oceanic crust was being subducted beneath a microcontinent situated between the rifted passive margins of the Pilbara and Yilgarn Cratons at approximately 2.0 Ga. An Andean-type magmatic arc would have developed on this microcontinent as a result of subduction, with a back-arc basin being formed near and/or along the rifted passive margin of the northern edge of the Yilgarn Craton (Fig. 2). At approximately 1.85 Ga, closure of intervening oceanic crust and oblique collision occurred between the Pilbara and Yilgarn Cratons. This resulted in a fold-and-thrust belt on the edge of the Pilbara Craton and thrusting of magmatic arc material and microcontinental slices southward onto the Yilgarn Craton.

Based on the above, the origin of the Yerrida and Bryah Basins, could be related to processes of back-arc opening. This may have occurred with the initial separation and rifting of continental crust, followed by development of ocean-floor spreading centres in one or more sub-basins. The sag-basin phase (Windplain Subgroup, siliciclastics and evaporite units) would have formed ahead of the rift propagation. In this way, basins may have formed, progressively from west to east, through a sequence of crustal rupture and graben formation which, in places, advanced just enough to develop oceanic crust, with localized volcanic islands (Narracoota Formation). A possible scenario applicable to the Bryah rift is shown in Figure 3. The progressive west to east rupture of continental crust and attendant oceanic crust development must have halted just west of the Goodin Inlier, along what is now the Goodin Fault. Rifting, however, continued beyond the inlier but without the formation of oceanic crust. Thus, although a rift basin was formed (Yerrida Group), the associated mafic magma erupted in the Yerrida rift sub-basin was of continental character (Killara Formation). The setting envisaged for the Yerrida sub-basin is shown in Figure 4.

In the region of the Yerrida and Bryah Basins, closure and collision events at c.1.85 Ga involving fragments of the Yilgarn Craton, such as the Marymia and Goodin Inliers and the Narryer Terrane, resulted in strong deformation, thrusting and metamorphism of the oceanic crust and associated volcanic islands, together with remnants of rift shoulder lithologies (e.g. Karalundi Formation). The ultramafic-dominated Trillbar Complex (Myers, 1990) and the Narracoota Formation would, in this model, represent remnants of oceanic material which, during collision, were squeezed between pieces of continental crust.

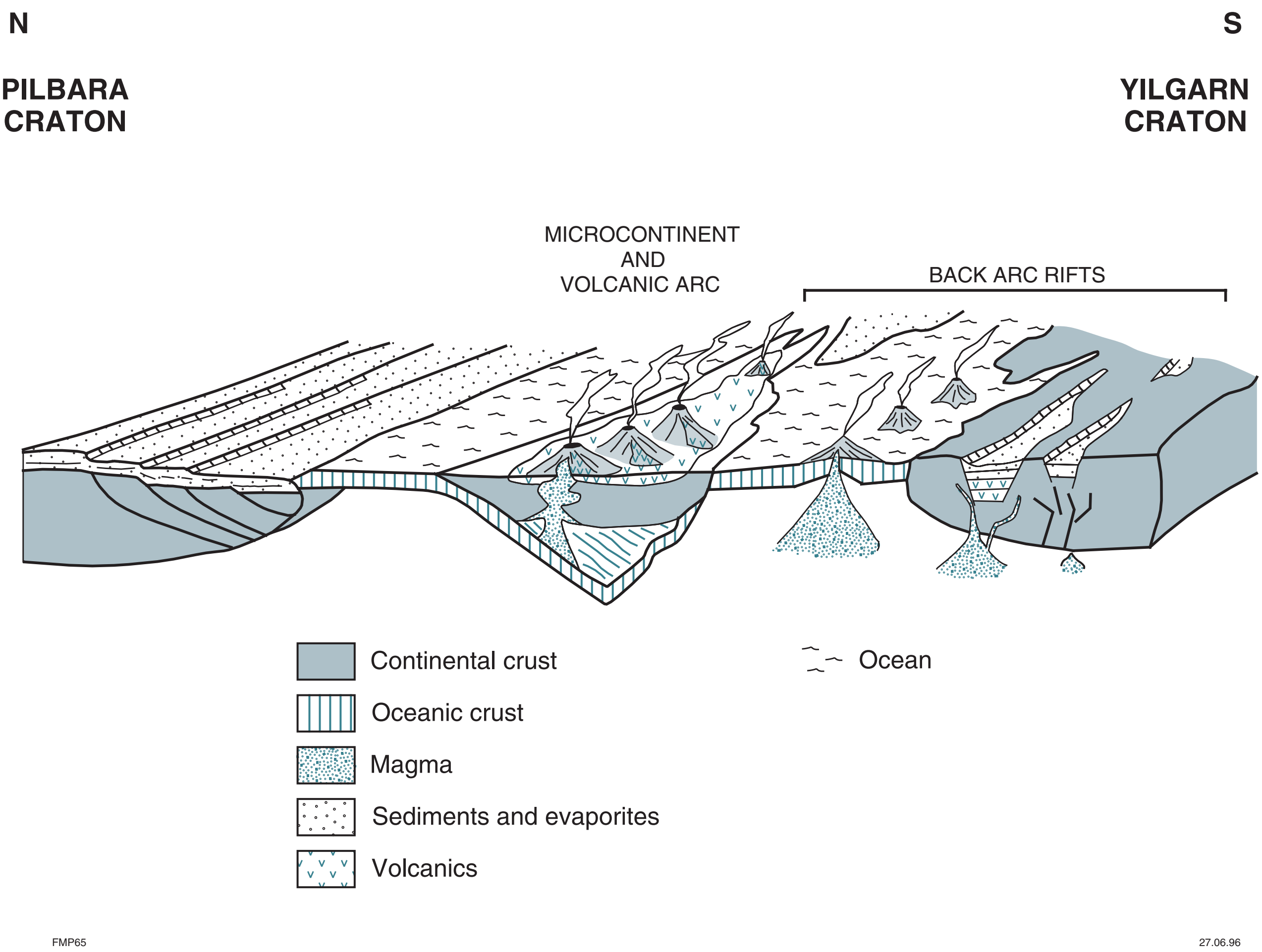


Figure 2. Schematic illustration showing a model of back-arc rifting to explain the origin of the Yerrida and Bryah Basins. Regional tectonics **based on** *Tyler and Thorne (1990), Myers (1993; pers. comm., 1996). Not to scale. See text for details.*

The pull-apart basin model

A pull-apart basin model involving rifting (due to sinistral strike-slip movements) has been proposed by Pirajno et al. (1995, fig. 2) to account for the domains defined by the Bryah and Yerrida Groups. According to this model an initial sag phase (Windplain Subgroup) was followed by rifting. The rifting phase was associated in space and time with the extrusion of tholeiitic basaltic lavas (Narracoota and Killara Formations respectively).

The dynamics of rift basins associated with strike-slip displacements are linked to variations in strike along the trace of a regional fault. Thus, a 'releasing bend' leads to local extension along the fault zone. These localized zones of extension result in 'pull-apart' basins (Allen and Allen, 1990). Dempster and Bluck (1995), who studied the evolution of pull-apart basins in the Scottish Highlands, recognize alternating periods of transtension and transpression, which result in distinctive metamorphic histories. These metamorphic and structural events accompany basin closure and are caused by a change from a transtensional to a transpressive regime (Dempster and Bluck, 1995). Mathematical modelling of pull-apart basin kinematics confirms that at least two depocentres or sub-basins can be formed sequentially during the progressive evolution of a pull-apart structure (Rodgers, 1980). During strike-slip movements, sub-basins may have formed sequentially in response to stress fields induced by successive configurations of the master faults (i.e. offset between master faults equals separation between them; Rodgers, 1980). In this way, deformation and metamorphism may occur as a result of progressive tectonic movements, which decrease in intensity with time. The model proposed here, which uses the Dempster and Bluck (1995) model as a prototype, is shown schematically in Figure 5 and discussed below.

In the Yerrida Basin area, a phase of initial transtension associated with sinistral shearing created a sag basin. This sag basin covered most of the area later occupied by the Bryah and Yerrida Groups. In this sag basin extensive aprons of siliciclastic, stromatolitic carbonate rocks and evaporites (Windplain Subgroup) were deposited in an epicontinental environment (Pirajno et al. 1995). The initial sag phase was followed by a sequence of extensional (rifting) and compressional episodes, which in

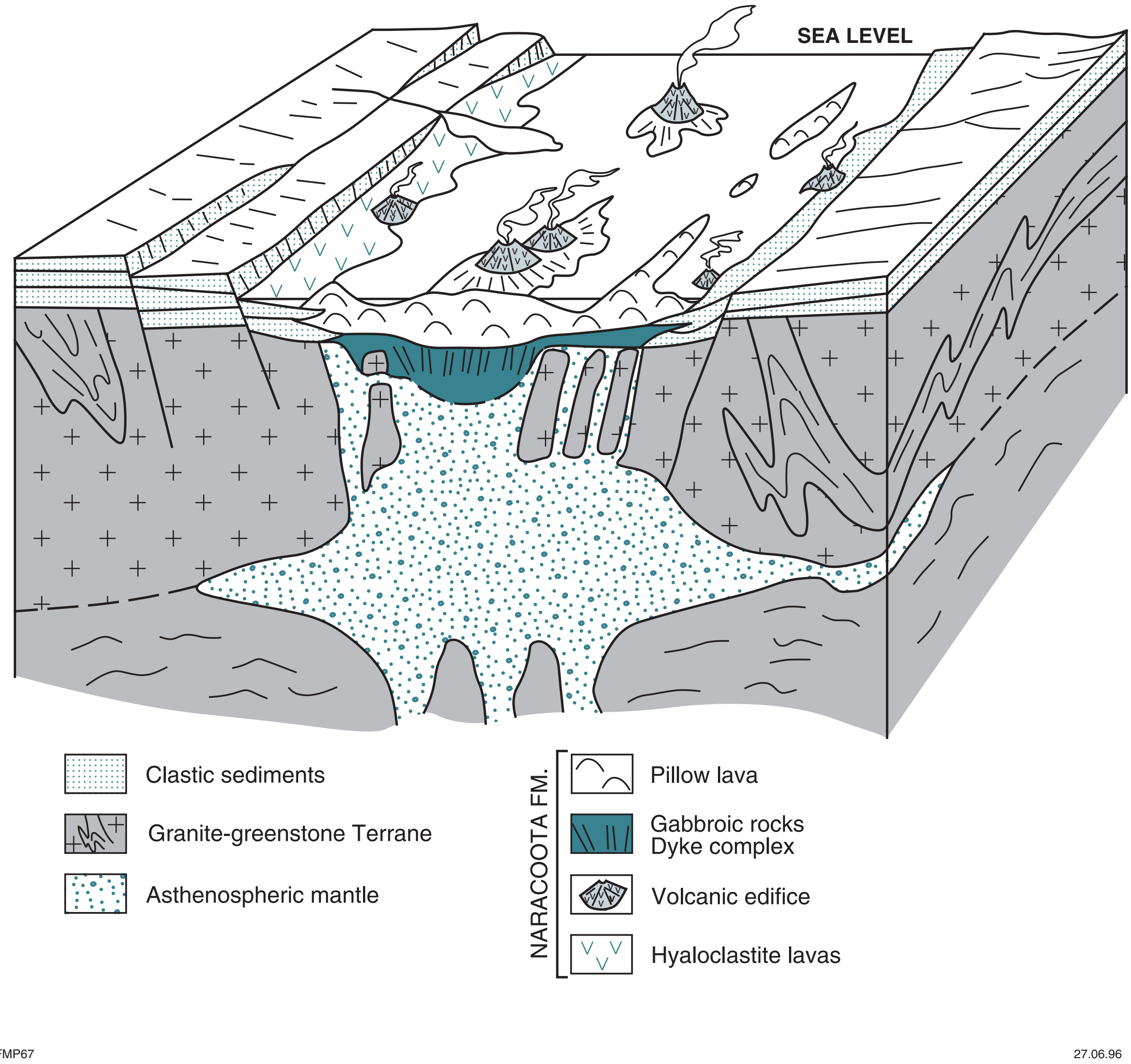


Figure 3. Tectonic setting for the origin and emplacement of the Narracoota Formation

the Bryah Basin may be traced through the deformation fabrics preserved in the rocks (deformation events D_1 to D_3 — Windh, 1992; Pirajno and Occhipinti, in prep.; Occhipinti et al., 1996).

Transpressional strike-slip movements led to rifting (Fig. 5a) during which the Bryah rift basin was formed on the west side of the future Goodin Inlier. A phase of north–south compression followed, leading to the D_1 deformation event in the rocks of the Bryah Group (Fig. 5b). This phase would be equivalent to basin closure and inversion in the Dempster and Bluck (1995) model, in which the volcano-sedimentary fill is deformed and metamorphosed. Periods of transtension, during which new sediments were deposited unconformably above the previously deformed units, alternated with periods of transpression. In this way the Bryah Group acted as a new 'basement' to incoming sediments, and each time the new basement–new cover interface would act as a shear surface during subsequent tectonic movements. This may explain the origin of the Padbury Group turbiditic sediments and the tectonic interleaving of these units with the Bryah Group (Occhipinti et al., 1996). Martin (1994) and Occhipinti et al. (1996) considered the Padbury Group to have been deposited in a foreland basin developed on top of the Bryah Basin during north–south thrust loading. Their concept is consistent with the model presented here.

Subsequent transtension movements produced a second pull-apart rift basin to the east, namely the Yerrida Basin (Fig. 5c), leaving the future Goodin Inlier as a separate basement block between the Bryah Basin and the newly developing Yerrida sub-basin. In this way, the Goodin Inlier became a central horst

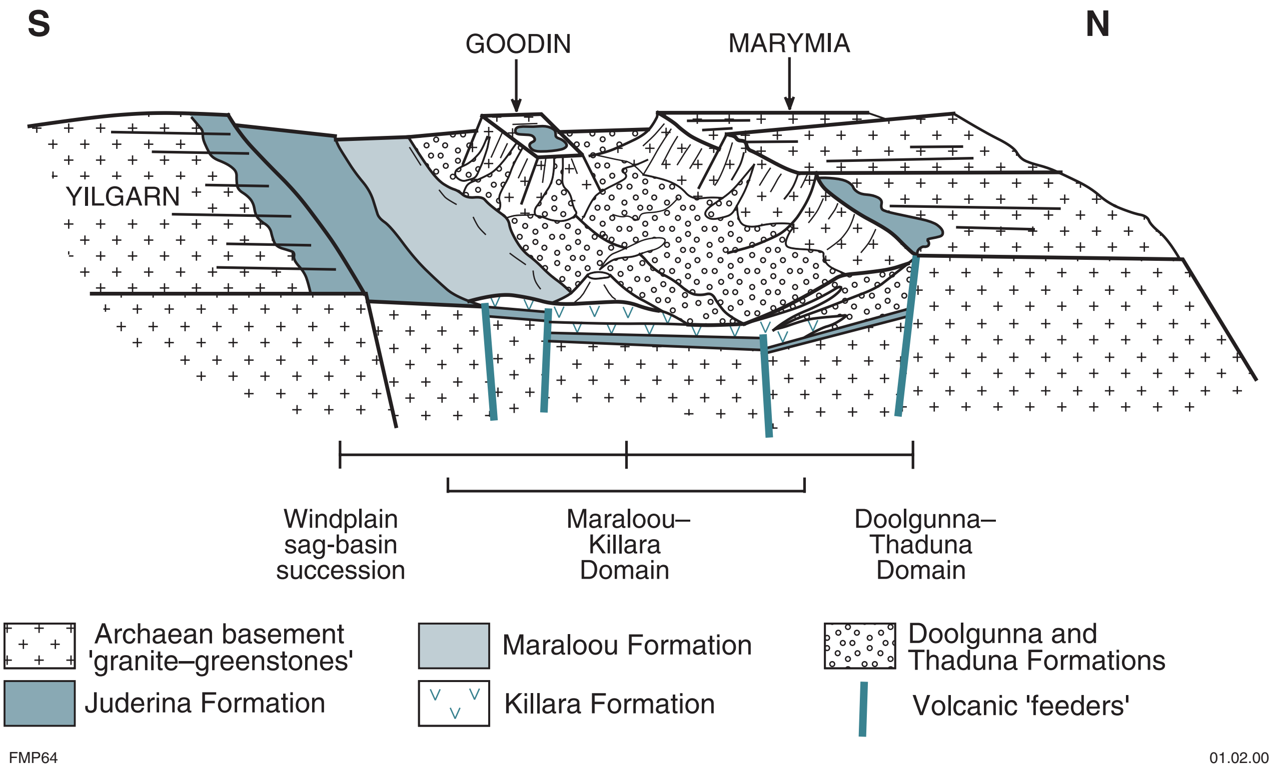


Figure 4. Tectonic setting for the Yerrida Basin and the emplacement of the Killara Formation.

structure (Fig. 1). In the evolution of pull-apart basins, the development of an 'insular region' that functions as a horst within the pull-apart basin is discussed by Sengor (1995, p. 110). The Goodin 'horst' provided a source for clastic sedimentation until the topographic high was effectively eliminated through erosional processes. This sedimentation was particularly important in the Doolgunna graben on the western side of the inlier (Fig. 1).

Further transpressive movements followed this phase of rifting. During this time an approximately east–west compression took place that resulted in the Bryah Basin succession being thrust over the rocks of the Doolgunna graben (Fig. 5d).

Discussion and conclusions

Rift development can be attributed to mantle processes (model of active rifting) or to tensional lithospheric stresses (model of passive rifting). In the former, an upwelling mantle plume interacts with the base of the lithosphere prior to crustal extension. This process results in convective thinning of the lithosphere from below. An important effect of this phenomenon is the formation of a crustal domal structure, which can reach horizontal dimensions of up to 2000 km in diameter and an uplift in excess of 3000 m (White and McKenzie, 1989). A prime example of active rifting is the East African Rift System. In the case of passive rifting, crustal thinning occurs due to lithospheric stresses, as mentioned above. The causes of these stresses are diverse, but continental collisions play a major role (the Baikal rift system is a good example). The reader is referred to the review articles by White and McKenzie (1989), Sengor (1995) and Busby and Ingersoll (1995) for details.

In general terms, active and passive rifts can be distinguished on the basis of their volcano-sedimentary record. For example, active rifts are generally floored by erosional unconformities and early, voluminous mafic volcanism. In contrast, passive rifting is generally characterized by early sagging and later mafic volcanism.

The history of the Bryah and Yerrida Basins was controlled by regional tectonics, and accordingly they evolved as passive rift systems. The associated lithospheric thinning allowed decompression melting of a depleted asthenospheric mantle, with the localized development of oceanic crust.

Field, geochemical and geophysical (gravity) evidence in the Bryah and Yerrida Basins also suggests that they were formed by processes of passive rifting, controlled by lithospheric stresses, set up along the northern margin of the Yilgarn Craton either during strike-slip faulting or back-arc rifting. Whether at some stage a mantle plume caused rupture of the lithosphere in the Bryah and Yerrida rifts, allowing mantle melts to be erupted, is not known.

In the terminology of Sengor (1995) the Bryah and Yerrida Basins could be classified as 'fossil rifts', meaning that they failed to generate an ocean. However, in the Bryah Basin, continental crust was breached and some oceanic crust was generated (Pirajno et al., 1995; Pirajno and Davy, 1996). In this case the Bryah

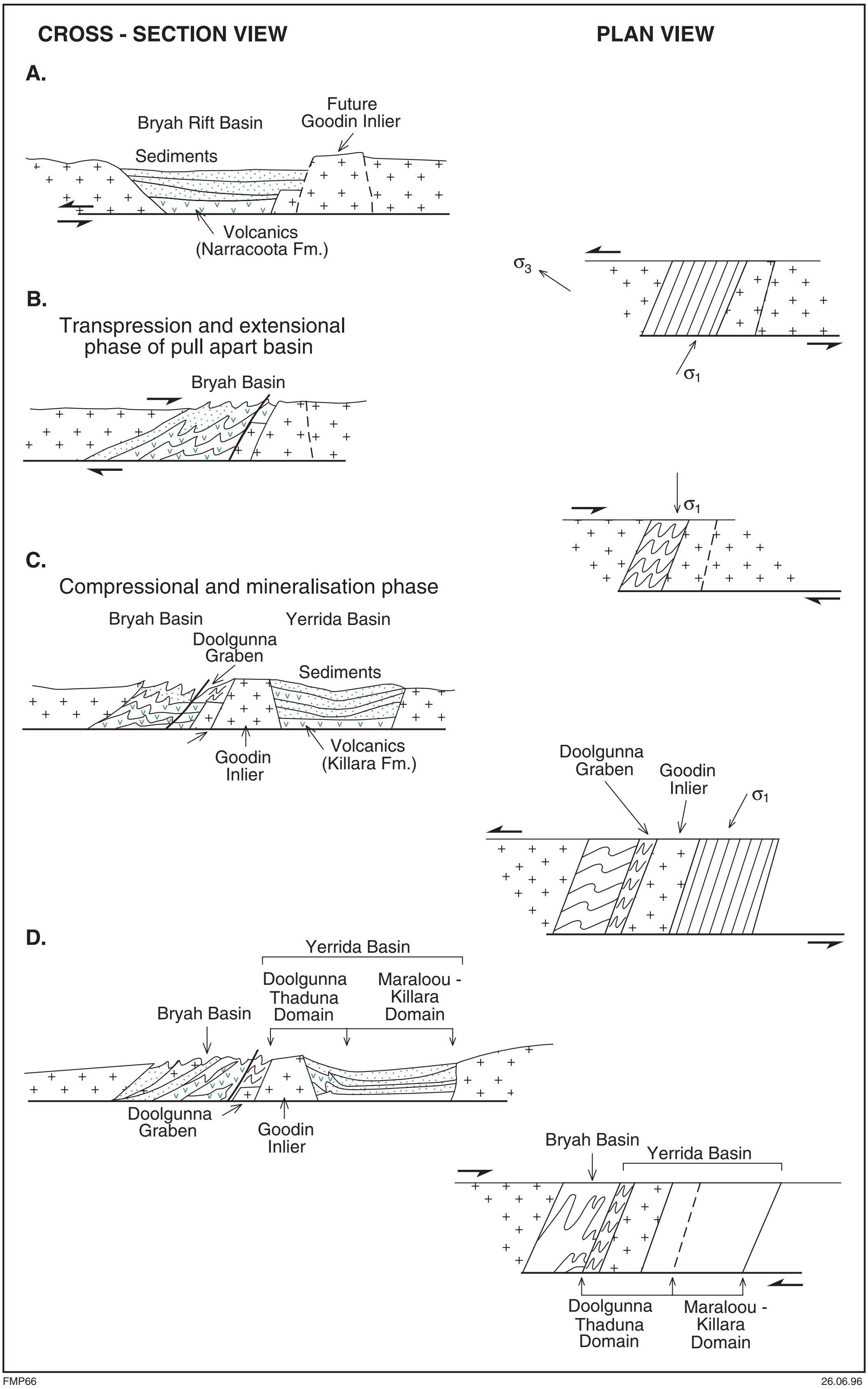


Figure 5 (A—D). Schematic illustration showing a pull-apart model for the origin of the Yerrida and Bryah Basins. Based on Dempster and Bluck (1995) and Pirajno et al. (1995). See text for details.

rift can be regarded as a proto-oceanic rift basin comparable with small spreading oceanic basins in modern transtensional environments, such as the Guaymas basin in the gulf of California. A comparable situation could be that of the Matchless Amphibolite Belt of the Damara Orogen in Namibia, for which both strike-slip and subduction-related models have been advocated (Breitkopf and Maiden, 1988).

The positive Bouguer anomalies spatially associated with the Narracoota and Killara Formations suggest that a large volume of dense material, probably a mafic body(ies), underlies the areas of volcanics. Positive gravity anomalies are common in intracontinental rift zones (e.g. Mid-Continent Rift — Hutchinson et al., 1990). Modelling of these positive gravity anomalies suggests that rifts are underlain by large volumes of mafic igneous material.

The structural and metamorphic history of these basins may be different in response to the regional geothermal gradients and to their collision with adjacent crustal blocks. The Bryah (and Padbury) Basin tectonically interacted with the Narryer Gneiss Complex and the southern margin of the Marymia Inlier, and was subsequently thrust over the western margin of the Glengarry basin (Doolgunna northeast-trending graben). The Yerrida Basin, on the other hand, was only mildly affected by tectonism. This occurred along the northern and western margins and along its boundary with the southern side of the Goodin Inlier (mainly within the Doolgunna–Thaduna domain).

Knowledge of the geology of these rift basins is still incomplete. Work is currently in progress to provide geochronological constraints and to elucidate aspects of sedimentological and metamorphic histories and volcanic geochemistry.

Acknowledgments

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References

ALLEN, P. A., and ALLEN, J. R., 1990, Basin analysis — principles and applications: Oxford, Blackwell Scientific Publications, 451p.

BREITKOPF, J. H., and MAIDEN, K. J., 1988, Tectonic setting of the Matchless Belt pyritic copper deposits, Namibia: Economic Geology, v. 83, p. 710–723

BUSBY, C. J., and INGERSOLL, R. V., 1995, Tectonics of sedimentary basins, *in* Tectonics of sedimentary basins *edited by* C.J. BUSBY and R.V. INGERSOLL: Blackwell Science p. 1–51.

DEMPSTER, T. J., and BLUCK, B. J., 1995, Regional metamorphism in transform zones during supercontinent breakup: Late Proterozoic events of the Scottish Highlands: Geology, v. 23; p. 991–994

GEE, R.D., and GREY, K., 1993, Proterozoic rocks on the Glengarry 1:250 000 sheet — stratigraphy, structure and stromatolite biostratigraphy: Western Australia Geological Survey, Report 41, 30p.

HUTCHINSON, D.R., WHITE, R. S., CANNON, W. F., and SCHULZ K. J., 1990, Keweenaw hot spot: geophysical evidence for a 1.1 Ga mantle plume beneath the Midcontinent rift system: Journal of Geophysical Research, v. 95, p. 10869–10884.

MARTIN, D. M., 1994, Sedimentology, sequence stratigraphy and tectonic setting of a Palaeoproterozoic turbidite complex, Lower Padbury Group, Western Australia: University of Western Australia, PhD thesis (unpublished).

MYERS, J. S., 1993, Precambrian history of the west Australian craton and adjacent orogens: Annual Review in Earth and Planetary Science, v. 21, p. 453–485.

MYERS, J. S., 1990, Gascoyne Complex, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 198–202.

OCCHIPINTI, S. A., SWAGER, C. P., and PIRAJNO, F, 1996, Structural and stratigraphic relationships of the Padbury Group, Glengarry Basin, Western Australia — implications for tectonic history: Western Australia Geological Survey, Annual Review 1995–96, p. 88–95.

PIRAJNO, F., ADAMIDES, N., OCCHIPINTI, S. A., SWAGER, C. P., and BAGAS, L., 1995, Geology and tectonic evolution of the Early Proterozoic Glengarry basin, Western Australia: Western Australia Geological Survey, Annual Review 1994–95, p. 71–80.

PIRAJNO, F., BAGAS, L., SWAGER, C.P., OCCHIPINTI, S.A., and ADAMIDES, N.G., 1996, A reappraisal of the stratigraphy of the Glengarry Basin: Western Australia Geological Survey, Annual Review 1995–96, p. 81–87.

PIRAJNO, F., and DAVY, R., 1996, Mafic volcanism in the Palaeoproterozoic Glengarry Basin, Western Australia, and implications for its tectonic evolution. Geological Society of Australia. Abstracts no. 41, p. 343.

PIRAJNO, F., and OCCHIPINTI, S. A., 1995, Base metal potential of the Palaeoproterozoic Glengarry and Bryah basins, Western Australia: Australian Institute of Geoscientists, Bulletin 16, p.51–56.

PIRAJNO, F., and OCCHIPINTI, S. A., in prep., Geology of the Bryah 1:100 000 sheet, Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

PIRAJNO, F., OCCHIPINTI, S. A., LE BLANC SMITH, G., and ADAMIDES, N. G., 1994, Pillow lavas in the Peak Hill and Glengarry terranes: Western Australia Geological Survey, Annual Review 1993–94, p. 63–66.

RODGERS, D.A., 1980, Analysis of pull-apart basin development produced by en echelon strike-slip faults. International Association of Sedimentologists, Special Publication no. 4, p. 27–41.

SENGOR, A.M.C., 1995, Sedimentation and tectonics of fossil rifts, *in* Tectonics of Sedimentary Basins *edited by* C. J. BUSBY and R. V. INGERSOLL: Blackwell Science, p. 53–118.

TYLER, I.M., and THORNE, A. M., 1990, The northern margin of the Capricorn Orogen, Western Australia — an example of an Early Proterozoic collision zone: Journal of Structural Geology, v. 12, p. 685–701.

TYLER, I. M., PIRAJNO, F., BAGAS, L., MYERS, J.S, and PRESTON, W.A., in press, The geology and mineral deposits of the Proterozoic in Western Australia: AGSO Journal of Geology and Geophysics, v. 17.

WHITE, R., and MCKENZIE, D., 1989, Magmatism at rift zones: the generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729.

WINDH, J., 1992, Tectonic evolution and metallogenesis of the early Proterozoic Glengarry Basin, Western Australia: University of Western Australia, PhD thesis (unpublished).

Magmatic–hydrothermal breccia dykes and hydrothermal alteration in the McHale Granodiorite, Halls Creek Orogen: a possible porphyry system

by W. K. Witt and T. Sanders[1]

Abstract

The 1827 ± 3 Ma McHale Granodiorite is exposed to the east of the Halls Creek Fault, approximately 10 km southeast of Warmun (Turkey Creek). Two main granitoid phases are extensively altered and cut by magmatic–hydrothermal breccia dykes. Alteration styles include propylitic and potassic alteration, sericitization, silicification and argillic alteration. Magmatic–hydrothermal breccia dykes are formed at shallow crustal levels by the violent release of a volatile phase from a subjacent magma chamber. The dykes and the documented styles of alteration in the McHale Granodiorite are found typically in mineralized porphyry-copper and epithermal environments. The rocks described in this paper may represent a fault-displaced portion of a larger porphyry/epithermal system that also hosts the Angelo copper deposit, south of Halls Creek.

KEYWORDS: Palaeoproterozoic, Kimberley Province, Halls Creek Orogen, McHale Granodiorite, magmatic–hydrothermal breccia dykes, hydrothermal alteration, mineralization

During 1995, the Geological Survey of Western Australia conducted a field and literature (including WAMEX) survey to document occurrences of economically significant minerals in the Halls Creek Orogen and adjoining areas of the Kimberley region. This project follows up a regional geological mapping program carried out in conjunction with the Australian Geological Survey Organisation, under the National Geoscience Mapping Accord.

A large area of hydrothermally altered granite cut by magmatic–hydrothermal breccia dykes was identified approximately 10 km southeast of Warnum (Turkey Creek). This area (Fig. 1) contains several minor copper occurrences and the geological features described in this paper suggest the potential for porphyry or epithermal precious and base metal mineralization. Other occurrences of epithermal mineralization, west and northwest of Halls Creek, have been described by Pirajno et al. (1994).

Regional geology

The area described lies immediately east of the Halls Creek Fault and lies within the central zone of the Lamboo Complex of the Halls Creek Orogen (Tyler et al., 1995). The area is underlain mainly by McHale Granodiorite which forms part of the Sally Downs Batholith (Sheppard et al., 1995). McHale Granodiorite has been dated by SHRIMP at 1827 ± 3 Ma (Page, R. W., 1994, pers. comm.) and is unconformably overlain by the Palaeoproterozoic Red Rock Formation. Younger, Meso- to Neoproterozoic sedimentary rocks (Helicopter Siltstone and Duerdin Group) to the east are in fault contact with McHale Granodiorite (Figs 1, 2). Farther south, between the Halls Creek Fault and the Osmond Fault, McHale Granodiorite intrudes a sequence of metasedimentary rocks that may be equivalent to the c. 1840 Ma Koongie Park Formation, exposed near Halls Creek (Tyler et al., in prep.). These two areas will be referred to as the northern, and southern occurrences, respectively, of the McHale Granodiorite.

McHale Granodiorite

Although termed McHale Granodiorite by Dow and Gemuts (1969), most samples collected during this study range from diorite to granodiorite, with leucocratic tonalite being the most common. The undeformed to weakly deformed nature of the McHale Granodiorite, in conjunction with the widespread alteration and other evidence for hydrothermal activity, contrasts with the prominent exposures of the coeval Mabel Downs Tonalite west of the Halls Creek Fault (Fig. 1). These outcrops of Mabel Downs Tonalite are locally strongly deformed but display little evidence of hydrothermal activity.

Southern occurrences of McHale Granodiorite

The least-altered outcrops of McHale Granodiorite lie in the Osmond Valley, between the Halls

[1] (Goldfields Geological Associates)

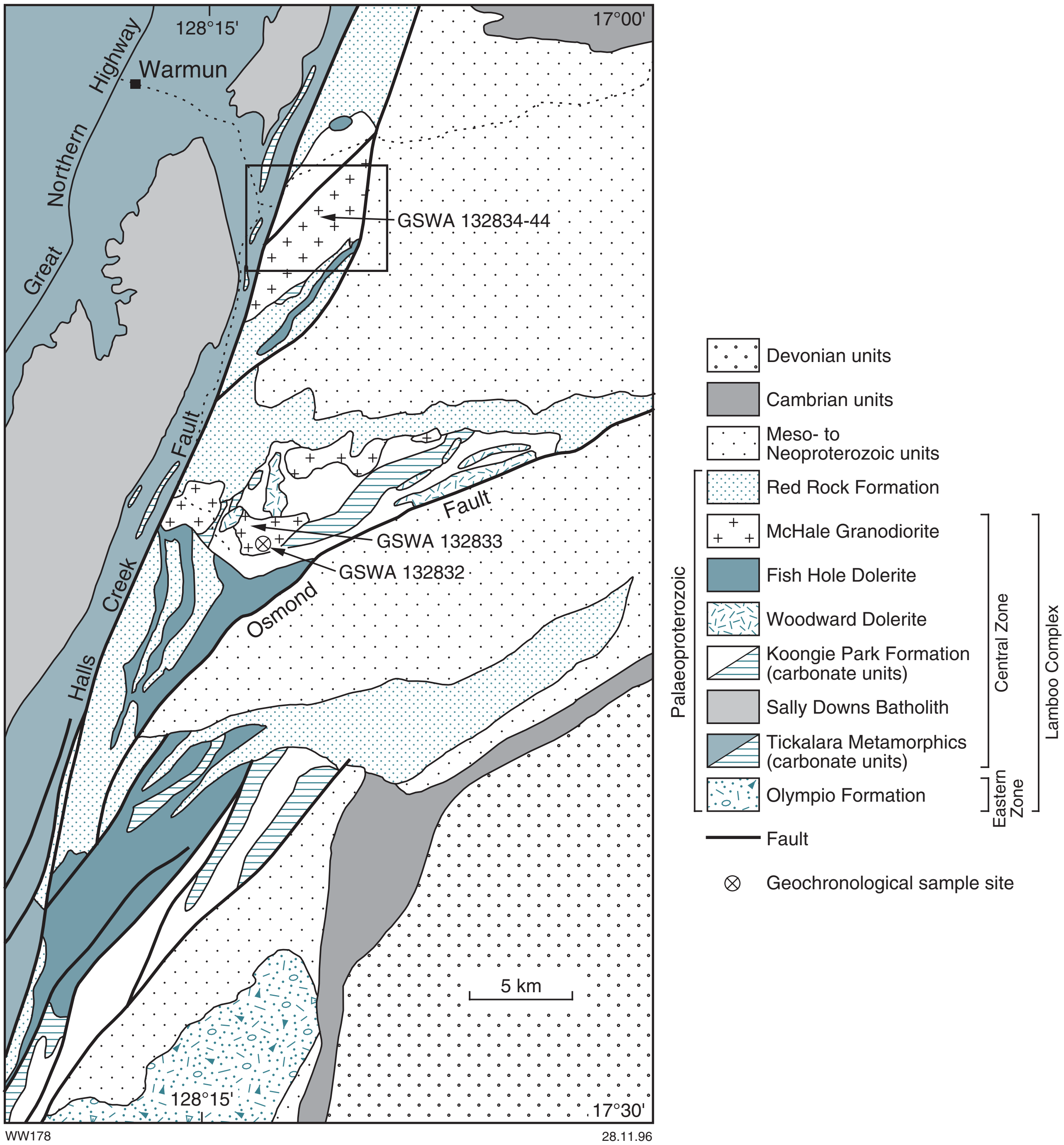


Figure 1. Regional geology of a part of the Halls Creek Orogen, showing distribution of the McHale Granodiorite and location of Figure 2

Creek Fault and the Osmond Fault (Fig. 1). Sample GSWA 132832 is a weakly foliated, equigranular, coarse-grained (2–4 mm) hornblende–biotite tonalite with about 8% biotite and 2% amphibole. Plagioclase (low-Ca andesine) is the dominant feldspar, with K-feldspar minor to absent. GSWA 132833 is texturally similar to GSWA 132832 but is less deformed and more intensely altered. Amphibole or pseudomorphs of amphibole were not recognized. Biotite is pseudomorphed by chlorite with minor neoblastic muscovite locally developed. Approximately 15% (?secondary) microcline occurs as fine-grained, granoblastic aggregates along grain boundaries between plagioclase and quartz.

The northern occurrence of McHale Granodiorite

The northern occurrence of the McHale Granodiorite is texturally similar to the southern occurrences

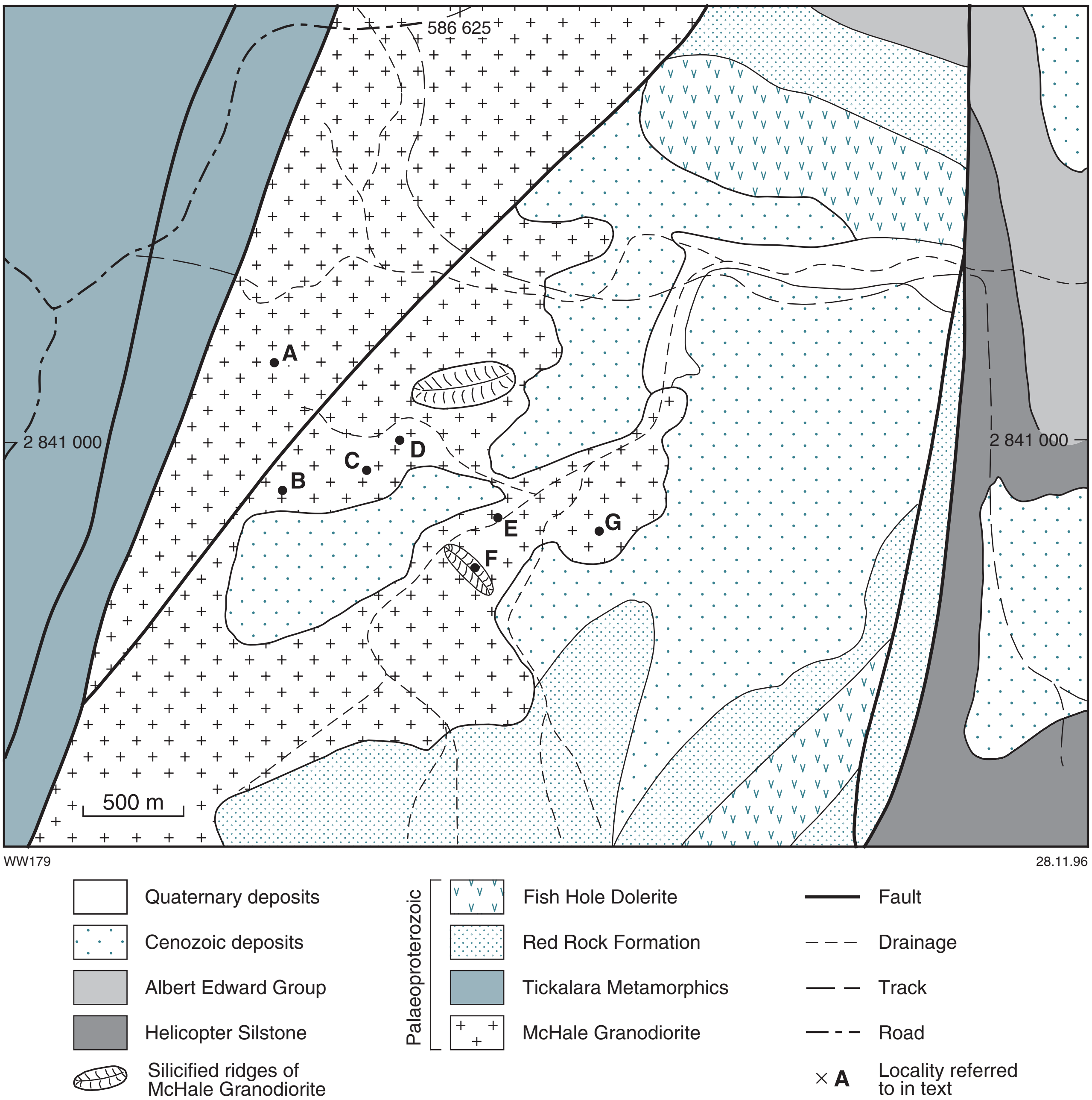


Figure 2. Geology of the Halls Creek Orogen, southeast of Warmun (Turkey Creek), showing localities referred to in the text

but is much more extensively and intensely altered and is cut by swarms of magmatic–hydrothermal breccia dykes. A pink to deep red colour reflects widespread to pervasive hematitization of the granitoid. The area is characterized by sparse, low, rubbly outcrop although there are two prominent ridges of silicified granodiorite (Fig. 2). Discontinuous pods, lenses and dykes of pegmatitic granite with bright pink feldspar occur within the granitoid, and at locality G appear to pass along strike into a magmatic–hydrothermal breccia dyke. Larger (1–2 m wide) veins of carbonate containing fragments of magmatic–hydrothermal breccia dykes are present at locality G. Weathered granitoid outcrops in the creek crossing at locality E (Fig. 2) are cut by numerous quartz and carbonate veins and veinlets, which are locally limonitic (?after pyrite or ankerite), and a magmatic–hydrothermal breccia dyke with well-rounded ('milled') clasts. The least-altered granitoid sample (GSWA 132834, from locality G, Fig. 2) is an equigranular, coarse-grained (2–3 mm) biotite tonalite with about 5% (?primary) K-feldspar and 10% chlorite and muscovite pseudomorphs after biotite. Low-Ca andesine is extensively sericitized and the rock is cut by several thin veinlets of quartz, carbonate and K-feldspar (?adularia). The two ridges shown in Figure 2 are composed of extensively fractured and altered granitoid, cut by several dykes of magmatic–hydrothermal breccia and quartz–feldspar porphyry. Sample GSWA 132835 (from locality F, Fig. 2) is texturally similar to GSWA 132834 but ferromagnesian minerals have been completely destroyed. The feldspathic component of the rock is pseudomorphed by cryptocrystalline quartz and clay minerals (probably interlayered illite–kaolin; Fig. 3G). Domains dominated by clay minerals are accompanied by fine-grained disseminated anatase (Fig. 3H). Fine-grained disseminations of dusty hematite are ubiquitous.

The relatively leucocratic granodiorite or tonalite described above occurs with irregular dykes and plugs of more melanocratic granitoids at localities A, B and C (Fig. 2). Relative-timing relationships are suggested by local exposures of leucocratic dykes and pegmatite cutting more melanocratic phases. The relatively mafic intrusive phase (GSWA 132844) is mainly coarse-grained (1–2 mm), equigranular diorite with about 40% amphibole. Although only weakly deformed, the diorite is pervasively altered with potassic alteration overprinting an earlier phyllic or propylitic stage. Plagioclase is extensively sericitized whereas amphibole is pseudomorphed by fine-grained chlorite, calcite, quartz and finely divided titanite. There is also 5–10% secondary quartz along grain boundaries and as inclusions in amphibole and veinlets of carbonate. The later, potassic stage of alteration produced irregular aggregates and discontinuous veinlets of biotite. Finer grained (0.5–1 mm) mafic rocks, interpreted as altered hornblendites on the basis of relict texture, are associated with the diorite. These rocks have been altered to a mass of chlorite and carbonate with irregular aggregates of secondary biotite. A later stage of alteration deposited epidote in fractures and joints. At locality A, irregular, discontinuous, coarse-grained quartz–carbonate–epidote veins are associated with the diorite and are cut by later carbonate veinlets.

Magmatic–hydrothermal breccia dykes

Several swarms of magmatic–hydrothermal breccia dykes have been recognized in the northern occurrence of McHale Granodiorite. The dykes, which occur at all localities (A–G) in Figure 2, are 1–2 m wide and strike north to northeast. Although magmatic–hydrothermal breccia dykes intrude diorite at localities A, B and C, they are invariably associated with dykes and apophyses of leucocratic tonalite or granodiorite which cut the more mafic phase. The matrix-supported breccias contain abundant angular to rounded clasts, up to several centimetres across, in a strongly silicified matrix of rock flour (Fig. 3A–F). Clast types vary from locality to locality but are mainly quartz–feldspar porphyry (?felsic volcanic or subvolcanic rock), granitoid, vein quartz, and quartz and feldspar crystal fragments. Dioritic clasts are dominant where the dykes cut the relatively mafic phase of McHale Granodiorite. The clasts display variable alteration, mainly sericitization and silicification. Less commonly (e.g. GSWA 132841, locality A, Fig. 2), there are clasts of massive carbonate up to several centimetres across (Fig. 3C). Rounded clasts display evidence of hydrothermal ‘milling’ during violent, gas-charged eruption of the dyke material, and fluidization structures have been observed (Fig. 3E,F). Coarse, euhedral limonitic pseudomorphs and limonitic matrix (?after pyrite) have been observed in samples (GSWA 132839, 132840) from locality C (Fig. 2). In some samples, overprinting relationships indicate repeated stages of dyke formation and brecciation (Fig. 3B). Breccia dykes are cut by later quartz and carbonate veinlets.

Partial whole-rock analyses of some magmatic–hydrothermal breccia dykes from the area shown in Figure 2 are given in Table 1. The samples give little indication of anomalous metal contents except for sample 132840, which has a limonitic matrix and contains moderately high copper.

Discussion

Hydrothermal alteration in the McHale Granodiorite may be related to any or all of several processes.

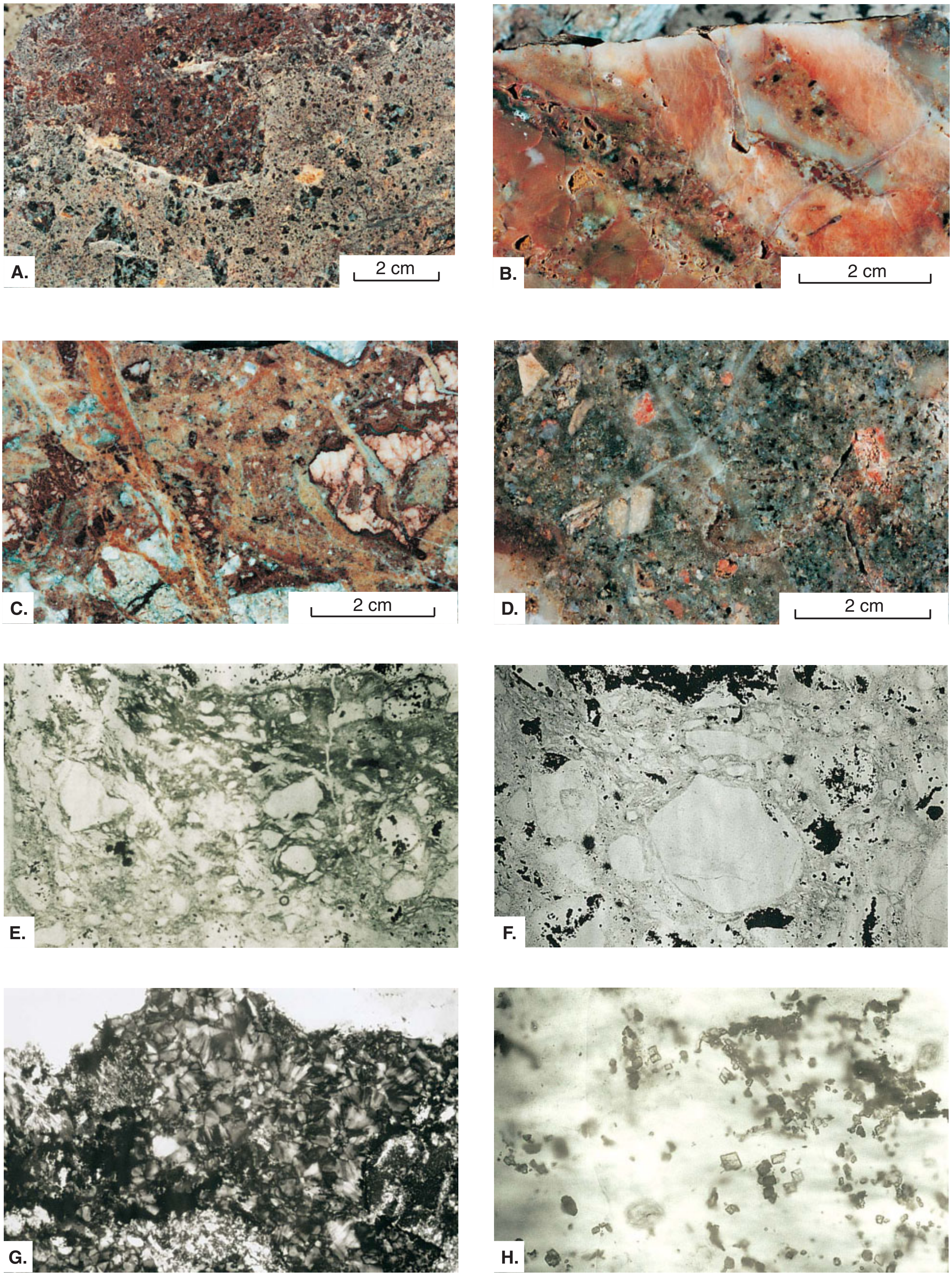
- Second boiling of McHale Granodiorite or other felsic magmas and subsequent circulation of magmatic (?and meteoric) fluids.
- Erosion and weathering at the unconformity at the base of the overlying Red Rocks Formation.
- Movement on the Halls Creek Fault.

However, the association of altered McHale Granodiorite with magmatic–hydrothermal breccia dykes strongly implies an important role for the first process.

Magmatic–hydrothermal breccias are produced by the violent release of hydrothermal fluids from magma chambers and are commonly located in the upper parts of plutons or stocks (Sillitoe, 1985). Rounded clasts are produced locally by attrition or milling (Sillitoe, 1985) or spalling as a result of decompressive shock (Kirwan, 1985). Fluidization structures record the gas-charged upwards streaming of particles in the high-energy environment that accompanies fluid saturation and second boiling of a magma at shallow crustal levels (Burnham, 1979).

The presence of magmatic–hydrothermal breccia dykes in the McHale Granodiorite is evidence of a shallow level of pluton emplacement and related hydrothermal activity, including second boiling. This feature is not easily reconciled with the coarse, equigranular texture of the McHale Granodiorite, which suggests a deeper level of pluton emplacement. This apparent inconsistency may indicate that hydrothermal fluid activity is related to an unexposed high-level pluton which post-dated emplacement of the McHale Granodiorite and subsequent uplift. There are two intrusive events which are known to post-date emplacement of the McHale Granodiorite. The Mount Christine Monzogranite (1810 Ma) and the San Sou Monzogranite (1790 Ma) have been identified mainly in the southern part of the Halls Creek Ororgen and are more felsic than the McHale Granodiorite.

A complex sequence of intrusion, dyke formation, brecciation, veining and hydrothermal alteration is evident in the northern occurrence of McHale Granodiorite. Based on



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initial observations, the sequence is as follows:

1. Intrusion of diorite and related rocks (e.g. hornblendites).
2. Intrusion of leucocratic tonalite and granodiorite with formation of pegmatite.
3. Emplacement of magmatic–hydrothermal breccias during second boiling of the McHale Granodiorite or an unexposed, subjacent pluton.
4. Hydrothermal alteration (propylitic alteration, potassic alteration, sericitization, silicification, argillic alteration) followed crystallization and release of hydrothermal fluids but may have partially overlapped brecciation as clasts commonly display a different style of alteration to the silicified rock-flour matrix.
5. Carbonation occurred during propylitic alteration and massive veins of carbonate contain fragments of breccia. However, massive carbonate clasts in some breccia dykes indicate overlap between carbonating fluids and brecciation. Carbonation continued during stage 5 as late, cross-cutting veinlets.
6. Epidote-rich veins and fracture-filling accompanied by varying amounts of carbonate.

Magmatic–hydrothermal breccia dykes, and the alteration styles documented in this paper (argillic alteration and residual silica enrichment), are commonly associated with porphyry and epithermal styles of mineralization — most commonly base and precious metals but also tin, tungsten and molybdenum (Sillitoe, 1985; Heald et al., 1987; Hedenquist et al., 1994). In some cases, the breccia dykes themselves are mineralized. The ocurrences described here may be related to a larger hydrothermal system, including mineralization at Mount Angelo South near Halls Creek which has been described as a possible porphyry copper deposit (Griffin et al., in prep.). This is consistent with estimates of sinistral movement along the Halls Creek Fault of at least 90 km (Tyler et al., 1995) and could indicate movement of up to 150 km.

Many of the small copper occurrences in and adjacent to the area described appear spatially related to the Halls Creek Fault

Table 1. Partial whole-rock geochemical analyses of magmatic–hydrothermal breccia dykes in the McHale Granodiorite, Halls Creek Orogen

Sample no.	*132836*	*132837*	*132838*	*132839*	*132840*	*132841*
Ti	521	769	3 371	429	880	420
Fe	2.35%	1.29%	2.34%	1.44%	13.7%	4.09%
Mn	253	181	20	77	2 096	1 751
Mg	861	1 094	188	468	1 430	9 630
Ca	2 594	2 785	240	418	387	10.1%
Na	207	1 532	92	282	290	4 428
K	9 000	1.18%	3 615	7 850	1.56%	8 750
P	168	276	374	113	836	223
As	5	3	-	5	-	-
Au	**-**	**3**	**-**	**50**	**-**	**-**
Ce	-	-	-	10	19	-
Co	-	2	-	-	19	-
Cr	174	435	139	557	188	135
Cu	26	59	14	50	1 838	65
Mo	-	-	-	-	9	-
Nb	-	-	8	-	-	-
Ni	5	7	-	8	20	9
Pb	20	16	30	14	16	8
Sb	4.2	1.4	0.8	7.4	1.2	1.0
Sr	3	13	136	59	77	111
Pd	**-**	**4**	**1**	**-**	**-**	**-**
U	2.6	2.7	3.7	2.5	4.5	1.9
V	17	21	73	14	26	34
W	0.5	0.7	2.9	0.7	1.0	0.3
Y	5	6	6	-	5	9
Zn	30	25	9	21	10	60
Zr	34	30	54	18	27	7

Notes: All analyses in ppm unless otherwise indicated (as % or in **bold type** which indicates **ppb**).

Ag (1 ppm), Bi (5 ppm), Cd (5 ppm), Sn(5 ppm), Pt (5 ppb) and Te (0.2 ppm) are all consistently below the lower limit of detection (shown in brackets) in all samples

132836, 132837 Magmatic–hydrothermal breccia dykes (locality G, Fig. 2); 132838 Magmatic–hydrothermal breccia dyke (locality F, Fig. 2); 132839 Magmatic–hydrothermal breccia dyke (locality D: Fig. 2); 132840 Magmatic–hydrothermal breccia dyke with limonitic matrix (locality D: Fig. 2); 132841 Magmatic–hydrothermal breccia dyke (locality A, Fig. 2).

Figure 3. Magmatic–hydrothermal breccia dykes from southeast of Turkey Creek, Halls Creek Orogen

A. GSWA 132838, locality F (Fig. 2), showing large, angular clasts of altered (silicified, argillized, hematitized) granitoid in a rock flour matrix

B. GSWA 132839, locality D (Fig. 2), showing late, very fine-grained breccia dykes (pink, chalcedonic appearance) cutting earlier, coarser breccia dyke

C. GSWA 132841, locality A, showing a breccia dyke with clasts of massive carbonate (upper right)

D. GSWA 132837, locality G (Fig. 2), showing detail of matrix; rounded ('milled') to angular clasts of hematitized granitoid (pink), felsic volcanic or subvolcanic rocks (white) and quartz and feldspar crystal fragments in a silicified rock-flour matrix

E. GSWA 132838, locality G (Fig. 2), photomicrograph of silicified breccia dyke matrix showing angular to rounded ('milled') rock and crystal fragments grading in size down to rock flour. The fine-grained disseminated dark material is hematite and diaspore. Plane polarized light; field of view is about 4 mm wide

F. GSWA 132838, locality F (Fig. 2), photomicrograph of rounded quartz crystal clast with indication of fluidized flow in matrix at top and top left of clast, and evidence of spalling of fragments of the top of the quartz-crystal clast. Plane polarized light; field of view is about 4 mm wide

G. GSWA 132835, locality F, Fig. 2), photomicrograph of probable interlayered kaolinite/illite after feldspar in altered McHale Granodiorite. Crossed polars; field of view is about 1.5 mm wide

H. GSWA 132835, locality F (Fig. 2), photomicrograph of disseminated anatase from altered feldspar domain in McHale Granodiorite. Plane polarized light; field of view is about 0.5 mm wide system. These could have been deposited, along with hematite, epidote and carbonate, from oxidized fluids during movement on the faults. However, magmatic–hydrothermal breccia dykes, propylitic and potassic alteration, silicification and argillization record the presence of magmatic to early post-magmatic hydrothermal activity, which may have been accompanied by as yet undiscovered base and precious metal mineralization.

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References

BURNHAM, W. C., 1979, Magmas and hydrothermal fluids, *in* Geochemistry of hydrothermal ore deposits (2nd edition) *edited by* H. L. BARNES: Wiley Interscience, p. 71–136.

DOW, D. B., and GEMUTS, I., 1969, Geology of the Kimberley Region, Western Australia: The East Kimberley: Western Australia Geological Survey, Bulletin 120, 135p.

GRIFFIN, T. J., TYLER, I. M., and SHEPPPARD, S., in prep., Geology of the Angelo 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

HEALD, P., FOLEY, N. K., and HAYBA, D. O., 1987, Comparative anatomy of volcanic-hosted epithermal deposits: acid sulfate and adularia–sericite types: Economic Geology, v. 82, p. 1–26.

HEDENQUIST, J. W., MATSUHISA, Y., IZAWA, E., WHITE, N. C., GIGGENBACH, W. F., and AOKI, M., 1994, Geology, geochemistry, and origin of high sulfidation Cu–Au mineralization in the Nansatsu District, Japan: Economic Geology, v. 89, no. 1, p. 1–30.

KIRWAN, D. J., 1985, Tourmaline breccia pipes: Townsville, James Cook University, M Sc thesis (unpublished), 139p.

PIRAJNO, F., RUGLESS, C. S., GRIFFEN, T. J., and TYLER, I. M., 1994, Hydrothermal vein gold and base metal deposits in the Halls Creek Province, East Kimberley, Western Australia: Geological Society of Australia, Abstracts, 37, p. 347

SHEPPARD, S., GRIFFIN, T. J., and TYLER, I. M., 1995, Geochemistry of felsic igneous rocks from the southern Halls Creek Orogen: Western Australia Geological Survey, Record 1995/4, 81p.

SILLITOE, R.H., 1985, Ore-related breccias in volcanoplutonic arcs: Economic Geology, v. 80, p. 1467–1514.

TYLER, I. M., GRIFFIN, T. J., PAGE, R. W., and SHAW, R. D., 1995, Are there terranes within the Lamboo Complex of the Halls Creek Orogen?: Western Australia Geological Survey, Annual Review 1993–94, p. 37–46.

TYLER, I. M., THORNE, A. M., BLAKE, D. H., HOATSON, D. M., and SHEPPARD, S., in prep., Geology of the Turkey Creek 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

Transient electromagnetic surveys for groundwater exploration in Tertiary sediments

by D. P. Commander, R. A. Smith, L. J. Baddock, C. J. Prangley, and A. Perry[1]

Abstract

Transient electromagnetic (TEM) and gravity surveys were carried out to provide drilling targets to explore for low-salinity groundwater in Tertiary sediments lying in palaeochannels and the Bremer Basin in the south and southwest of Western Australia. Interpretation of the TEM data correlated well with drilling results where the analysis was straightforward, but where the analysis was difficult interpretation and drilling results differed. The ease of interpretation depends on the geological and hydrogeological conditions. The method was generally successful where the sediments exceeded 30 m in thickness, and where there was no highly conductive near-surface layer.

KEYWORDS: Groundwater, geophysics, transient electromagnetic, gravity, drilling.

Groundwater exploration in the Tertiary sediments of southwest Western Australia is difficult because the aquifers are concealed beneath surficial deposits, and occupy irregular palaeochannels or embayments which cannot be easily mapped from the surface. Drilling programs carried out in 1993–94 had limited success in intersecting the Tertiary aquifers from transect drilling, and it was considered that geophysical surveys could be an appropriate way of selecting drilling targets and reducing drilling costs.

The Tertiary sediments are the most important aquifers in the region, especially where they contain low-salinity groundwater. The Eocene sediments are preserved in the Tertiary Bremer Basin along the south coast (Smith, 1995), in palaeochannels in broad drainage lines inland (Waterhouse at al., 1995), and also as dissected remnants (Thorpe, 1994). The stratigraphy of the Eocene Plantagenet Group consists of a basal sandstone with lignite and carbonaceous clay (Werillup Formation) overlain by a siltstone (Pallinup Siltstone), which in the Esperance area has intercalations of spongolite.

The transient electromagnetic method (TEM) was selected as this had been used successfully in similar conditions to locate palaeochannel aquifers in the Eastern Goldfields (Smyth and Barrett, 1994). Further, the TEM method could give an indication of the depth and nature of the sediments as well as the groundwater salinity, an important factor as the groundwater exploration programs were largely aimed at locating low-salinity groundwater.

Specifications and costs were sought from geophysical contractors in September 1994, and World Geoscience Corporation completed the surveys in December 1994 (Fig. 1). Gravity surveys were also carried out to assist with the interpretation of the TEM results. Between January and April 1995, the geophysical surveys were followed-up by drilling on locations selected from the TEM results (Table 1). The purpose of this paper is to review the results from the drilling in the context of the appropriateness of the TEM method in these particular hydrogeological conditions.

Transient electromagnetic method

The transient electromagnetic method allows measurement by indirect means of the electrical properties of the earth directly below the instrument. A surface transmitter loop provides a primary electromagnetic field which is rapidly shut off, inducing secondary electromagnetic fields in the subsurface.

The secondary electromagnetic fields, often described by analogy as 'smoke rings', propagate downwards and outwards from the transmitter loop with velocities and rates of amplitude decay that are dependent on the electrical properties or geoelectrical responses of the subsurface material. In particular, if the subsurface is conductive, the velocity and rate of amplitude decay of the 'smoke rings' are slow, whereas they are faster in resistive ground.

[1] World Geoscience Corporation

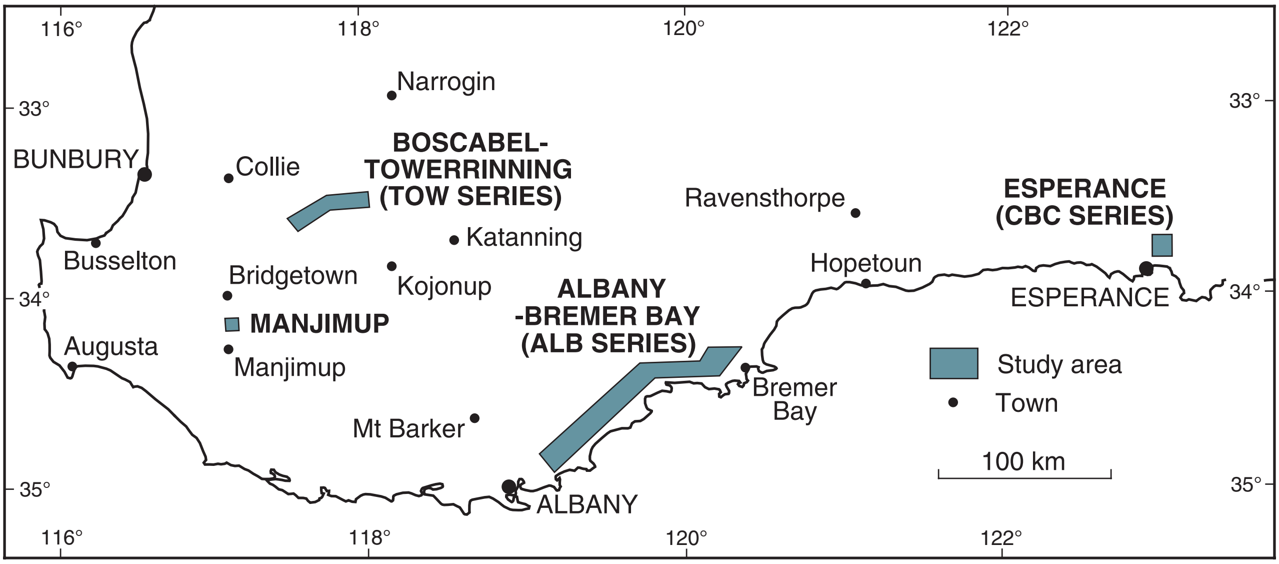


Figure 1. Location of TEM study areas

The decay of this secondary electromagnetic field can be measured as a voltage in a receiver coil. This voltage is measured over a series of discrete time windows with early response relating to electrical properties at shallow depth, and later time windows to those that are deeper. These data can then be used to interpret the geoelectrical section of the subsurface.

The ramp time of the transmitter is the finite time it takes to shut off the primary electric field. During the ramp time it is not possible to measure the secondary field, so that early time data equating to the shallowest effects cannot be acquired. In resistive terrains, such as the unsaturated zone where the 'smoke rings' have high velocities, shallow data (<50m) are unobtainable.

The surveys used a Zonge system including a GDP16 receiver, 50 by 50 m transmitter loop and an in-loop configuration where the receiver coil is placed centrally in the transmitter loop. Initially, a Zerotem transmitter utilizing a 32 hertz (Hz) base frequency and 90 microsecond (µsec) ramp time allowed a first window centre time of 114 µsec. Analysis of data from the Zerotem equipment indicated that earlier window times were preferable, and subsequent surveying was completed using a Nanotem transmitter with a 5 µsec ramp time and first window centred at 12.2 µsec.

It is difficult to measure the properties of the near-surface unsaturated zone using TEM. This is because the 'smoke rings' pass so quickly through this resistive zone that it is poorly resolved in the TEM data.

Survey results are plotted as profiles with position along the x-axis and receiver voltage in µV/A along the y-axis (Perry, 1994). All 31 data windows are plotted on the same graph. These data are then interpreted using an inversion algorithm which assumes a 1–D or layered-earth model. This interpretation assumes:

- Homogeneous layers with distinct resistivity contrasts between the layers
- Horizontal discrete contacts between the layers
- Absence of 3–D inhomogeneities such as dykes and vertical contacts.

In general these assumptions applied to the survey area with the main problems being in areas with vertical contacts and rapid variations in layer thicknesses. At these locations the inversion results are not reliable; however, the problem areas can usually be detected by rapid amplitude variations on the plots of the raw TEM data.

This type of inversion is time consuming, with manual input required for inversion of most survey points. Rapid 1–D methods, SPIKER and NEKUT, requiring no user input are available and were tested. For these methods to be effective, ideal TEM conditions including strong resistivity contrasts are required.

In some cases it is not possible to resolve a modelled layer in the earth explicitly into its thickness and resistivity. This effect is termed equivalence, and the layer must be classified by its conductivity–thickness product. The highly variable near-surface conductive layer encountered in the Boscabel–Towerrinning area is an example of this effect.

TEM surveys are severely affected by powerline noise. In some of the transects, data as far as 50m from powerlines are affected.

Groundwater salinity was estimated using Archie's formula (Archie, 1942) assuming a formation factor (F) of five.

Table 1. Geophysical survey and exploratory drilling statistics

Project	No. of transects	Length of transects (km)	No. of bores drilled	Aggregate drilling (m)
Albany–Bremer	6	39.5	4	429
Esperance	6	19.6	6	226
Boscabel	4	18.4	7	260
Towerrinning	7	12.4	29	710
Manjimup	3	4.8	5	123
Totals	**26**	**94.7**	**51**	**1 748**

Gravity survey

A gravity survey was also carried out on each transect. The density contrast between the target Tertiary sediments and granitic basement is quite high, suggesting the gravity method should indicate thickening of the sediments.

A LaCoste–Romberg (model G) gravimeter was used for the survey, and levels and distances were obtained with EDM equipment.

Results

Albany–Bremer Bay

Four bores (Johnson, 1995) drilled on four of the transects surveyed across the Bremer Basin sediments between Albany and Bremer Bay were sited where the bedrock is interpreted to be relatively deep, and where the resistivity of the upper intermediate layer is comparatively high.

It was not possible to interpret the TEM data fully with the rapid 1–D method of inversion. Full 1–D interpretation was also difficult and time consuming. The TEM and gravity surveys indicated 85–100 m of sediments at the selected sites, with two intervening layers between the near-surface conductor and the bedrock suggesting low-salinity groundwater overlying more saline groundwater, although the deeper, more-saline layer is relatively thin in ALB 8 (Fig. 2).

Depth to bedrock correlated well with the geophysical surveys (Fig. 2). The bulk resistivity indicated by the TEM also correlated well in general terms with groundwater salinity (Table 2).

Esperance

TEM surveys were undertaken on six transects within an investigation area located in the Coramup–Bandy Creek area approximately 15 km northeast of Esperance townsite (Baddock, 1995). One site was subsequently drilled on each of five of the geophysical transects (Table 2).

Both the full 1–D inversion and rapid 1–D inversion methods worked well in this area, as a result of strong resistivity contrasts.

The geophysical survey indicated that the transects were underlain predominantly by sediments, with some areas of shallow basement along most transects. Four layers were modelled in the profile. A thin, discontinuous, near surface conductor with a value less than 1 siemen (S) was generally present. A high-resistivity zone 20 to 35 m thick, present through most of the surveyed area, was interpreted to represent groundwater with a salinity generally less than 1000 mg/L. The underlying layer is a low-resistivity layer of variable thickness to some 60 m, which represents a unit with high-salinity water and/or conductive clay. The unweathered granitic basement at the bottom of the profile has a high resistivity at depths to 90 m, although areas of shallow basement were shown where the lower intermediate layer of low resistivity is absent.

The drilling sites were selected over the thickest profiles with the highest resistivity in the upper intermediate layer (as indicated by the geophysics). It was found that the low-resistivity zone and the overlying high-resistivity zone identified in the TEM survey corresponded closely to two units identified within the Pallinup Siltstone. The upper unit comprises up to 35 m of unconsolidated, oxidized silt and fine-grained sand, which in the east is replaced by interlayered clay and a siliceous sponge-limestone unit referred to as spongolite. The underlying unit is a carbonaceous claystone and siltstone forming an aquitard that is typical of the Pallinup Siltstone. The granitic basement was not intersected in any of the boreholes.

Bores constructed within the upper unit of the Pallinup Siltstone contained low-salinity groundwater between 320 and 1200 mg/L; one bore within the lower unit yielded groundwater with a salinity of 3310 mg/L. The watertable depth ranges from about 4 m to about 22 m below the surface at the bore sites, and the saturated thickness of the upper facies is between 8 and 25 m.

Boscabel–Towerrinning (Beaufort Palaeochannel)

Eleven transects were surveyed across the Beaufort Palaeochannel of which three representative transects (B5, B7 and B8) are shown in Figure 2. The palaeochannel sediments lie in narrow channels buried within broad valleys in the granitic bedrock (Prangley, 1995a).

Analysis of the TEM survey was hampered by the poor resistivity contrast between the sediments and basement. Further complications due to the effects of a highly variable and conductive near-surface layer made interpretation by the full 1–D method extremely difficult, while rapid 1–D inversion techniques did not work at all.

On transect B5 three bores intersected a palaeochannel with up to 35 m of sediments. Overall, the TEM correlates with the drilling results in relation to depth of sediments. The groundwater salinity in TOW 29 and TOW 30 also appears to correlate well with the interpreted bulk resistivities.

The data from transect B7 indicated a target zone of potential sediments at the northern end. Two sites were drilled, with each encountering up to 30 m of weathered bedrock. Another two sites, TOW 27 and

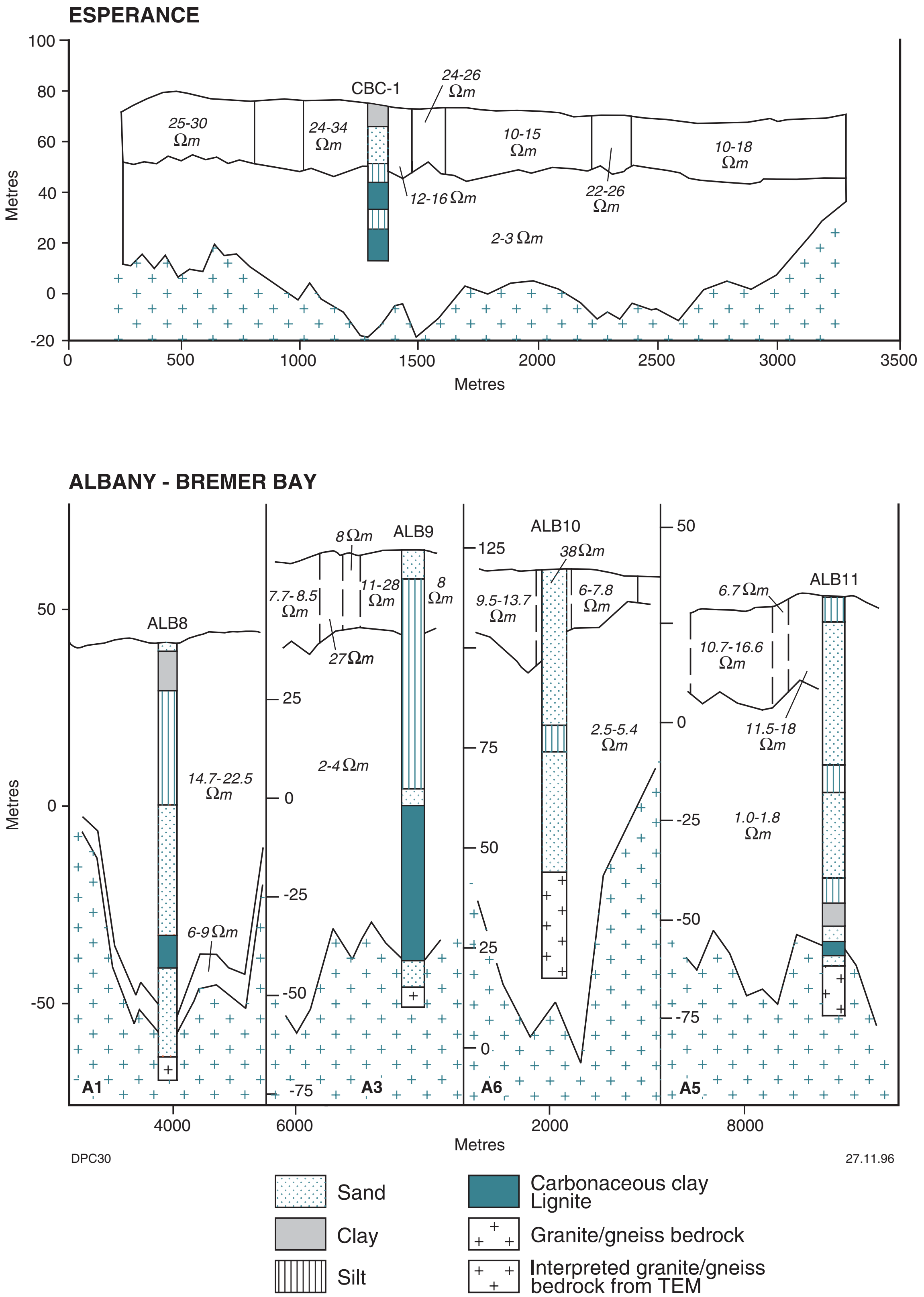


Figure 2. TEM profiles and drilling results

BOSCABEL - TOWERRINNING

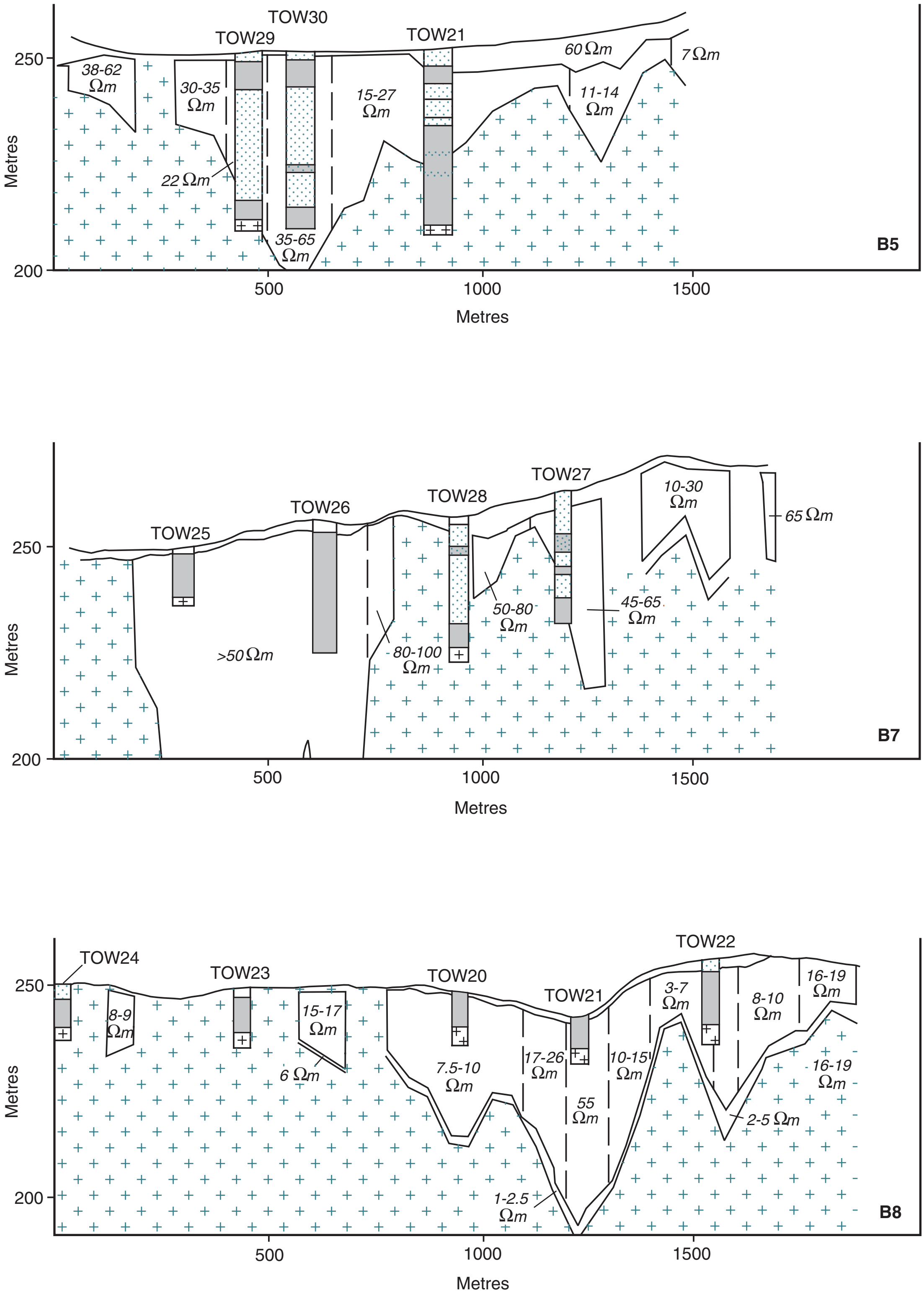


Table 2. Comparison of predicted and actual groundwater salinity

Bore	*Watertable depth (a) (m bgl)*	*Tested interval (m bgl)*	*Bulk resistivity (Ωm)*	*Predicted salinity (mg/L) (b)*	*Actual salinity (mg/L)*	*Lithology*
ALB 8	15.6	65 – 71	14.7 – 22.5	1 540	1 420	fine sand
ALB 9	27.1	47 – 53	2 – 4	10 800	5 180	siltstone
ALB 10	26.0	58 – 64	2.5 – 6	7 450	5 430	fine sand
ALB 11	22.7	85 – 91	2 – 2.2	15 800	13 800	fine/med. sand
CBC 1S	10.0	18 – 24	24 – 35	800–1 200	320	fine sand, silt
CBC 2	8.6	17.5 – 23.5	16.8 – 20.8	1 400–1 700	370	fine sand, silt
CBC 3	21.6	23.7 – 29.7	29.5 – 33	850–950	880	fine sand, silt
CBC 4	21.4	23.6 – 29.6	23.2 – 24.6	1 150–1 200	1 200	fine sand, silt
CBC 5	4.0	20.6 – 26.6	9 – 16	1 800–3 350	530	clay, spongolite
TOW 27	7.8	18 – 24	45 – 65	400–600	1 980	fine sand, silt
TOW 28	11.5	19 – 25	–	–	1 380	sand, silt
TOW 29	1.6	26 – 32	22	1 500	2 360	sand, pebbly, clay
TOW 30	1.6	28 – 34	35 – 65	680–900	1 430	sand, pebbly, clay
TOW 31	2.2	10 – 16	15 – 27	1 200–2 300	340	fine sand, silty

Notes: (a) Potentiometric level in the deeper bores
(b) Predicted salinity from bulk resistivity using F=5 in Archie's formula

TOW 28, were drilled farther to the south, with both intersecting sediments. The thickest sedimentary sequence of 25 m was at TOW 28 where the TEM could not be interpreted owing to the near-surface zone having a high conductivity–thickness product masking the signal from below.

On transect B8 the TEM modelled several target zones with moderate to high resistivity and a depth ranging to 60 m. Initial drilling, however, intersected only a thin layer of weathered clay overlying fresh granite; further drilling showed that these conditions extended the total length of the transect (Table 2).

Manjimup

Geological conditions at Manjimup are very similar to those at Boscabel and Towerrinning, and the interpretation of the TEM data suffered from the same factors. A thin cover of Tertiary sediments, 20–30 m thick and saturated with relatively fresh water, overlies a granitic and schistose basement. Of the three transects surveyed all showed potential targets. However, sediments were encountered only on one of the transects, and drilling on the other transects intersected shallow and weathered basement.

The TEM survey at Manjimup (Prangley, 1995b) indicated targets with up to 30 m of sediments and groundwater salinity ranging up to 1900 mg/L (from bulk resistivities of 18–25 Ωm). Drilling indicated a maximum sediment thickness of 22 m and a salinity of 600–700 mg/L.

Discussion

The TEM surveys were effective in mapping sediments and their properties in the Esperance and Albany–Bremer Bay areas but were less effective in the Boscabel–Towerrinning and Manjimup areas. The main reason for this difference lies in the electrical properties of the sediments involved and their resistivity contrast with the basement.

In the Esperance area the sediments have strong resistivity contrasts with the basement. In particular, the deeper sedimentary units of carbonaceous claystone and siltstone had a low resistivity which allowed excellent mapping of its boundaries against the overlying sediments and underlying basement.

In the Boscabel–Towerrinning and Manjimup areas the sediments do not have strong resistivity contrasts, and interpretation is made extremely difficult by a highly variable near-surface conductor.

The Albany–Bremer Bay area has sediments with physical properties similar to those of the Boscabel–Towerrinning area, except that the near-surface conductor is generally absent. This makes the interpretation difficult and time consuming, but the results compare well with drilling.

The different geological environments gave variable results. In general the TEM technique worked well in the deeper, more continuous sediments of the south coast and correlated better with groundwater salinity, especially where the watertable is deep.

The following factors appear to affect the results significantly.

Resistivity contrast

The absence of a distinct contrast in bulk resistivity between freshwater-saturated sediments and granite led to ambiguous interpretation (at Towerrinning).

Near-surface conductive layer

Possible conductive layers near the surface (e.g. a very low-resistivity salty layer in the unsaturated zone) could mask the signal and make interpretation difficult, as at TOW 28 where the conductivity–thickness product of the layer is 4–5 S.

Thickness of unsaturated zone

The upper intermediate layer modelled at ALB 9,10 and 11 appears to correspond to the unsaturated zone. However, the TEM could not distinguish the unsaturated zone at ALB 8 and at Esperance, even when this zone was 20 m thick. This is probably because the velocity of the 'smoke rings' was too fast, leading to an error in estimating bulk resistivity of the upper intermediate layer.

Groundwater salinity

The upper intermediate zone modelled by the TEM at ALB 9,10 and 11 corresponded to the unsaturated zone, because the groundwater salinity below is relatively high. Where the groundwater salinity is lower, at

ALB 8 and at Esperance, the unsaturated zone was not distinguished.

The estimation of groundwater salinity by Archie's formula (assuming F=5) was reasonably correct at Albany–Bremer Bay, but only in the sand/silt facies at Esperance where the watertable was at a depth of 20 m. It was not effective in the clay/spongolite facies at Esperance where F is uncertain.

Depth of sediments

Where the sediments are thick the TEM and gravity analysis correlated well with actual bedrock depth. The interpretation of the TEM at Esperance and Albany was assisted because of the relatively high resistivity contrast between the lower intermediate layer and the underlying granitic bedrock.

Stratification

The TEM interpretation was accurate at Esperance where the sediments are stratified, but not at Beaufort or Manjimup where there is no distinct stratification. At ALB 9 the high groundwater salinity masked the presence of a significant clay layer.

Type of sediments

The bulk resistivity at Esperance is affected by the type of sediments; the formation factor of the spongolite facies was about 50% of that for the sand/silt facies. Thus bulk resistivity contrasts may exist, even though groundwater salinity is comparable.

Conclusions

Where hydrogeological conditions permitted the straightforward processing of the TEM, as at Esperance and Albany–Bremer Bay, the method was successful for both locating low-salinity groundwater, and for distinguishing areas of shallow bedrock.

TEM was unsuccessful where there is a conductive near-surface layer and where the palaeochannel sediments are less than 30 m thick, as at Boscabel–Towerrinning. In these conditions the TEM is difficult to interpret and the analysis not only was unable to determine the presence or absence of palaeochannels, but also gave false indications of palaeochannels.

In future, a trial TEM survey should be carried out first to see if the interpretation is straightforward. If this is the case, it is likely that the results will give an accurate indication of subsurface conditions.

References

ARCHIE, R. P., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: American Institute of Mining, Metallurgical and Petroleum Engineers, v. 146, p. 54–62.

BADDOCK. L. J., 1995, Coramup–Bandy Creek, Esperance groundwater investigation. Western Australia Geological Survey, Hydrogeology Report 1995/13 (unpublished).

JOHNSON, S., 1995, Albany groundwater investigation bore completion reports, ALB 8–12: Western Australia Geological Survey, Hydrogeology Report 1995/29 (unpublished).

PERRY, A., 1994, Geophysical surveys for freshwater mapping, Albany–Bremer Bay area, Beaufort Palaeochannel, Coramup–Bandy Creek Palaeochannel, and Manjimup area. World Geoscience Corporation, reports for Geological Survey of Western Australia (unpublished).

PRANGLEY, C. J., 1995a, Beaufort River palaeochannel bore completion reports TOW 13–40. Western Australia Geological Survey, Hydrogeology Report 1995/43 (unpublished).

PRANGLEY, C. J., 1995b, Manjimup shallow basin drilling project phase 4. Western Australia Geological Survey, Hydrogeology Report 1995/37 (unpublished).

SMITH, R. A., 1995, Mt Barker–Albany, W.A.: Western Australia Geological Survey, 1:250 000 Hydrogeological Series.

SMYTH, E. L., and BARRETT, D. M., 1994, Geophysical characteristics of the Tertiary palaeochannels in the Yilgarn Block, Western Australia, *in* Geophysical signatures of Western Australian mineral deposits *edited by* M. C. DENTITH, K. F. FRANCOMBE, S. E. HO, J. M. SHEPHERD, D. I. GROVES, and A. TRENCH, University of Western Australia, Geology and Geophysics Department Key Centre and University Extension, Publication no. 26, p. 417–425.

THORPE, P. M., 1994, Manjimup shallow basins drilling project, Stage 3: Western Australia Geological Survey, Hydrogeology Report 1994/2 (unpublished).

WATERHOUSE, J. D., COMMANDER, D. P., PRANGLEY, C. J., and BACKHOUSE, J., 1995, Newly recognized Eocene sediments in the Beaufort River Palaeochannel: Western Australia Geological Survey, Annual Review 1993–94, p. 82–86.

Refinement of the stratigraphy of the Whim Creek Belt, Pilbara granite–greenstone terrain: new field evidence from the Sherlock 1:100 000 sheet

by R. H. Smithies

Abstract

Recent mapping of the SHERLOCK 1:100 000 sheet has led to changes in the stratigraphy of the late Archaean Whim Creek Group and has shown that the group, and the overlying basalts, extended beyond the limits of the previously inferred depositional basin. The Whim Creek Group is a volcano-sedimentary succession near the top of the Pilbara Supergroup, and was previously thought to be restricted to the Whim Creek Belt. Faults bounding the Whim Creek Belt had been regarded as defining the limits of a narrow ensialic pull-apart basin related to regional northeast-directed strike-slip movement, late in the evolution of the Pilbara Supergroup. The Whim Creek Group had been interpreted as unconformably bounded below by the Mallina Formation (De Grey Group) and above by basaltic rocks of the Mount Negri Volcanics.

Textural and geochemical evidence provides a firm basis for the subdivision of the mafic volcanics that immediately overlie the Whim Creek Group into the Louden Volcanics (spinifex textured basalts) and the overlying Mount Negri Volcanics (variolitic basalts). Contacts between the Whim Creek Group and the Louden Volcanics are mostly faulted and the existence of an intervening unconformity cannot be confirmed. More evidence exists for an unconformity between the Louden Volcanics and the Mount Negri Volcanics. Likewise, the Mallina Formation and the Whim Creek Group are always in faulted contact and an unconformity between the two cannot be demonstrated.

KEYWORDS: Pilbara, granite–greenstone, Whim Creek Group, stratigraphy

The volcanic and sedimentary rocks that constitute the Whim Creek Group (Fitton et al., 1975), and the immediately overlying basalts, form the upper portion of the Archaean Pilbara Supergroup (Hickman, 1983). Outcrop of these rocks is primarily confined to a fault-bounded belt (the Whim Creek Belt) centred on the western Pilbara settlement of Whim Creek (Fig. 1). The belt is up to 15 km wide and extends for about 70 km in a northeasterly direction. Felsic volcanics in the lower part of the Whim Creek Group are dated at c. 2.99 Ga (Barley et al., 1994). The poorly outcropping area to the north of the belt is dominated by the c. 3.0 Ga Caines Well Granite (Fitton et al., 1975), whereas the poorly outcropping area to the south of the belt is dominated by turbidites of the Mallina Formation. Hickman (1990) suggested that the Mallina Formation unconformably underlies the Whim Creek Group, but Fitton et al. (1975) and (Horwitz, 1979, 1990) suggested that the turbidite succession correlates with the upper part of the Whim Creek Group; specifically to a sandstone- and slate-rich interval which hosts significant massive-sulfide mineralization at Whim Creek and at Mons Cupri (Fig. 1).

Most models for the evolution of the Whim Creek Belt view the Whim Creek Group, and the immediately overlying mafic volcanics (below the Mount Bruce Supergroup), as very local accumulations, with present outcrops essentially marking the original extent of deposition. Barley (1987) thus suggested that the faults bounding the belt (the Kents Bore Fault in the north and the Loudens Fault in the south) define the edges of a fault-bounded basin, and exercised a fundamental control on deposition of the rocks. This interpretation involves an ensialic pull-apart basin that developed in response to craton-wide sinistral movement along east-northeasterly trending faults, such as the Sholl Shear Zone, which forms the northern margin of the Whim Creek Belt (Fig. 1).

Regional mapping of the Whim Creek Belt, on the SHERLOCK* 1:100 000 sheet, has provided a more detailed stratigraphy of the Whim Creek Group and of the immediately overlying mafic volcanics, and has questioned the hypothesis that the group was originally of only very local distribution. The mapping, in conjunction with continuing mapping to the south (MOUNT WOHLER), and preliminary geochronology, has also helped to

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

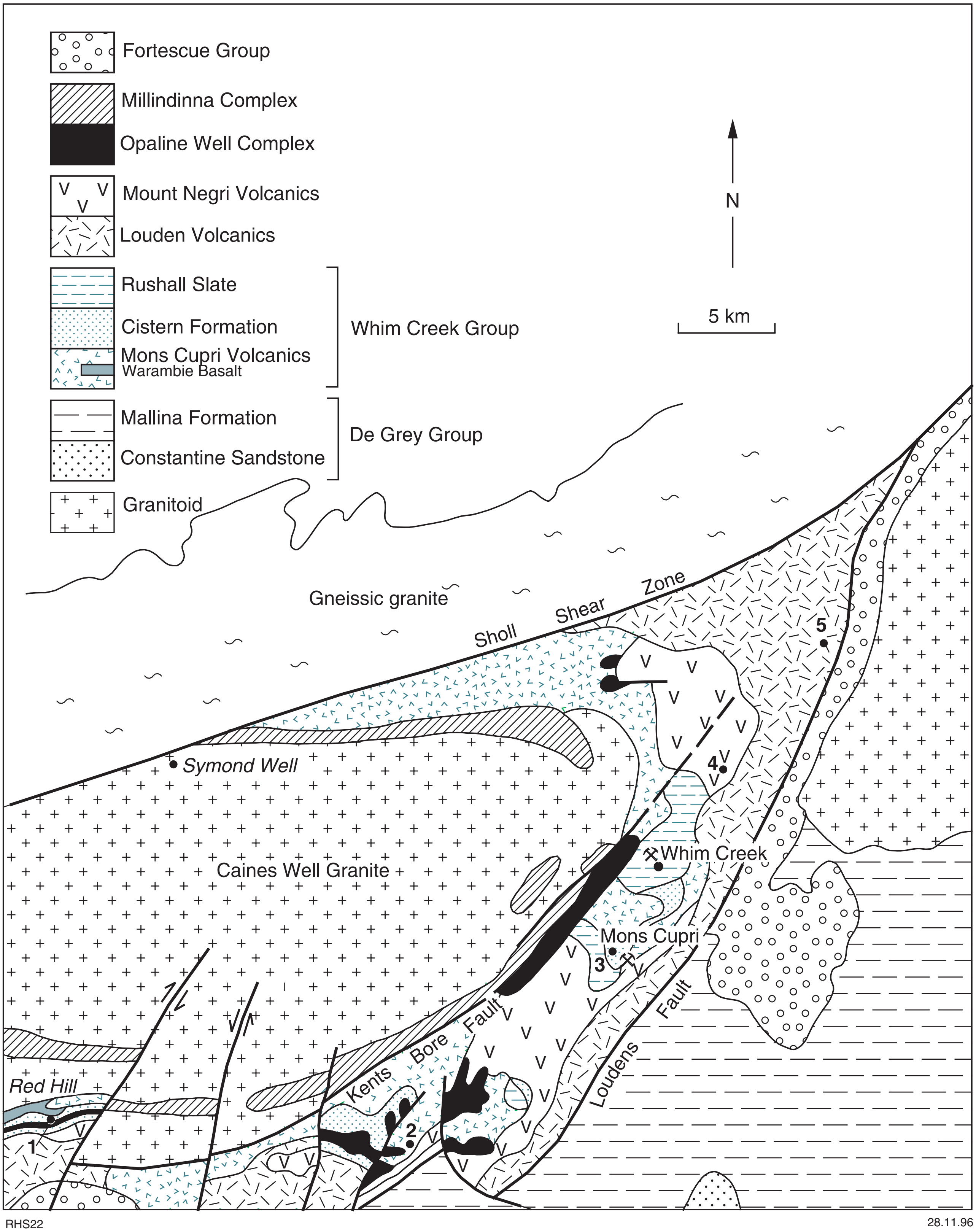


Figure 1. Simplified geology of SHERLOCK. *Numbers 1–5 refer to general locality of stratigraphic sections presented in Figure 3*

elucidate the relationship between the Whim Creek Group and the Mallina Formation.

Stratigraphy

The Whim Creek Group lies adjacent to the southern and eastern margins of the Caines Well Granite. The strata have shallow to moderate dips away from that granite and are dislocated by numerous faults, many of which show evidence for multiple reactivation. The full stratigraphy is nowhere preserved.

Figure 2 provides some early stratigraphic interpretations of the Whim Creek Belt. The base of the Whim Creek Group was considered to be the tholeiites of the Warambie Basalt (Fitton et al., 1975), which shows unconformable relationships to the Caines Well Granite in the far west of the belt. The basalt was thought to be overlain by rocks of the Mons Cupri Volcanics, which was subdivided into a lower sequence of dacitic to rhyolitic lavas and tuffs, referred to as the Mount Brown Rhyolite Member, and an upper sequence of pyroclastics and volcanoclastics (Fitton et al., 1975). The upper sequence includes felsic pyroclastics (including crystal-lithic, crystal- and lithic-vitric tuff, and welded tuff) and tuffaceous and clastic sedimentary rocks ranging in grain size from boulder conglomerate to shale. The range of rock types found within the Mons Cupri Volcanics suggests a marginal subaerial to subaqueous environment of deposition.

The Mons Cupri Volcanics is conformably overlain by a sequence of fine- to medium- grained sedimentary rocks. Hickman (1983) refered to this unit as the Rushall Slate but Fitton et al. (1975) and Horwitz (1979, 1990) correlated the sedimentary rocks with the Mallina Formation. The sedimentary rocks include thin and commonly upward-fining, fine- to medium-grained interbeds that formed in local restricted basins. They may be carbonaceous or pyritic, and some layers are tuffaceous. At Mons Cupri, however, Miller and Gair (1975) recognized a thin arkosic sandstone locally separating the Mons Cupri Volcanics from the Rushall Slate, and refer to this horizon as the Cistern Formation. They also recognise a mafic to intermediate volcanic lens near the base of the Rushall Slate, and refer to this lens as the Comstock Andesite Member.

According to Fitton et al. (1975) and Hickman (1977, 1990), the Whim Creek Group appears to be in unconformable contact with the overlying mafic volcanic rocks, which have been grouped by Fitton et al. (1975) into the Negri Volcanics. Hickman (1977), however, recognized that this sequence could be subdivided and later (Hickman, 1983) described a lower spinifex-textured (and locally pillowed) unit, the Louden Volcanics, and an upper variolitic unit, the Negri Volcanics

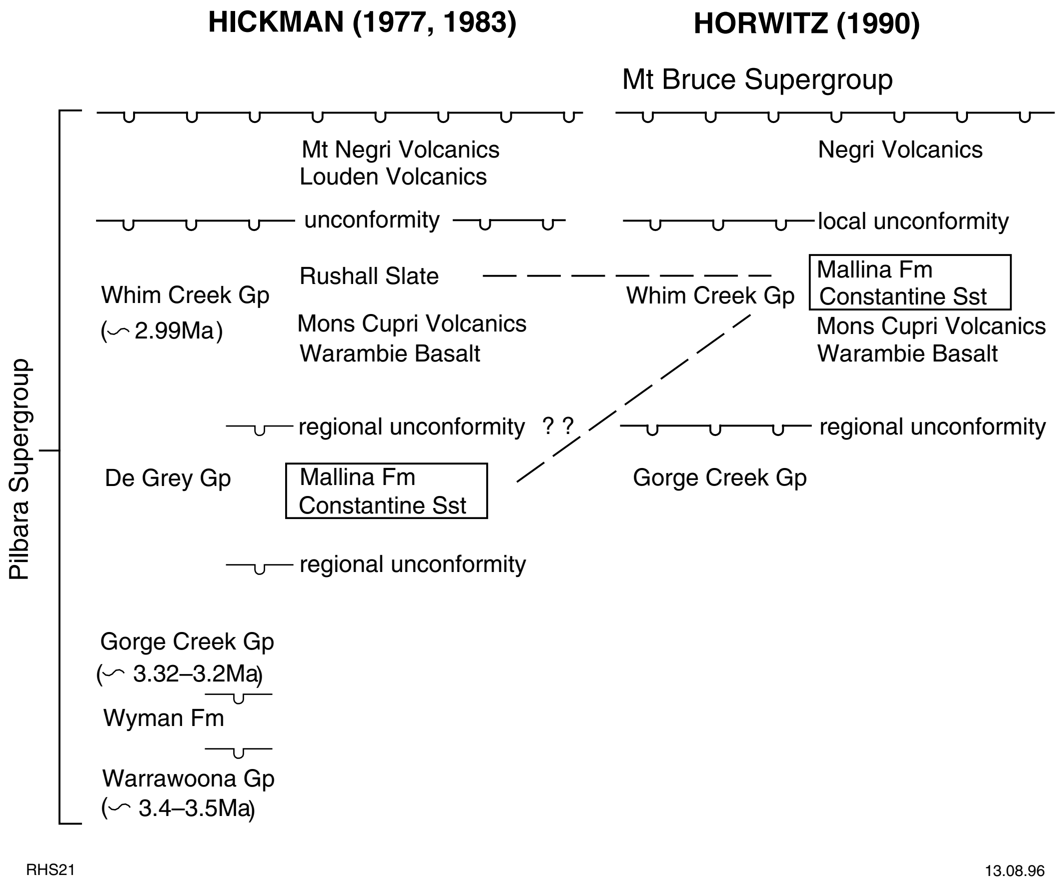


Figure 2. Early stratigraphic interpretations of the Whim Creek Belt

(later re-named the Mount Negri Volcanics — Hickman, 1990). The two volcanic units are separated by a low-angle unconformity in the vicinity of Mount Negri. Like the Whim Creek Group, the Louden Volcanics generally dips gently (<40º) away from the Caines Well Granite, whereas the Mount Negri Volcanics is shallow dipping (<20º). The contact between the Mount Negri Volcanics and the overlying rocks of the Mount Bruce Supergroup is also marked by a low-angle unconformity.

A suite of mafic dykes intruded the Caines Well Granite adjacent to the contact with Whim Creek Group. Fitton et al. (1975) correlated these with a regional set of dykes which they called the Millindinna Complex, and it was speculated that the dykes relate to the same magmatism that produced the Negri Volcanics (as defined *by* Fitton et al., 1975).

The Mallina Formation is a turbidite sequence of arkosic sandstone and shale, which commonly forms upward-fining layers on a sub-metre scale. The fine to medium grain size of the arkoses possibly reflects a felsic volcanic source component.

Revised stratigraphy

Figure 3 shows the revised stratigraphy of the Whim Creek Belt (including the Mount Negri and Louden Volcanics) by way of a range of stratigraphic columns selected to exemplify stratigraphic variation across the belt. Of note is that although the Warambie Basalt locally forms the base of the Whim Creek Group, the Mons Cupri Volcanics forms the base throughout most of the belt. In the Red Hill region, the Mons Cupri Volcanics (the Mount Brown Rhyolite Member) is only thinly developed and immediately to the west the unit pinches out altogether and the Warambie Basalt lies at the base of the group. Over a short distance, the Mons Cupri Volcanics and the Warambie Basalt interfinger, and it appears that rocks of the Mons Cupri Volcanics both underlie and overly the basalt. Hence, the Warambie Basalt is partly synchronous with the lower portion of the Mount Brown Rhyolite Member, rather than underlying that member.

Throughout the Whim Creek Belt, boulder conglomerate, previously placed within the upper Mons Cupri Volcanics, was found to represent a stratigraphic marker horizon. Below this conglomerate, the volcanic rocks consist of a homogeneous sequence dominated by felsic lavas and massive pyroclastics; volcanoclastic and clastic rocks are scarce, and are concentrated mostly in the upper part of the section. Above the conglomerate, the package includes very little lava and is dominated by welded tuffs, crystal-lithic tuffs, volcaniclastics and clastics in a generally upward-fining sequence that is locally capped by the Rushall Slate. The interval from the base of the conglomerate to the base of the Rushall Slate has been redefined as the Cistern Formation (Smithies, in prep.), giving this unit far greater stratigraphic significance than did the original definition.

The redefined Cistern Formation also contains several thin basaltic layers. The presence of basalt within this otherwise felsic unit reflects a period of bimodal volcanism. It is this stratigraphic interval, and the lower portion of the immediately overlying Rushall Slate (which includes the Comstock Andesite Member — actually a basalt), that hosts the notable massive sulfide mineralization within the Whim Creek Belt.

Abundant field evidence was found to support earlier suggestions (Hickman, 1977, 1983) that the mafic volcanic succession that overlies the Whim Creek Group can be subdivided into a lower, olivine and pyroxene spinifex-textured suite of basalts (Louden Volcanics) and an upper suite of variolitic-textured basalts (Mount Negri Volcanics). Although previous geochemical surveys of the mafic volcanics failed to identify criteria for making such distinctions (Barley, 1987), replotting of previous geochemical data in terms of the newly defined lithological boundaries clearly justifies the subdivision. Figure 4, which presents a plot of TiO_2 against FeO/MgO, shows a compositional distinction between the Mount Negri Volcanics (high TiO_2) and the Louden Volcanics (low TiO_2) which cannot be reconciled through fractional crystallization.

Although a low-angle unconformity can commonly be recognized between the Louden Volcanics and the Mount Negri Volcanics, an unconformity between the Louden Volcanics and the Whim Creek Group has not been recognized during this study. In the southwest of the belt, at least, the relationship appears conformable, or possibly disconformable.

All mafic intrusions within the Whim Creek Belt have been correlated previously with the Millindinna Complex (Fitton et al., 1975), but two distinct groups are now recognized. A large intrusion comprising coarse-grained equigranular gabbro and quartz-gabbro outcrops almost continuously along the contact between the Caines Well Granite and the Whim Creek Belt. Following Fitton et al. (1975), these rocks are referred here to the Millindinna Complex, although this correlation remains to be proven. A suite of distinctly more mafic (includes olivine and pyroxene cumulates), inequigranular, gabbroic and peridotitic rocks intrudes the Cistern Formation and upper Mons Cupri Volcanics in the Opaline Well region. These are now collectively referred to as the Opaline Well Complex. Finer grained examples of the latter rock show close petrological similarities to the Louden Volcanics and it is speculated here that they may represent sub-volcanic equivalents to the Lounden Volcanics.

Recent mapping has shown that all contacts between the Mallina Formation and the Whim Creek Group are tectonic. Thus, observations from SHERLOCK provide few clues as to relationships between these two units. The requirement that arkoses within the Mallina Formation be derived from a felsic source, and the lithological similarities between rocks of the formation and rocks within the upper part of the Whim Creek Group (i.e. the Rushall Slate and some clastic/volcanoclastic rocks of the Cistern Formation), provide *prima facie* evidence that the Whim Creek Group may correlate with part of the Mallina Formation. The available geochronology identifies a c. 3.0 Ga detrital component within rocks of the Mallina Formation on SHERLOCK (preliminary U–Pb zircon data — Nelson, D. R., 1996, pers. comm.), but this component may derive from the c. 3.0 Ga Caines

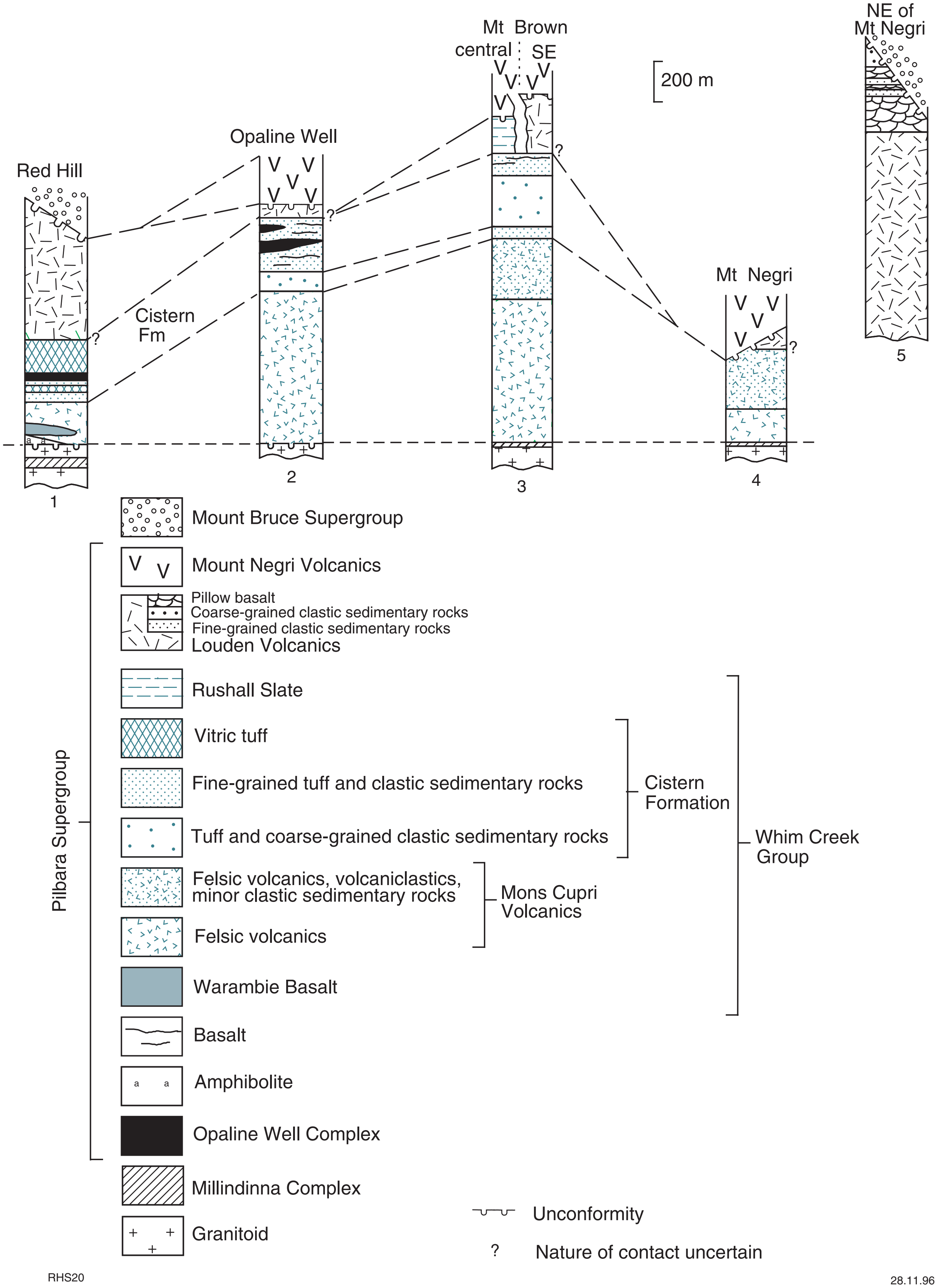


Figure 3. Stratigraphic columns showing stratigraphic variation across the Whim Creek Belt (numbers refer to localities in Figure 1)

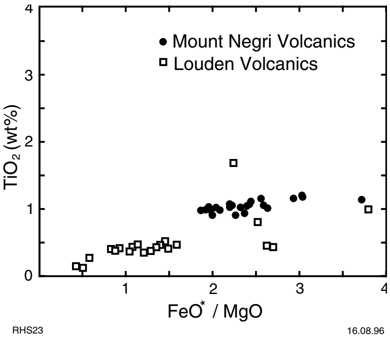


Figure 4. Compositional variation diagram comparing the Louden and Mount Negri Volcanics (data **from** *Glikson et al., 1986)*

Well Granite, which unconformably underlies the Whim Creek Group, rather than reflecting synchroneity with the c. 2.99 Ga Whim Creek Group. Regional mapping to the south of SHERLOCK (Smithies, in prep.) has shown that rocks of the Mallina Formation on MOUNT WOHLER have undergone at least two phases of deformation that cannot be recognized in rocks of the Whim Creek Group, and consequently appear to pre-date that group.

Original extent of the Whim Creek Group

Barley (1987) proposed a model for the evolution of the Whim Creek Group in which the rocks were deposited essentially within the confines of a fault-bounded strike-slip basin. In this model, the bounding Kents Bore Fault and the Loudens Fault are thought to have exercised a fundamental control on deposition of the group, and are themselves a response to sinistral movement along the regional Sholl Shear Zone, leading to formation of a pull-apart basin.

The northeast trace of the Kents Bore Fault, however, passes to the south of Mount Negri (Fig. 1) and intersects outcrop of the Whim Creek Group. Thus, the group outcrops on both sides of the fault. More significantly, the Whim Creek Group is folded around the northeast portion of the Caines Well Granite, forming a broad anticlinal feature with a fold axis that is oriented inconsistently with simple sinistral drag folding along the Sholl Shear Zone. Outliers of the Whim Creek Group are found as far to the northwest as Symond Well, and it is clear that the group originally extended well beyond the area of rock that is now preserved, mainly to the south, as an apron around an unroofed domal fold structure.

References

BARLEY, M. E., 1987, The Archaean Whim Creek Belt, an ensialic fault-bounded basin in the Pilbara Block, Australia: Precambrian Research, v. 37, p. 199–215.

BARLEY, M. E., McNAUGHTON, N. J., WILLIAMS, I. S., and COMPSTON, W., 1994, Age of Archaean volcanism and sulphide mineralization in the Whim Creek Belt, west Pilbara: Australian Journal of Earth Sciences, v. 41, p. 175–177.

FITTON, M. J., HORWITZ, R. C., and SYLVESTER, G. C., 1975, Stratigraphy of the early Precambrian of the west Pilbara, Western Australia: CSIRO Division of Mineralogy, Minerals Research Laboratory Report FP11, 41p.

GLIKSON, A. Y., PRIDE, C., JAHN, B., DAVY, R., and HICKMAN, A. H., 1986, RE and HFS (Ti, Zr, Nb, P, Y) element evolution of Archaean mafic–ultramafic volcanic suites, Pilbara Block, Western Australia: Australia BMR, Record 1986/6, 85p.

HICKMAN, A. H., 1977, Stratigraphic relations of rocks within the Whim Creek Belt: Western Australia Geological Survey, Annual Report 1976, p. 68–72.

HICKMAN, A. H., 1983, Geology of the Pilbara Block and its environs: Western Australia Geological Survey, Bulletin 127, 268p.

HICKMAN, A. H., 1990, Geology of the Pilbara Craton, *in* Excursion Guidebook no. 5: Pilbara and Hamersley Basin *edited by* S. E. HO, J. E. GLOVER, J. S. MYERS and J. R. MUHLING: Third International Archaean Symposium, Perth, 1990. University of Western Australia, Geology Department and University Extension, Publication 21, p. 2–13.

HORWITZ, R. C., 1979, The Whim Creek Group, a discussion: Journal of the Royal Society of Western Australia, v. 61, pt 3, p. 67–72.

HORWITZ, R. C., 1990, Palaeogeographic and tectonic evolution of the Pilbara Craton, northwestern Australia. Precambrian Research, v. 48, p. 327–340.

MILLER, L. J., and GAIR, H. S., 1975, Mons Cupri copper–lead–zinc deposit, *in* Economic geology of Australia and Papua New Guinea; metals *edited by* C. L. KNIGHT: Australasian Institute of Mining and Metallurgy, Monograph 5, p. 195–202.

SMITHIES, R. H., (in prep.) Geology of the Sherlock 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

Targeting mineralization using a Greenstone Chalcophile Index: results of regional and project-scale regolith geochemistry in the northern Eastern Goldfields

by C. J. Kojan, J. J. Bradley, J. A. Faulkner, and A. J. Sanders

Abstract

High concentrations of chalcophile and associated elements (Ag, As, Au, Bi, Ge, Mo, Sb, Se, Sn and W) in lateritic material may indicate areas of mineralization in the Yilgarn Craton. Several additive type indices are derived from various combinations of these elements. A similar type of additive index is proposed to identify gold and volcanic-hosted massive sulfide (VMS) mineralization in greenstone belts of the northern Eastern Goldfields using data acquired by both the Geological Survey of Western Australia (GSWA) and two mineral exploration companies.

Data for the two greenstone belts containing both Survey and company project data were processed in order to calculate Greenstone Chalcophile Index values (GCIV). Those CGIV calculated from GSWA data highlight five anomalous areas in the Yandal Belt, of which three correspond to known areas of mineralization. All five areas of anomalous GCIV have distinctive geochemistry: two contain anomalous amounts of barium and tellurium. No evidence of VMS mineralization was noted.

The Barlee Terrane is poorly mineralized in comparison with the Yandal Belt. Some elevated GCIV calculated from both GSWA and company data can be correlated with known gold centres and high molybdenum, arsenic and antimony. There is good correlation between GSWA and company data from similar catchment areas.

KEYWORDS: northern Eastern Goldfields, Yandal Greenstone Belt, Barlee Terrane, Greenstone Chalcophile Index values (GCIV), Regolith geochemistry, gold, base metal, mineralization.

In mineral exploration, geochemical associations have led to the concept of pathfinder elements that can be used to search for concealed ore bodies. Some of the more important geochemical associations of elements have been listed by Hawkes and Webb (1962). In Australia the use of pathfinder elements to locate specific types of mineralization has led to the concept of additive indices (Smith and Perdrix, 1983; Smith et al., 1987, 1989). Smith et al. (1989), with reference to exploration in the Yilgarn Craton, describe the CHI6*X chalcophile index of As+Sb+Bi+Mo+Ag+Sn+W+Se and the PEG4 pegmatite index of As+Sb+Sn+Ga+W+Nb+Ta using weighted scores for each element. These indices are calculated empirically and are based on the analysis of lateritic materials. Cruikshank (1994), describes indices for gold, base metal, heavy metal, porphyry copper, platinum and uranium mineralization from a regional geochemistry project in the Georgetown Inlier, North Queensland.

As part of the Geological Survey of Western Australia (GSWA) Regional Regolith Geochemistry Mapping program, Bradley et al. (1995) applied the chalcophile and pegmatite indices of Smith et al. (1989) to data from the LEONORA* 1:250 000 sheet, and one of the authors (A. J. Sanders) has derived a base-metal index comprising Cu+Pb+Zn which he has applied to the GLENGARRY data. Results from these studies demonstrate that chemical data can be better correlated with known mineralization if these data are statistically processed. This involves correction for downslope weathering effects, and statistical enhancement of anomalous values.

The GSWA dataset for the northern Eastern Goldfields covers the area shown in Figure 1, and includes the MENZIES, LEONORA and SIR SAMUEL map sheets (Kojan and Faulkner, 1994; Bradley et al., 1995; Kojan et al., 1996). The dataset includes analytical results for 47 elements from 3100 samples. Each stream or sheetwash sample consists of regolith material derived from the surrounding catchment. In the current study the authors have used

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

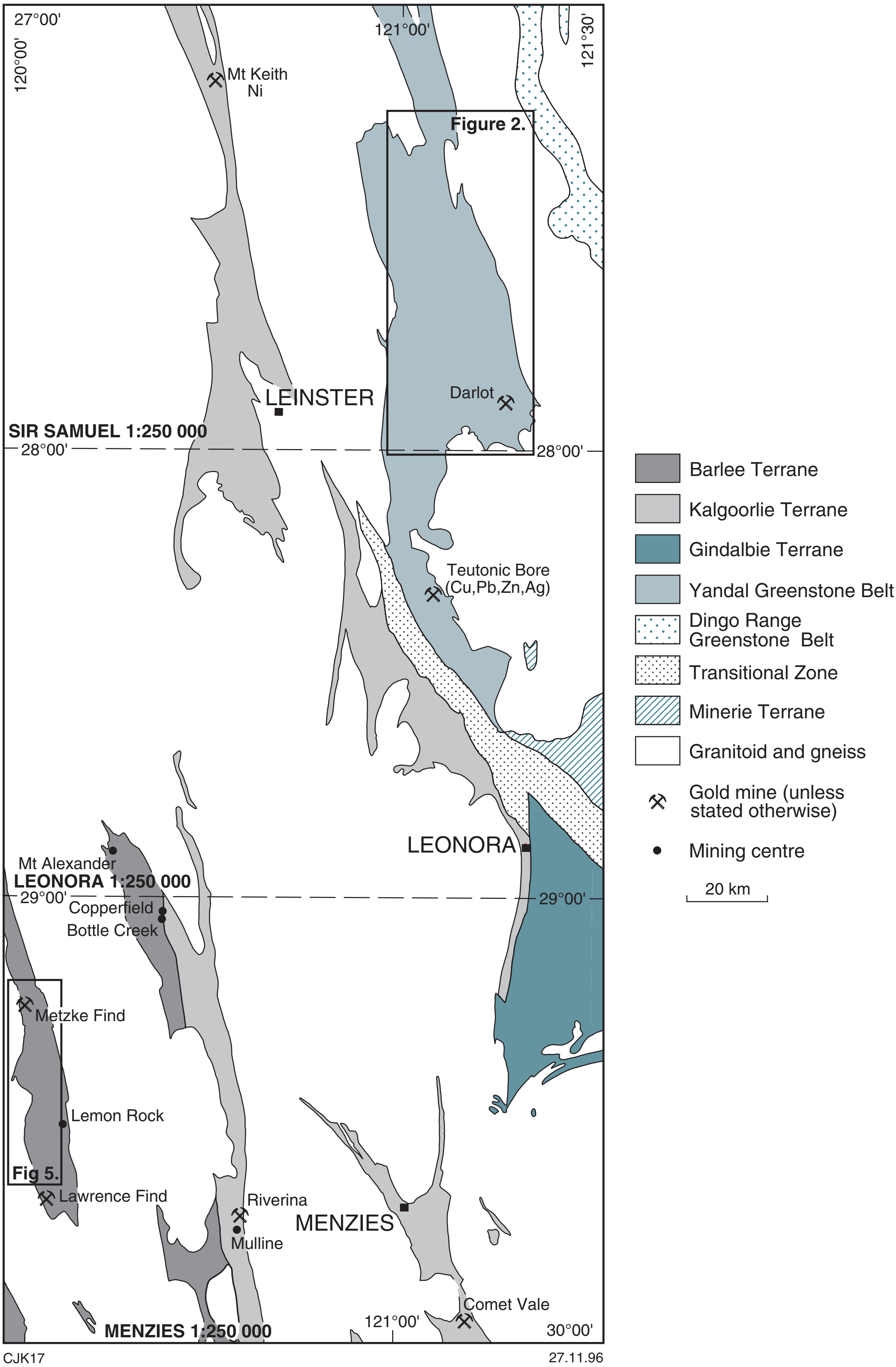


Figure 1. Greenstones of the northern Eastern Goldfields

subsets of these data to calculate Greenstone Chalcophile Index values for samples sourced from the Ilaara Belt (within the Barlee Terrane) and the Yandal Greenstone Belt. Greenstone Chalcophile Index values have also been calculated for two project-scale datasets obtained by exploration companies from the same two greenstone belts. One dataset comprises multi-element analyses of 'laterite' samples from the Ilaara Greenstone Belt (CRA, 1987), whereas the other dataset comprises rock-chip samples from the Yandal Greenstone Belt (Electrolytic Zinc, 1987). The locations of the project areas are shown in Figure 1.

Regional geochemistry and geology

The greenstone belts of the northern Eastern Goldfields host significant gold, nickel, copper, lead and zinc mineralization. Many of these deposits form, or have formed, the basis of substantial mining operations. Some of these deposits are shown in Figures 1 and 2. Each deposit contains a particular geochemical association of elements. Nickel deposits such as Mount Keith comprise a Ni–Co–Cr–Cu–As association, whereas volcanic-hosted massive-sulfide (VMS) deposits, such as Teutonic Bore, contain a Cu–Pb–Zn–Ag–As–Sb–Bi association. The geochemical associations of gold deposits are diverse and in part reflect the paragenesis of the deposits. Using the associations as defined by Guilbert and Park (1986), typical hypothermal associations include Comet Vale on MENZIES, which contains Au–W–Bi–Cu–Pb–Zn and the Woorana–Langfords Find–Popes Patch zone on SIR SAMUEL, which contains Au–Pt–Mo–W–Sn. Typical epithermal associations include Riverina on MENZIES (Au–Cu–Pb–Zn–Ag) and the Success–Parmelia–Dragon zone on SIR SAMUEL (Au–Pt–As–Cu–Pb–Zn).

Principal component analysis of the GSWA data from LEONORA (Bradley et al., 1995) and SIR SAMUEL (Kojan et al., 1996) shows that the chalcophile elements As, Sb, Se, Te, Co, Ni, Cu and Zn have a strong association with typical mafic greenstone oxides and elements (Fe_2, O_3,TiO_2 , MnO and V). Other elements including Bi, Sn, W, Ta and Nb show a separate independent association; however, these elements are invariably associated with hypothermal gold mineralization in the eastern Goldfields, which is in turn confined to greenstone belts. On this basis it was decided to study greenstone belts within the northern Eastern Goldfields with the aim of defining anomalous zones of chalcophile and associated elements within these belts. The greenstone belts of the northern Eastern Goldfields comprise seven major belts or terranes each of which contains a distinctive suite of rocks. The seven groups of greenstone are the Barlee Terrane, the Kalgoorlie Terrane, the Gindalbie Terrane, the Yandal Greenstone Belt, the Dingo Range Greenstone Belt, the Transitional Zone of the Keith–Kilkenny lineament, and the Minerie Terrane (Fig 1). The geology and mineralization of the Barlee Terrane and Yandal Belt are the main subject of this study, as there are both GSWA and appropriate company multi-element data available for both belts. The greenstone rocks in the northern Eastern Goldfields have been metamorphosed to either greenschist or amphibolite facies; however, the prefix 'meta' is omitted in referring to specific rock types.

Barlee Terrane

The Barlee Terrane corresponds to the northeastern section of the Southern Cross Province of the central Yilgarn Craton. Part of this terrane lies within the western part of Menzies, where it includes the Ilaara Belt and the western domain of the Mount Ida Belt. The Ida Fault marks the contact between the Barlee Terrane and the Kalgoorlie Terrane to the east. The main rock sequence comprises a basal quartzite, basalt with minor BIF and gabbro, and a clastic sedimentary sequence that consists of pelitic schist with minor massive sulfide lenses (Griffin, 1990).

The Barlee Terrane on MENZIES does not contain any major mines or mineral deposits. The former gold mining centres of Copperfield, Bottle Creek, Riverina and Mulline are largely or entirely located within the adjacent Kalgoorlie Terrane. Minor mineralization has been reported from the Ilaara Belt. A small amount of gold (20 kg) has been produced from Metzke Find, and gold has been reported from nearby Lawrence Find (Fig. 1). Elsewhere trace amounts of copper and arsenopyrite have been reported.

Yandal Greenstone Belt

The southern and central Yandal Belt is covered by the LEONORA and SIR SAMUEL map sheets. The belt, which is mainly north trending, is bounded to the south by the Keith–Kilkenny tectonic zone, to the west by the Mount McClure Fault, and to the east by the Rosewood and Ninnis Faults (formerly Celia Lineament). The main rock sequence comprises basalt with minor ultramafic rock overlain by a thick sequence of felsic volcanics and volcaniclastic sedimentary rocks interleaved with basalt and intruded by numerous gabbro sills (Wyche and Westaway, 1995).

In contrast to the greenstone belts of the Barlee Terrane on MENZIES, the Yandal Greenstone Belt on LEONORA and SIR SAMUEL is highly mineralized. Major gold mines are located at the Darlot, Mount McClure and Bronzewing mining centres shown on Figures 1 and 2, and in addition there is a large number of older workings and several new prospects. The Yandal Belt also hosts the Teutonic Bore volcanic-hosted massive sulfide (VMS) deposit (Fig. 1), located on LEONORA near the boundary with the Transitional Zone of the Keith–Kilkenny Lineament. The Teutonic Bore Cu–Pb–Zn–Ag deposit occurs in a sequence of pyritic black shale, chert and felsic volcaniclastic sedimentary rocks. According to Witt et al. (in prep.) these rocks were deposited in deep water with pyroclastic debris, possibly derived from a shallow water to subaerial source. These authors report similar bimodal volcanic sequences from Melita (Gindalbie Terrane) and Spring Well in the central Yandal Belt.

Regolith geochemistry

The GSWA data used in this study comprise 3100 samples collected and analysed in the course of the MENZIES, LEONORA and SIR SAMUEL

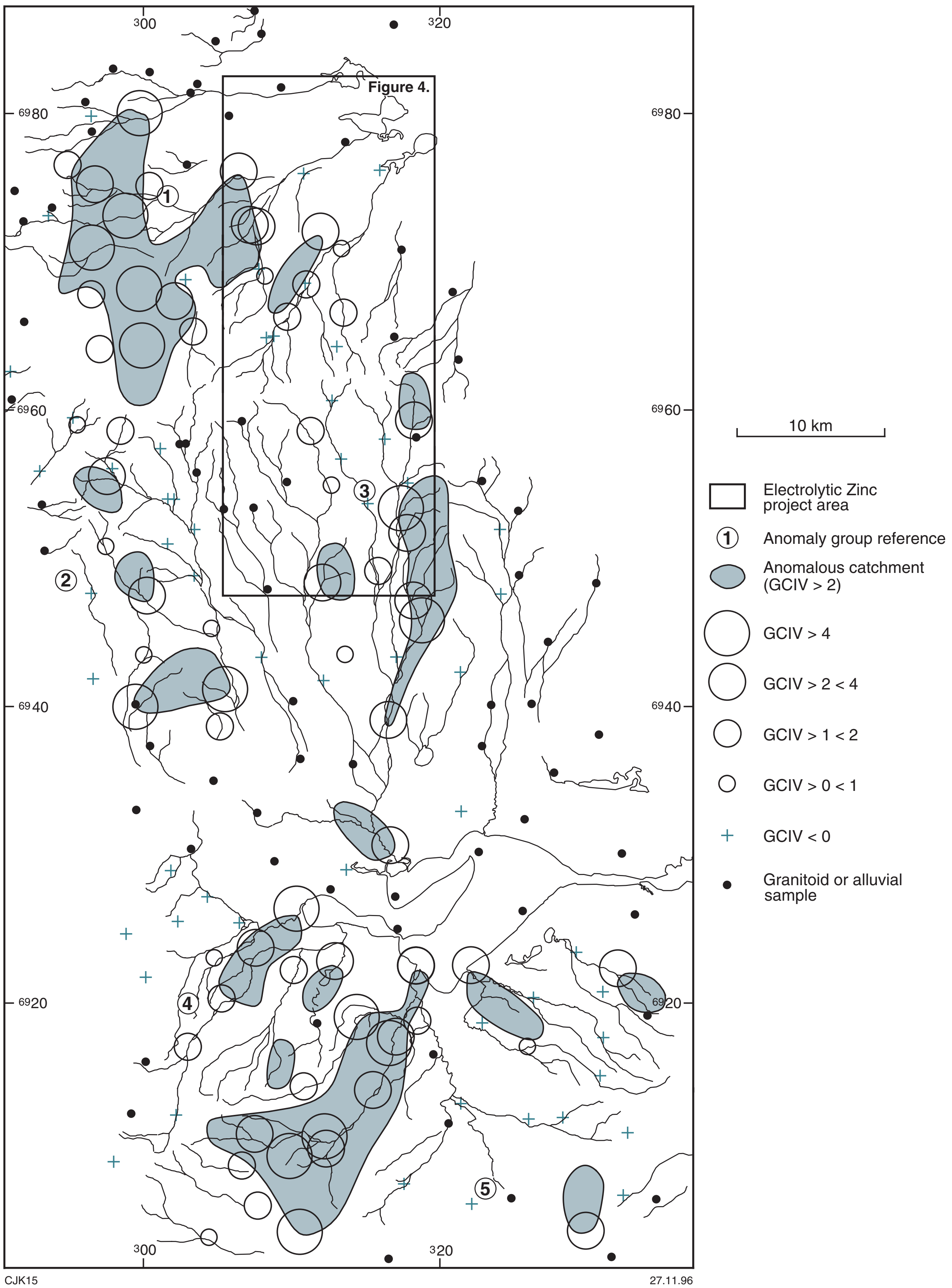


Figure 2. GSWA Greenstone Chalcophile Index values (GCIV) and anomalous catchments in the central Yandal Greenstone Belt

Regional Regolith Geochemical Mapping projects in the northern Eastern Goldfields. The samples were collected at a nominal density of one per 16 km^2. Each sample was taken within 10–40 cm from the surface and sieved to obtain a size fraction <2 mm and >0.45 mm, which was submitted for chemical analysis in a commercial laboratory. All samples were analysed for 47 elements.

All samples selected for this study were, at least in part, sourced from greenstones and consisted either of stream-sediment or sheetwash material representative of the local regolith. The regolith material sampled at each site was classified into one of 22 regolith units according to the field description of the sample material and the major-element chemistry. The GSWA classification scheme shown in Table 1 is similar to the one devised by Anand et al. (1993). For the purposes of this study, five combined regolith units were investigated comprising E1 and E2v (fresh rock and saprock), E4v and R2 (highly ferruginous material), DC1 and DC1v (coarse mixed lithic and ferruginous colluvium), DC2 and DC2v (medium ferruginous colluvium), and DC3 and DC3f (fine ferruginous colluvium).

Table 1. Regolith codes and descriptions (*from* Kojan and Faulkner, 1994)

Regolith code	*Description*
Relict regime	
R1	Ferruginous pisolites and nodules
R2	Iron-rich duricrust/hardpan forming remnant landsurfaces
R3	Silcrete and silicified rock
R4	Sand overlying presumed or known lateritic material
Erosional regime	
E1	Exposed mottled zone and saprolite
E2g	Granitoid and granitoid gneiss saprock, bedrock and ferruginous bedrock
E2v	Metamorphosed volcanic and sedimentary (greenstone) saprock, bedrock and ferruginous bedrock
E4g	Lag of lithic detritus and/or feldspar in a sand-rich matrix associated with actively eroding outcrop/subcrop; mainly confined to granitoid terranes
E4v	Lag of locally derived ferruginous and lithic detritus in a sand-rich matrix associated with actively eroding outcrop/subcrop; mainly confined to greenstone terranes
Depositional regime	
	Dominantly colluvial
DC1	Medium to coarse detritus mainly of lithic or ferruginized lithic clasts (most >25 mm), in colluvium with a sand or sandy clay matrix
DC1g	DC1 derived mainly from granitoid rocks
DC1v	DC1 derived mainly from greenstone rocks
DC2	Fine to medium detritus (clasts 4–25 mm) mainly of lithic or ferruginized lithic origin, in a red sandy clay colluvial matrix or mainly quartz in a sandy clay matrix
DC2g	DC2 derived mainly from granitoid rocks
DC2v	DC2 derived mainly from greenstone rocks
DC3	Sand/clay dominated colluvium or sheetwash (±feldspar); merges into alluvial plains (DA5)
DC3f	Predominantly non-lithic ferruginous detritus (most clasts <10mm) some magnetic, in a red sandy clay matrix in sheetwash areas. Includes, but is not exclusive to, buckshot gravels
	Dominantly alluvial
DA4	Gravelly sands and sandy clays of active alluvial channels with mixtures of lateritic, non-lateritic, and variably altered lithic clasts
DA5	Sand or clay-rich alluvium on or adjacent to broad drainage floors with negligable detritus; calcrete nodules common
DA6	Gypsiferous alluvial and eolian sediments adjacent to playa lakes; usually vegetated
DA7	Saline clays and sandy clays of playa lakes; usually lacking vegetation
DA8	Extensive and continuous calcrete outrop in broad drainage floors (valley calcrete)

Regional regolith geochemical mapping program data

Each of the 3100 GSWA sample numbers were listed together with AMG coordinates, regolith unit, geology, sample type and the results of the analysis for 47 elements. The seven separate datasets required for each of the seven greenstone belts were extracted from the initial database using ARC/INFO. The two datasets selected include one from the Barlee Terrane and one from the Yandal Greenstone Belt. Results of previous investigations (A. J. Sanders, unpublished data) indicate that, where the original data have been corrected for downslope weathering effects and anomalous values are statistically enhanced, a map of index values shows a better correlation than the raw data with known mineralization.

To compensate for downslope variation between regolith units (attributable to weathering effects), the raw values for each element within each regolith unit were multiplied by a correction factor (CF) to permit comparison with the parent (E2v) material:

1. $$CF = \frac{\text{geomean } \Sigma \text{ element value (E2v)}}{\text{geomean } \Sigma \text{ element value (regolith unit)}}$$

e.g. the correction factor for As in E4v is obtained as follows:

$$CF = \frac{\text{geomean } \Sigma \text{ As(E2v)}}{\text{geomean } \Sigma \text{ As(E4v)}}$$

The corrected element value is then obtained by multiplying the individual element values by the appropriate correction factor:

2. *corrected element value = element value ×CF*

e.g. the corrected As value in E4v is obtained as follows:

$$\text{corrected As(E4v)} = \text{As(E4v)} \times \text{CF(As(E4v))}$$

Each corrected value was then expressed as a logarithm in order to approximate a normal distribution.

3. *log(corrected element value)*

e.g. the corrected values for As is expressed as its logarithm:

log(corrected As)

Standard scores for each element included in the calculation of the final Greenstone Chalcophile Index value were then derived for the corrected and log-transformed data for each element using the 'standardize' function in Microsoft EXCEL. Standard scores (S) are used in preference to element values; the score is an expression in standard deviations of a particular element's position in relation to the overall distribution of values. This allows an As score, for example, to be directly compared with an Sb score. Similarly, scores for different elements can be combined in an additive index, with equal weighting being accorded to each element irrespective of the absolute range of values of that element.

$$4. \quad S = \frac{\text{log(corrected element value)} - \text{mean } \Sigma \text{ log(corrected element value)}}{\text{standard deviation } \Sigma \text{ log (corrected element value)}}$$

e.g. the standard score for As is expressed as:

$$4. \quad (As) = \frac{\text{log(corrected As)} - \text{mean } \Sigma \text{ log(corrected As)}}{\text{standard deviation } \Sigma \text{ log (corrected As)}}$$

The Greenstone Chalcophile Index value (GCIV) attributable to each greenstone-sourced sample was then obtained by simple addition of the appropriate element scores:

$$5. \quad GCIV = S(element1) + S(element2) + S(element3) \text{ etc.}$$

e.g. the Greenstone Chalcophile Index value applied to the GSWA data:

$$GCIV = S(As) + S(Bi) + S(Mo) + S(Sb) + S(Se) + S(Sn) + S(W)$$

This chalcophile index differs from the CHI6*X index (Smith et al., 1989) in that Ag was excluded as the Ag values are generally too close to the detection level to be meaningful.

Exploration company data

A total of 393 exploration company projects located on MENZIES, LEONORA or SIR SAMUEL and listed in the WAMEX database includes results of surface geochemical sampling. Only 15 of these projects contained multi-element results, including the four key elements (As, Bi, Mo and Sb), that would enable comparison of our Greenstone Chalcophile Index values for the GSWA data.

In order to make a meaningful comparison with the GSWA data it was also necessary to use large datasets from the exploration companies representing an area corresponding to at least 20 GSWA samples (i.e. 320 km^2). Two of the 15 projects met this requirement: a laterite sampling project in the Ilaara Belt of the Barlee Terrane by CRA (1987) and a rock-chip sampling project in the Yandal Greenstone Belt by Electrolytic Zinc (1987). The CRA project involved 80 samples of laterite/ferricrete collected over the entire project area of 395 km^2 and analysed for Ag, As, Au, Bi, Co, Cu, Ge, Mo, Pb, Sb, Se, Sn, W and Zn. The GSWA collected 35 samples over the same area. The Electrolytic Zinc project comprised 124 rock samples, each averaging 2.5 kg, collected over 115 km^2 and analysed for Ag, As, Au, Bi, Cu, Mo, Pb, and Sb. Locations were reported only as map positions to the nearest 500m.

Data processing

As the sample medium collected by CRA and Electrolytic Zinc was either fresh rock (E2v) or laterite (E4v), no correction for downslope weathering effects was considered necessary. The two company datasets were processed to derive element scores which were then used to calculate Greenstone Chalcophile Index values for each sample point. For the Electrolytic Zinc data the values were calculated from the As, Bi, Mo, and Sb scores for a selected group of 50 samples. For the CRA data the values were calculated from all seven element scores using the full set of 80 samples.

GSWA Greenstone Chalcophile Index values

Barlee Terrane

The greenstone belts of the Barlee Terrane within the area of study are not significantly mineralized. Five anomalous groups of drainage catchments are identified from the GSWA data; i.e. those catchments with Greenstone Chalcophile Index values greater than 2.0. Results are reviewed with reference to the locations shown in Figure 1.

Area 1 with a maximum Greenstone Chalcophile Index value of 6.8 and anomalous Mo corresponds to banded iron-formation at Mount Alexander. Area 2 with a maximum value of 9.2 has anomalous Mo and Bi and relates to the Copperfield mining centre. Area 3 with a maximum value of 5.5 has anomalous Mo and is situated 6 km south of the Bottle Creek gold-mining centre. Area 4 with a maximum value of 5.4 has anomalous As and is north of Lemon Rock in shale and basalt. Area 5 with a maximum value of 9.9 has anomalous As and Sb values and is situated approximately 5 km south-southwest of Lemon Rock in pelitic schist and altered basalt. Gold concentrations determined by GSWA for the Barlee Terrane range between 0 and 22 ppb with the highest values from the southeast corner of the study area, which corresponds to the Mulline mining centre. There is poor correlation between the gold concentrations and those groups with elevated Greenstone Chalcophile Index values.

Yandal Greenstone Belt

GSWA Greenstone Chalcophile Index values for the central section of the Yandal Belt are presented in Figures 2 and 3. These figures also show the location of Electrolytic Zinc's project area, which is shown in detail in Figure 4. Figure 2 shows all GSWA sites located in the central Yandal belt in relation to drainage. Most samples are stream sediment taken from creeks, and a few consist of sheetwash. A Greenstone Chalcophile Index value has been calculated for all greenstone-sourced samples; i.e. those with regolith codes E1, E2v, E4v, DC1, DC1v, DC2, DC2v, DC3 and DC3f. Samples with a positive value (ranging from 0 to 10.4) are displayed as a circle. Samples with a negative value are shown with a cross. Of the 160 samples plotted on Figure 2, 138 are greenstone-sourced samples for which a Greenstone Chalcophile Index value has been calculated. The remaining 32 samples represent granitoid-sourced samples or those located in alluvial areas and lakes.

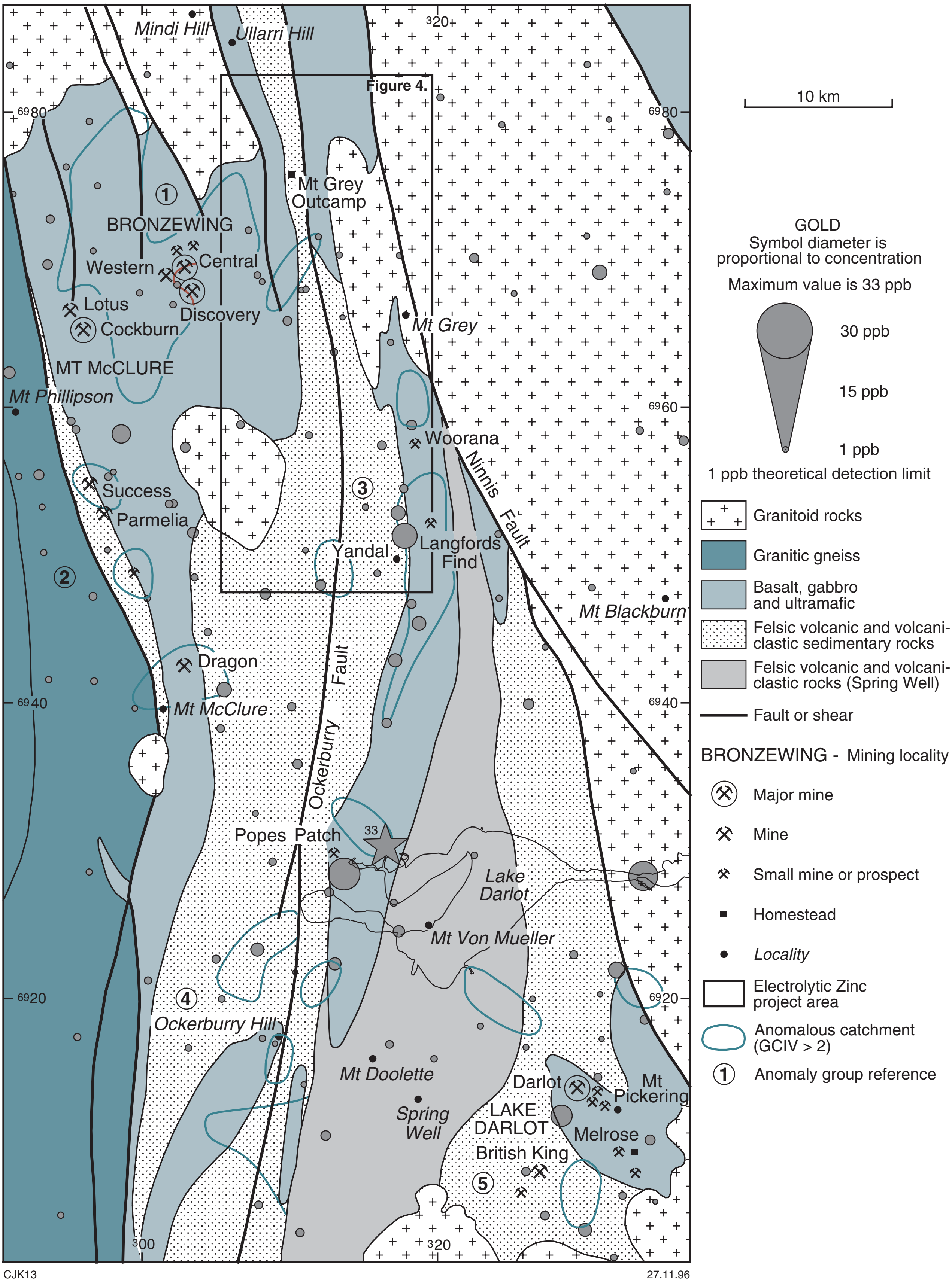


Figure 3. GSWA anomalous chalcophile catchments, gold values, gold mineralization and geology in the central Yandal Greenstone Belt

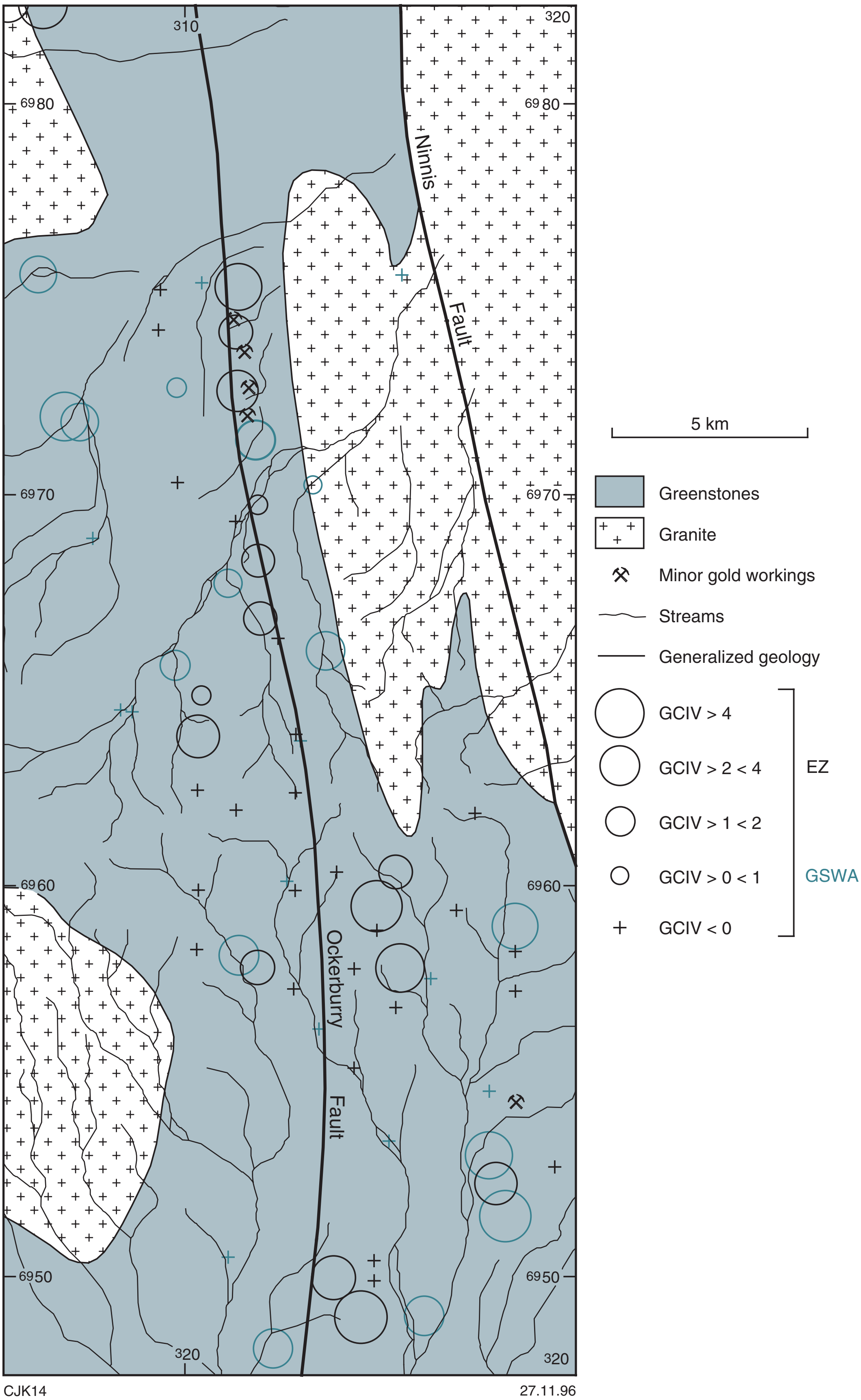


Figure 4. GSWA GCIV results in relation to the GCIV from Electrolytic Zinc (EZ) data for the central Yandal Greenstone Belt

Figure 2 also shows the highly anomalous drainage catchments; i.e, those catchments with values greater than 2.0.

Figure 3 shows the same anomaly groups as Figure 2 in relation to geology and GSWA raw gold concentrations. The major gold mines and some smaller workings and prospects are also shown. Five Greenstone Chalcophile Index anomaly groups are defined. Area 1 corresponds to the large anomaly located near the Bronzewing mines and the two northern mines of the Mount McClure project; area 2 includes three anomalies that correspond to the northwest-trending line of former Mount McClure gold mines located on the western margin of the Yandal Belt; area 3 corresponds to the two anomalies located on the north trending mineralized zone which includes Woorana, Langfords Find and Popes Patch; area 4 includes the large anomaly located in the Spring Well–Ockerburry Hill area and the two small anomalies north of Ockerburry Hill; and area 5 includes the three anomalies near the Darlot gold mine.

The characteristics of these groups are summarized in Table 2. The two larger anomalies (areas 1 and 4) are less obviously associated with gold mineralization. The northern anomaly (area 1) is flanked by the major gold mines of Cockburn and Lotus (Mount McClure) and Discovery and Central (Bronzewing). The southern anomaly (area 4) covers the faulted western margin of the Spring Well Volcanics and the adjacent Ockerburry Fault. There is no record of significant mineralization in area 4; however, gold values up to 5 ppb were recorded from the northern anomalies in this group. Drilling by Yardarino in this area has reported encouraging gold anomalies, with the best intersections of 4 m grading 4.45 grams/tonne and 8 m at 1.31 g/t (Paydirt, 1996).

All five anomalous groups have distinctive geochemistry, possibly reflecting variations in depth of formation of the mineralization and proximity to post-tectonic granitoids. The Spring Well and Darlot anomalies both contain highly anomalous amounts of barium and also anomalous amounts of tellurium. No evidence of VMS mineralization was noted.

Table 2. Characteristics of Greenstone Chalcophile Index (GCI) Anomalies — central Yandal Greenstone Belt

Anomaly group	*Mines or prospects*	*No. of GCI values >2*	*Max GCI*	*Max Au*	*Anomalous elements*
1	Lotus, Cockburn, Bronzewing	10	10.4	2	Bi, Mo, Nb, Sn, Ta W
2	Success, Parmelia, Challenger, Dragon	4	4.5	6	Au, As, Pt, Cu, Zn
3	Woorana, Langfords Find, Popes Patch	6	4.9	33	Au, Pt, Mo, W, Sn
4	None	15	6.9	5	As, Sb, Ba, Mo, Nb, Sn, Te
5	Darlot, British King	3	3.8	7	Au, Ba, Te

Comparisons of GSWA Greenstone Chalcophile Index values with those from exploration company data

Figure 4 shows GSWA Greenstone Chalcophile Index values in relation to the values derived from the Electrolytic Zinc data (Yandal Belt), and Figure 5 shows GSWA Greenstone Chalcophile Index values in relation to the values derived from the CRA data (Ilaara Belt, Barlee Terrane).

Yandal Greenstone Belt

In Figure 4, Electrolytic Zinc's positive Greenstone Chalcophile Index values range from 0 to 7.9, with 12 samples exceeding 2.0. The majority of the elevated values lie close to the Ockerburry Fault. There are elevated values near minor gold workings in the northwest and southeast of the area. The GSWA Greenstone Chalcophile Index values highlight the southeastern mineralization but, due to a lower sampling density, detect only one of the northwestern workings. Generally, samples from the same catchment areas demonstrated similar values. One exception relates to three elevated Electrolytic Zinc Greenstone Chalcophile Index values centred around AMG 315500E 6958500N (Fig. 4). The GSWA sample within that catchment has a negative value.

Barlee Terrane

The CRA project Greenstone Chalcophile Index values in the Ilaara Greenstone Belt (Barlee Terrane) have a positive range of 0–8.7, with 28 samples over 2.0 (Fig. 5). The highest value is around AMG 220000E 6750000N and corresponds to laterite overlying an altered gabbro and basalt bedrock. The only mineralization within the area is Metzke Find (Fig. 5) and is not highlighted by elevated values. The GSWA Greenstone Chalcophile Index values show good agreement with the CRA values. However, there is one area of elevated GSWA values (area 5 for the Barlee Terrane) that is not highlighted by the CRA values. Neither the CRA nor the GSWA values highlight the Metzke Find gold mineralization.

Conclusions

A Greenstone Chalcophile Index (As+Bi+Mo+Sb+Se+Sn+W) similar to CHI6*X has proved useful in highlighting gold mineralization associated with hydrothermal alteration in the Yandal Greenstone Belt. Gold mineralization associated with epithermal/mesothermal alteration is also highlighted but with some vertical or lateral displacement.

The Greenstone Chalcophile Index outlines the highly mineralized Bronzewing and Mount McClure areas in the Yandal Belt. In contrast, the GSWA raw gold data fail to show any elevated concentrations in the area.

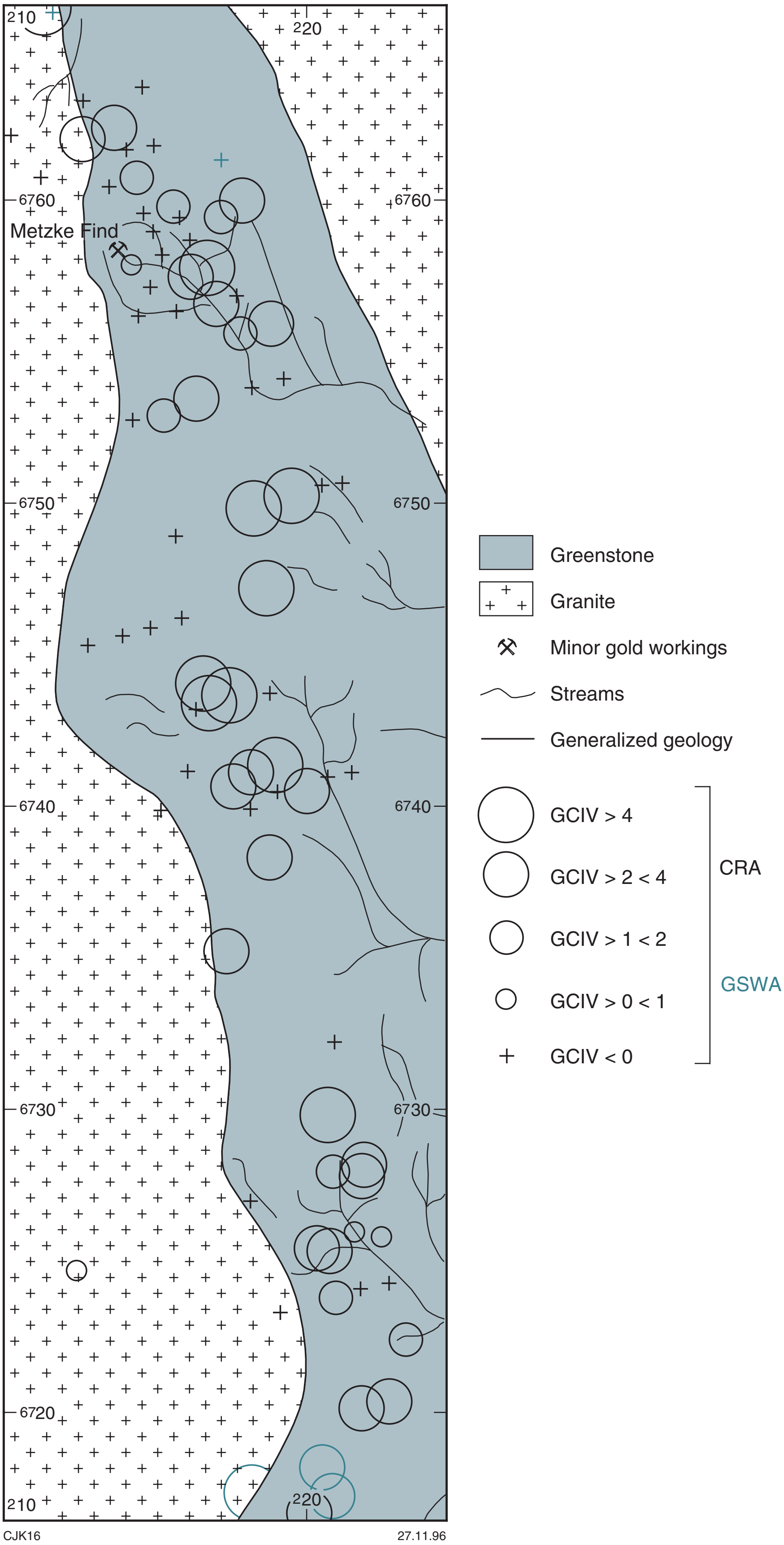


Figure 5. GSWA GCIV in relation to the GCIV derived from CRA data for the Ilaara Greenstone Belt

Another area of anomalous Greenstone Chalcophile Index values in the Yandal Greenstone Belt (east of Darlot in the Spring Well–Ockerburry Fault area) represents a promising exploration target for gold. A new gold discovery has recently been announced in this area. There are also anomalously high concentrations of Ba and Te associated with the high Greenstone Chalcophile Index values.

In the Barlee Terrane area, anomalous Greenstone Chalcophile Index values have highlighted the Copperfield Mining Centre. Other areas of anomalous values can mainly be attributed to sulfidic metasedimentary rocks and elevated Mo within banded iron-formation.

There is good correlation between the GSWA Greenstone Chalcophile Index values and those generated from exploration company data in both the Yandal Belt and the Barlee Terrane. However exploration company data listed in the GSWA WAMEX open-file database are of limited usefulness on account of the low percentage of projects that report multi-element data.

Strong potential exists for future studies involving chalcophile and other indices in the Eastern Goldfields identifying areas of potential gold and base-metal mineralization.

References

BRADLEY, J. J., SANDERS, A. J., VARGA, Z. S., and STOREY, J. M., 1995, Geochemical mapping of the Leonora 1:250 000 sheet : Western Australia Geological Survey, Explanatory Notes, 88p.

CRA EXPLORATION PTY LTD, 1987, Laterite geochemical survey, E29/44, E30/20 : Western Australia Geological Survey, M-series Open File, Item 5820, Accession 24272 (unpublished).

CRUIKSHANK, B. I., 1994, Stream sediment geochemistry of the Ebagoola 1:250 000 sheet area, Cape York Peninsular, north Queensland : Australian Geological Survey Organisation, Record 1994/8.

ELECTROLYTIC ZINC Co., 1987, Annual report on exploration, E37/75 : Western Australia Geological Survey, M-series Open File, Item 5548, Accession 21227 (unpublished).

GRIFFIN, T. J., 1990, The Southern Cross Province, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 60–76.

GUILBERT, J. M., and PARK, C. F., 1986, The geology of ore deposits: New York, W. H. Freeman and Company.

HAWKES, H. E., and WEBB, J. S., 1962, Geochemistry in mineral exploration: Harper International Student Reprint, p. 19–21.

KOJAN, C. J., and FAULKNER, J. A., 1994, Geochemical mapping of the Menzies 1:250 000 sheet: Western Australia Geological Survey, Explanatory Notes, 75p.

KOJAN, C. J., SANDERS, A. J., and FAULKNER, J. A., 1996, Geochemical mapping of the Sir Samuel 1:250 000 sheet: Western Australia Geological Survey, Explanatory Notes, 100p.

PAYDIRT, 1996, Yardarino farms out Yandal ground: Volume 1, Issue 13, p. 48.

SMITH, R. E., PERDRIX, J. L., and DAVIS, J.M., 1987, Dispersion into pisolitic laterite from the Greenbushes mineralized Sn–Ta pegmatite system, Western Australia: Journal of Geochemical Exploration, no. 28, p. 251–265.

SMITH, R. E., BIRRELL, R. D., and BRIGDEN, J. F., 1989, The implications to exploration of chalcophile corridors in the Archaean Yilgarn Block, Western Australia, as revealed by laterite geochemistry: Journal of Geochemical Exploration, v. 32, p. 169–184.

SMITH, R. E., and PERDRIX, J. L., 1983, Pisolitic laterite geochemistry in the Golden Grove massive sulphide district, Western Australia: Journal of Geochemical Exploration, v. 18, p. 131–164.

WITT, W. K., MORRIS, P. A., WYCHE, S., and NELSON, D. R., 1996, The Gindalbie Terrane as a target for VMS-style mineralization in the Eastern Goldfields Province of the Yilgarn Craton, Western Australia Geological Survey, Annual Review 1995–96, p. 41–47.

WYCHE, S., and WESTAWAY, J. M., 1995, Darlot, W.A.: Western Australia Geological Survey, 1:100 000 Geological Series.

The stratigraphic and structural development of the Officer Basin, Western Australia: a review

by D. Perincek

Abstract

The age of Neoproterozoic–Palaeozoic sedimentary rocks within the Centralian Superbasin can be constrained by using major sequence-bounding unconformities.

Previously defined Supersequence LP1 is modified and sub-divided into two sequences. Sequence LP1A includes the Townsend–Heavitree Quartzites and the Lefroy and Pindyin Formations. Sequence LP1B includes the Spearhole, Browne, Skates Hills, Hussar, Kanpa, and Steptoe Formations. The Lupton and Turkey Hill Formations have been included in Supersequence LP2 or LP3 and the Boondawari Formation in Supersequence LP3. The McFadden and Tchukardine Formations postdate the Petermann Ranges Orogeny. These formations and the Durba Sandstone are considered to lie within Supersequence LP4. However, the presence of a major unconformity between the Table Hill Volcanics and these underlying units requires that the Table Hill Volcanics be excluded from Supersequence LP4 and included in Sequence Pz1. The units considered within Supersequence LP4 include the McFadden and Tchukardine Formations, which are correlated with the Trainor Hill Sandstone and Relief Sandstone, and the Observatory Hill and Ouldburra Formations of the eastern Officer Basin. The Lennis Sandstone and Wanna Formation, and the Paterson Formation belong in Supersequences Pz4 and Pz5, respectively.

In the Officer Basin at least nine periods of tectonic activity may be interpreted from seismic data. This activity commenced early in the Neoproterozoic and finished by the end of Cretaceous. The Areyonga Movement (Blake Movement), Petermann Ranges Orogeny, Delamerian Orogeny, Alice Springs Orogeny, post-Permian and Miocene movements are the major events affecting and recorded in the sedimentary section of the basin.

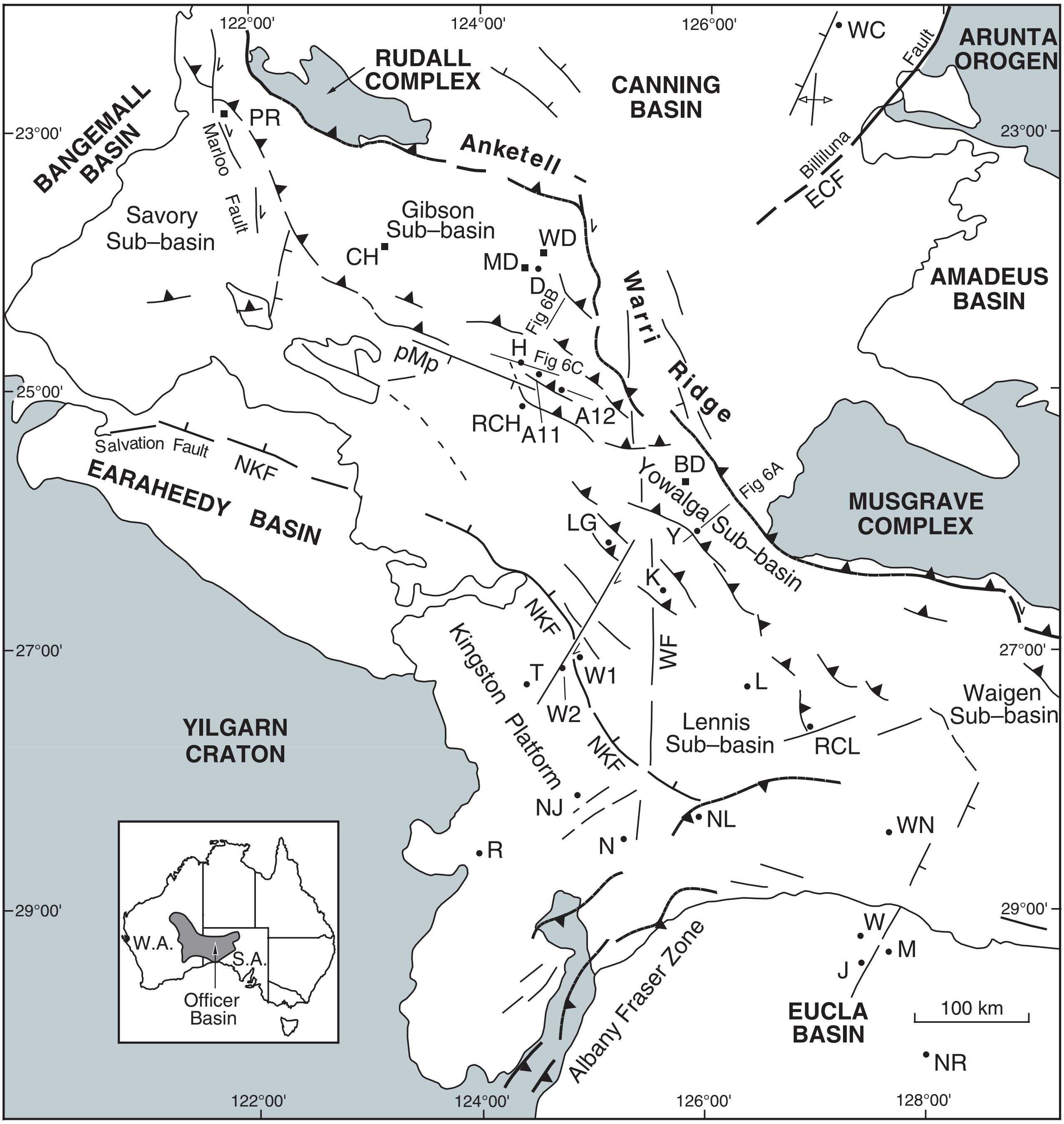
KEYWORDS: Petermann Ranges Orogeny, Officer Basin, Neoproterozoic, Areyonga Movement (Blake Movement), Alice Springs Orogeny, petroleum potential, stratigraphic nomenclature, Table Hill Volcanics.

Detailed information on the stratigraphy of the Officer Basin (Fig. 1) has been provided by Jackson and van de Graaff (1981), Townson (1985), Iasky (1990), Williams (1994), Gravestock and Lindsay (1994), Walter and Gorter (1994) and Walter et al. (1995). A generalized stratigraphic column for the basin is shown in Figure 2.

Recent geological investigations and the petroleum exploration history of the western Officer Basin are summarized in three papers (Townson, 1985; Phillips et al., 1985; Perincek, 1996), in which the main focus is the Upper Proterozoic to Palaeozoic sequence. There are several formation names defined for the same stratigraphic unit within the western Officer Basin. A nomenclature proposed in this paper (Fig. 1) should provide a sound basis for future study.

In 1980–81, Shell drilled Yowalga 3, currently the deepest well in the basin (TD 4196 m). This well was followed in 1983 by Kanpa 1A (TD 3803 m), the only well to penetrate fully the Upper Proterozoic sequence. Other wells drilled in the western Officer Basin are Hussar 1 (TD 2040 m, 1982), Dragoon 1 (TD 2000 m, 1982) and Lungkarta 1 (TD 1770 m, 1984), and exploration corehole NJD 1 (TD 517 m, 1981). In addition to these wells, 47 stratigraphic and mineral wells (TD 100 to 1000 m) have also been drilled since 1971. Recently modified stratigraphic data from those wells have greatly improved the understanding of the stratigraphy of the Officer Basin (Figs 3, 4 and 5).

Figure 1 shows the regional setting of the western Officer Basin and the relationship between the various sub-basins. The development of the Officer Basin is coeval with that of the Amadeus, Ngalia, Georgina and Warburton Basins and the Adelaide Geosyncline. The Officer Basin is an asymmetrical 'half-graben' trough, with its deepest part adjacent to the Musgrave and Rudall Complexes (Townson, 1985).



NR	NRH 3	RCL	90 RCLE 005	W2	BMR Westwood 2
M	Mason 1	NL	BMR Neale 1A - 1B	RCH	90 RCHE 003
J	Jubilee 2	R	BMR Rason 2	A11	89 RCWA 011
W	Weedy 1	T	BMR Throssell 1	A12	89 RCWA 012
WN	BMR Wanna 1	W1	BMR Westwood 1	NJ	NJD 1

Figure 1. Location and simplified structural elements map of the Officer Basin showing basement highs, basins, key seismic lines and exploration wells. D=Dragoon 1, H=Hussar 1, K=Kanpa 1A, L=Lennis 1, LG=Lungkarta 1, Y=Yowalga 3, NR=NRH 3. M=Mason 1, J=Jubilee 2, W=Weedy 1, WN=BMR Wanna 1, RCL=90RCLE 005, NL=BMR Neale 1A-1B, R=BMR Rason 2, T=BMR Throssell 1, W1=BMR Westwood 1, W2=BMR Westwood 2, RCH=90RCHE 003, A11=89RCWA 011, A12=89RCWA 012. WC=Wilson Cliffs 1, BD=Browne Diapir, CH=Constance Headland, MD=Madley Diapirs, PR=Poisonbush Range, WD=Woolnough Hills Diapir, pMp=post-Middle Proterozoic fault, ECF=east Canning fault, NKF=north Kingston fault, WF=Westwood Fault, WC=Wilson Cliffs 1 (after *Perincek, 1996)*

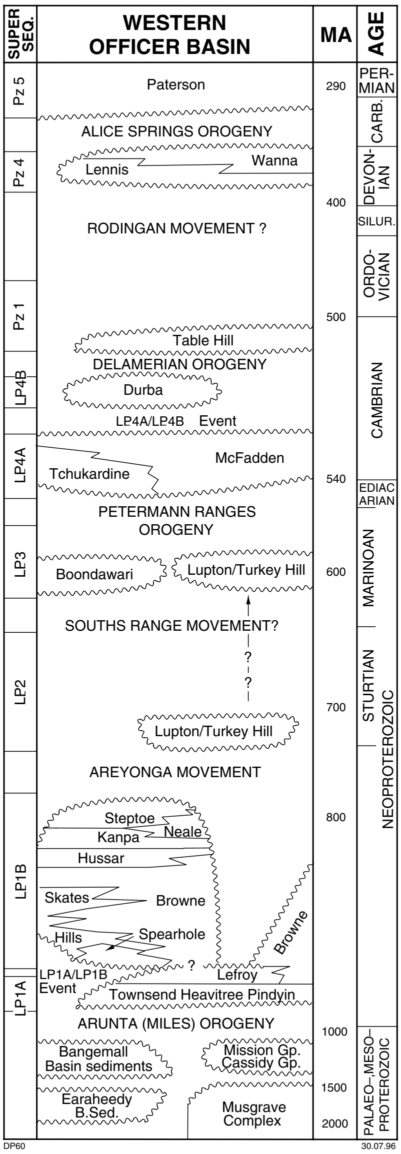


Figure 2. Generalized stratigraphic column and tectonic events of the Officer Basin. Modified **after** *Perincek (1996)*

Throughout most of the Officer Basin, sedimentation ceased at the end of the Neoproterozoic or in the Early Cambrian. An intermittent connection between the Canning Basin and the Great Artesian Basin, via the Officer Basin, existed in the Early Ordovician and Early Permian (Phillips et al., 1985). The Warri–Anketell Ridge forms the northeastern boundary to the western Officer Basin, and separates the Officer Basin from the Canning Basin to the north.

The redefined Officer Basin (Perincek, 1996) incorporates strata previously included within the Officer Basin, the Kingston Platform (Townson, 1985), the Savory Basin, and a portion of the thrust belt within the Paterson Orogen of Williams (1992). Bagas et al. (1995) reported that Upper Proterozoic Tarcunyah Group, Savory Group, and Officer Basin successions were probably a single tectonic unit.

Stratigraphy

A generalized stratigraphic column for the Officer Basin is shown in Figure 2. The basin contains thick Neoproterozoic clastics and evaporites, underlain in some areas by Palaeo- to Neoproterozoic sedimentary rocks and the Yilgarn Craton (Figs 3 and 4).

The Officer Basin is dominated by northwest-oriented structural trends (Fig. 1) and bounded to the northeast by the Musgrave and Rudall Complexes. The Musgrave Complex consists of metasedimentary and meta-igneous rocks, which are overlain by the Mission and Cassidy Groups (Fig. 2). The Rudall Complex consists of igneous and metamorphic rocks that underwent greenschist metamorphism during the Miles Orogeny, which occurred between 820 and 1290 Ma (Bagas et al., 1995). Shaw et al. (1991) stated that the Arunta Orogeny (865–900 Ma) predated the Neoproterozoic and caused regional uplift and erosion within the Amadeus Basin. Therefore, it is possible that the Arunta Orogeny and the Miles Orogeny may be the same event. The Officer Basin is bounded to the southwest by the Archaean Yilgarn Craton and the Mesoproterozoic metamorphic rocks of the Albany–Fraser Province, and to the west by the Palaeo- and Mesoproterozoic sedimentary rocks of the Earaheedy and the Bangemall Basins. The southern margin of the Officer Basin is covered by Tertiary sedimentary rocks associated with the Eucla Basin.

The Archaean (pre-2500 Ma) Yilgarn Craton formed a stable southwestern margin during the development of the Officer Basin (Jackson and van de Graaff, 1981).

The northeast-trending Albany–Fraser Zone is a complex Mesoproterozoic thrust belt zone. The Fraser Complex within the Albany–Fraser Zone consists predominantly of metamorphosed mafic and volcano-sedimentary sequences.

The central–western portion of the Officer Basin is underlain by the Earaheedy and Bangemall Basins (Figs 1 and 2). The Earaheedy Basin is Palaeoproterozoic in age and contains sandstone, shale, siltstone, minor dolomite and chert. Earaheedy Basin sedimentary rocks lie unconformably on the Yilgarn Craton and are unconformably overlain by the Bangemall Basin, which contains mainly Middle Proterozoic sandstone and shale with minor dolomite.

Walter et al. (1994, 1995) recognized four supersequences for the Neoproterozoic portion of the Officer Basin, which is part of the Centralian Superbasin. The Centralian Superbasin is defined to encompass the Neoproterozoic fill of the Amadeus, Georgina, Ngalia, Officer and Savory Basins (Walter et al., 1995). Existing GSWA nomenclature has been used for Proterozoic and Phanerozoic sequences (Iasky, 1990).

The four supersequences are named LP1 to LP4. Based on re-interpretation of the well and seimic data, supersequence LP1 is modified and further sub-divided into two sequences: 1) sequence LP1A including the Townsend Quartzite (lateral equivalent of Heavitree Quartzite), and the Lefroy and Pindyin Formations; 2) sequence LP1B including the Spearhole, Browne, Skates Hills, Hussar, Kanpa and Steptoe Formations (Fig. 2). The Lupton and Turkey Hill Formations could be included in Supersequence LP2 or LP3 and the Boondawari Formation in Supersequence LP3.

The Tchukardine and McFadden Formations (Sequence LP4A) and the Durba Sandstone (Sequence LP4B) are considered to lie within Supersequence LP4. A major unconformity separates the LP4 units from the Table Hill Volcanics. For this reason the Table Hill Volcanics is excluded from Supersequence LP4 and included in Sequence Pz1. The Lennis Sandstone and Wanna Formation, and the Paterson Formation belong in Sequences Pz4 and Pz5 respectively.

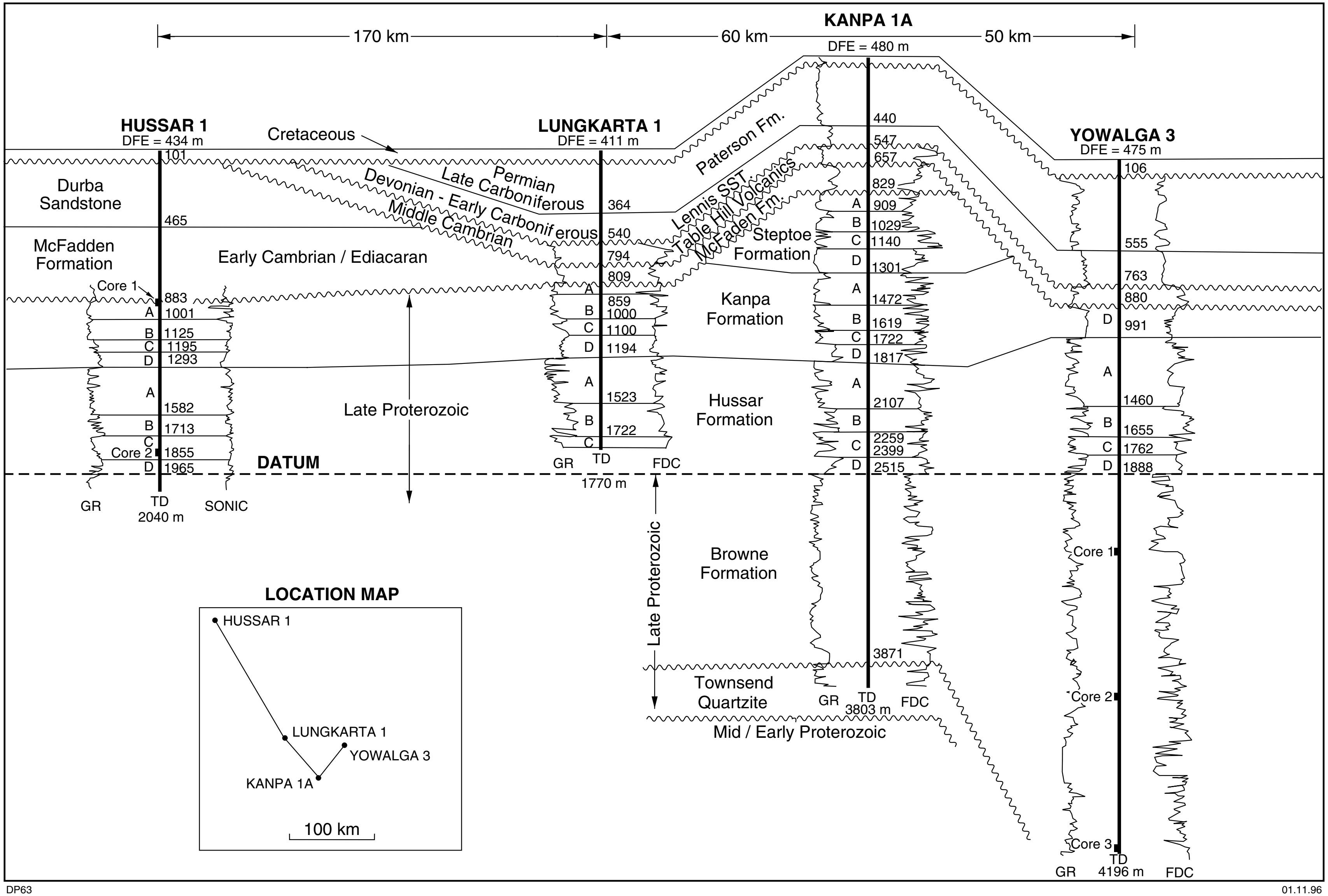


Figure 3. Well correlation: Hussar 1, Lungkarta 1, Kanpa 1A and Yowalga 3. Modified after *Townson (1985)*

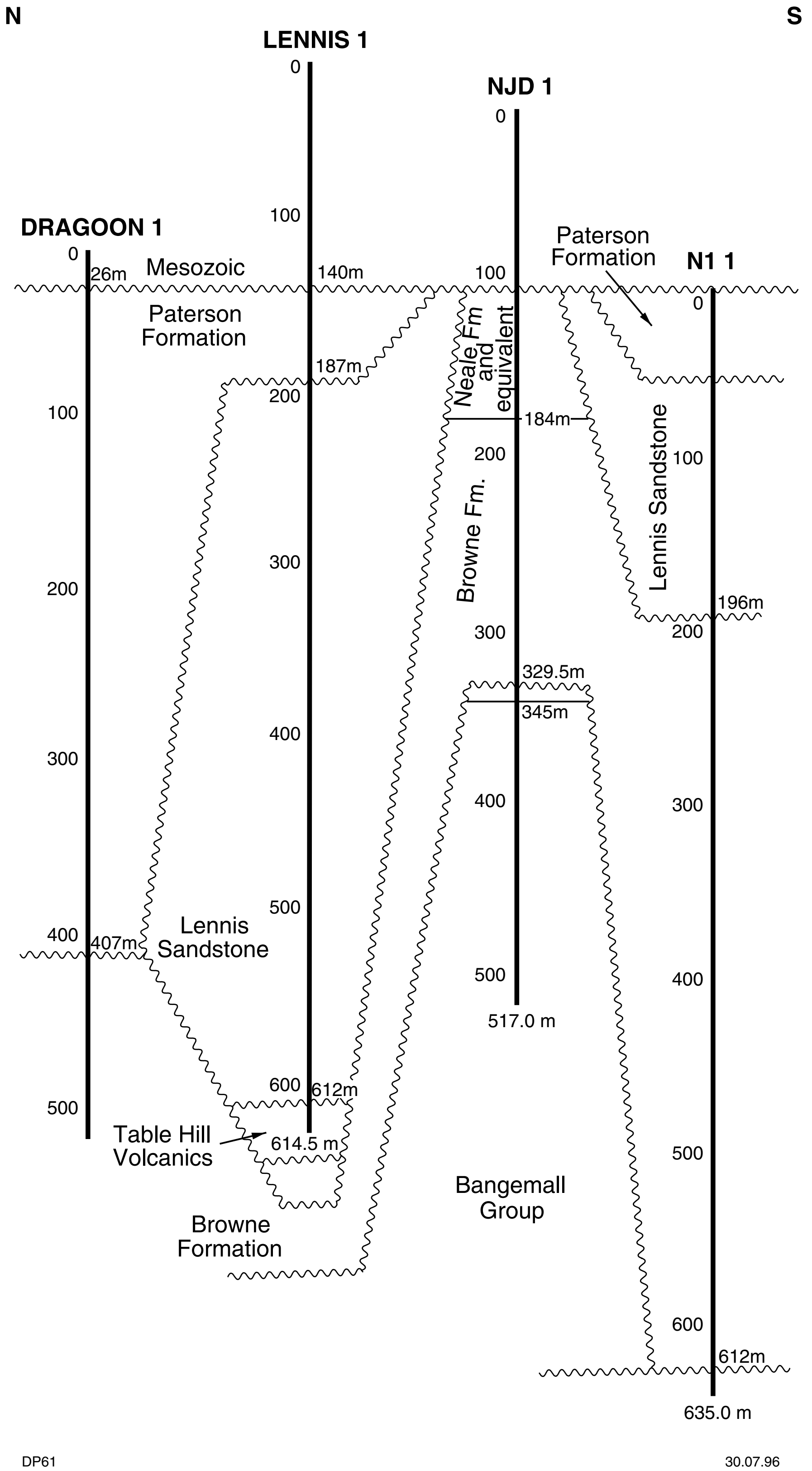


Figure 4. Well correlation: Dragoon 1, Lennis 1, NJD 1 and N1 1. Location of well shown in Figure 1.

Supersequence LP1

Townsend (Heavitree) Quartzite, Lefroy Formation (sequence LP1A)

The Townsend Quartzite and the Lefroy Formation outcrop along the southwest margin of the Musgrave Complex. In the geological map of Western Australia (Myers and Hocking, 1988) outcrops of the Townsend Quartzite–Robert Formation and Browne–Neale–Ilma Formations in the Officer Basin are shown as the Heavitree Quartzite, Bitter Springs Formation and similar formations. The Townsend Quartzite and Browne Formation are the lateral equivalent of the Amadeus Basin section of Heavitree Quartzite and Bitter Springs Formation respectively. The latter names may be reconsidered for the Officer Basin during future nomenclature revision.

The Townsend Quartzite is the basal transgressive unit of the Upper Proterozoic sequence that unconformably overlies the Musgrave Complex. A lateral equivalent of this formation overlies the sedimentary rocks of the Bangemall and Earaheedy Basins on the western margin of the basin (Townson, 1985). The Townsend Quartzite, an orthoquartzitic, fluvial to shallow marine unit, has a gradational contact with the overlying Lefroy Formation, which consists of sandstone, siltstones and marine shales. The Lefroy Formation is missing in Kanpa 1A where the Townsend Quartzite is directly overlain by the Browne Formation (Fig. 3).

The Townsend Quartzite and Lefroy Formation are correlated with the basal two units of Supersequence LP1 in the Savory Sub-basin; the Glass Spring and Jilyili Formations respectively. The Glass Spring Formation consists of medium- to coarse-grained sandstone and siltstone with scattered conglomerate lenses at the base. In this unit the sandstone is cleaner to the west, and contains evidence of westerly directed palaeocurrents. The Glass Spring Formation is interpreted as a transgressive, shallow-water, marine-shelf deposit (Williams, 1992). The Jilyili Formation overlies the Glass Spring Formation and consists of interbedded sandstone, siltstone and shale with minor mudstone and conglomerate. Palaeocurrent data indicate west- to northwest-directed flows, similar to those of the underlying Glass Spring Formation. The Jilyili Formation was deposited in a marine-modified delta that prograded northwestwards over the Glass Spring Formation (Williams, 1992).

The overall sedimentary environment for the Townsend Quartzite and Glass Spring Formation was transgressive, from fluvial to shallow marine. This was followed by the marine and marine-modified deltaic sedimentation of the Lefroy, and Jilyili Formations which represent the regressive portion of the sequence.

Browne, Spearhole and Skates Hills Formations, (sequence LP1B)

The Browne Formation (Cockbain and Hocking, 1989) consists of shale and siltstone, with interbedded halite, anhydrite and dolomite. Browne 1 and 2 were drilled on the Browne Diapir and penetrated dolomite, calcareous shales, anhydrite and gypsum, with minor oil and gas shows. This Neoproterozoic evaporitic sequence also outcrops in the Woolnough Hills and Madley Diapirs (Fig. 1) and has been intersected by a number of shallow stratigraphic boreholes in that area (Jackson and van de Graaff, 1981). Phillips et al. (1985) indicated that the Browne Formation can be correlated with the Madley Formation of the Gibson Sub-basin based on stratigraphic, seismic correlation.

In the Gibson Sub-basin the Browne Formation (previously called Madley Formation) outcrops at Constance Headland (see Fig. 1 for location). These sedimentary rocks extend into the northern Savory Sub-basin (previously known as the Karara Basin).

Palynomorphs and stromatolites recovered from the Browne Formation in Yowalga 3 (Figs 3 and 6A) indicate a middle Neoproterozoic age, equivalent to Supersequence LP1 (Grey, 1995). The depositional environment of the Browne Formation ranges from shallow marine, to restricted shallow marine, sabkha and playa lake settings, with strong oxidizing influences (Townson, 1985).

The Neoproterozoic evaporites of the Browne Formation are correlated with the Bitter Springs Formation of the Amadeus Basin (Townson, 1985; Grey, 1995). The correlation between the Browne Formation and the Mundadjini and Spearhole Formations is based on similarities in lithostratigraphy, depositional environment and the underlying unconformities (Perincek, 1996). These units overlie a sequence-bounding unconformity that separates Sequence PL1A from Sequence PL1B. The Mundadjini Formation (Williams, 1994) is represented by fine- to coarse-grained sandstone, conglomerate, siltstone, minor shale, mudstone and dolomite, with occasional poorly preserved stromatolites and evaporite. This unit was deposited under intertidal, lagoonal and shallow-marine environments. The appearance of evaporites in the western Officer Basin is more indicative of sabkhas than basinal conditions. The Spearhole Formation consists of coarse- to medium-grained sandstones with scattered pebbles and interbedded pebbly conglomerate. This unit unconformably overlies the Jilyili Formation (not shown in Fig. 2) and was deposited under high-energy conditions in a braided-fluvial system (Williams, 1992). The Skates Hills Formation consists of thinly bedded dolomite, chert, evaporites, fine- to medium-grained sandstone, siltstone, shale and lenticular conglomerate. Stromatolitic dolomite in this formation has been correlated with the Bitter Springs Formation in the Amadeus Basin (Grey, 1995). The Woolnough Formation (not shown in Fig. 2) is correlated with the Skates Hills Formation and consists of a predominantly siliciclastic lower part with interbedded siltstone, dolomite, and minor limestone, and an upper part consisting of dolomite, and minor limestone (Jackson and van de Graaff, 1981; fig. 20) in the vicinity of the Woolnough Hills Diapir. Initial examination of the poorly preserved stromatolites from the Woolnough Hills Diapir suggests that the Woolnough Formation contains the stromatolite form which has been identified in the Skates Hills Formation (Grey, 1995). Depositional settings for the Skates Hills Formation range from restricted fluvial fans and beach environments to intertidal, intratidal and near-shore marine conditions. Red beds at the top of the formation indicate arid or semi-arid and oxidizing conditions (Williams, 1992). During deposition of the Spearhole, Mundadjini and Skates Hills Formations, shallow-marine conditions gradually extended to the east and northeast.

Hussar Formation (sequence LP1B)

The Hussar Formation consists of interbedded siltstone, shale, and sandstone, with thin beds of dolomite and limestone, and conformably overlies the Browne Formation. Phillips et al. (1985) suggested that the Hussar Formation was deposited in shallow-marine or sabkha and beach to eolian environments. The eolian-dune sandstones have porosity of 12–21% and provide the primary petroleum reservoirs sought by exploration in the basin.

Kanpa Formation (sequence LP1B)

This unit is represented by interbedded shale, siltstone, claystone and anhydrite with thin sandstone and dolomite layers. Phillips et al. (1985) and Townson (1985) stated that the Upper Proterozoic Kanpa Formation was deposited in a sabkha enviroment, with some shallow-marine influences, similar to the depositional environment of the conformably underlying Hussar Formation.

The interbedded shales and widespread lower shale of the Kanpa Formation provide potential seals for the well-rounded, commonly well-sorted porous sandstones of the Kanpa and Hussar Formations (Phillips et al., 1985).

Steptoe Formation (sequence LP1B)

The Steptoe Formation, which consists of fine- to coarse-grained sandstone, dolomite, siltstone and shale, is separated from younger units by an angular unconformity. This formation includes eolian sandstone interpreted to be deposited in an inland-playa environment, and is considered to be one of the potential reservoirs for the Officer Basin (Townson, 1985; Phillips et al., 1985).

Supersequences LP2 and LP3

Lupton and Turkey Hill Formations

The Lupton Formation is a sequence of diamictite and sandstone outcropping south of the Musgrave Complex. This unit consists of massive conglomerate with scattered boulders, and sandstone with interbeds of siltstone and diamictite. The Lupton Formation unconformably overlies the Lefroy Formation on the southern flank of the Musgrave Complex. In this area the absence of the Browne Formation and its equivalents indicates extensive erosion prior to deposition of the Lupton Formation. The Turkey Hill Formation, which consists of sandstone, siltstone, claystone, and minor diamictite, is exposed on the western margin of the Officer Basin and unconformably overlies Archaean granites of the Yilgarn Craton (Jackson and van de Graaff, 1981).

Townson (1985) suggested that much of the locally deposited sedimentary material of the Lupton and Turkey Hill Formations were removed by erosion during the Neoproterozoic to Early Cambrian, particularly in the western Officer Basin. The Lupton and Turkey Hill Formations are lateral equivalents of the Sturtian (Supersequence LP2) or Marinoan (Supersequence LP3) glaciations that are well documented in the eastern Officer Basin, the Amadeus Basin and the Adelaide Geosyncline.

The Boondawari Formation has been included in Supersequence LP3 of the Centralian Superbasin (Walter et al., 1994) and is tentatively correlated with the Pertatataka Formation of the Amadeus Basin (Williams, 1992). The Boondawari Formation consists of diamictite, conglomerate, sandstone, siltstone, shale, and dolomite. The carbonates contain distinctive oolitic and pisolitic limestone, and stromatolitic dolomite.

Supersequence LP4

McFadden Formation (sequence LP4A)

This paper suggests the replacement of the name Babbagoola Formation where applied to rocks of sequence LP4A with the name McFadden Formation, which was originally defined in the Savory Sub-basin (Williams, 1992). Sequence LP4A consists of interbedded sandstone, claystone and siltstone; micaceous shale and siltstone are always present within the section and a basal conglomerate is present in Hussar 1 (Phillips et al., 1985).

The name Babbagoola Formation was first used by Jackson (1966) for rocks intersected in Yowalga 2. These rocks were originally assigned an earliest Cambrian age (Jackson and van de Graaff, 1981). Based on recent palynological studies, the Babbagoola Formation in Yowalga 2 is now assigned to Supersequence LP1 (Grey and Cotter, 1996). Well-log correlation and seismic inter-pretation indicate that the section previously identified as Babbagoola Formation in Yowalga 3 (Fig. 3) is part of the Kanpa Formation of Supersequence LP1.

The sections (Fig. 3) intersected in Hussar 1, Lungkarta 1 and Kanpa 1A were interpreted as Babbagoola Formation by Townson (1985) and Phillips et al. (1985). They are now considered to be equivalent to the Tchukardine and McFadden Formations of sequence LP4A (Perincek, 1996) that outcrop in the Savory Sub-basin (Williams, 1992). The previously named Babbagoola Formation of the sequence LP4A has been distinguished from underlying and overlying formations by major bounding uncormities (Figs 3, 5A and 6A,B,C) that have been used for seismic–stratigraphic mapping within the Officer Basin (Townson, 1985; Perincek, 1996).

Seismic evidence shows that, after a period of tectonism related to the Petermann Ranges Orogeny, the sediments now assigned to the McFadden Formation and its equivalent were unconformably deposited on the Browne, Hussar and Kanpa Formations (Figs 3, 5A and 6A,C) by onlap of the unit onto structural highs (Townson, 1985).

No reliable palynological dates are available for Supersequence LP4A of the Officer Basin (Grey, K., 1996, pers. comm.). On the basis of regional seismic, well-log and stratigraphic correlation, a Cambrian to Ediacarian (late Neoproterozoic) age range is assigned to the Formation in the western Officer Basin (Townson, 1985; Perincek, 1996). This date is dependent upon correlation to the

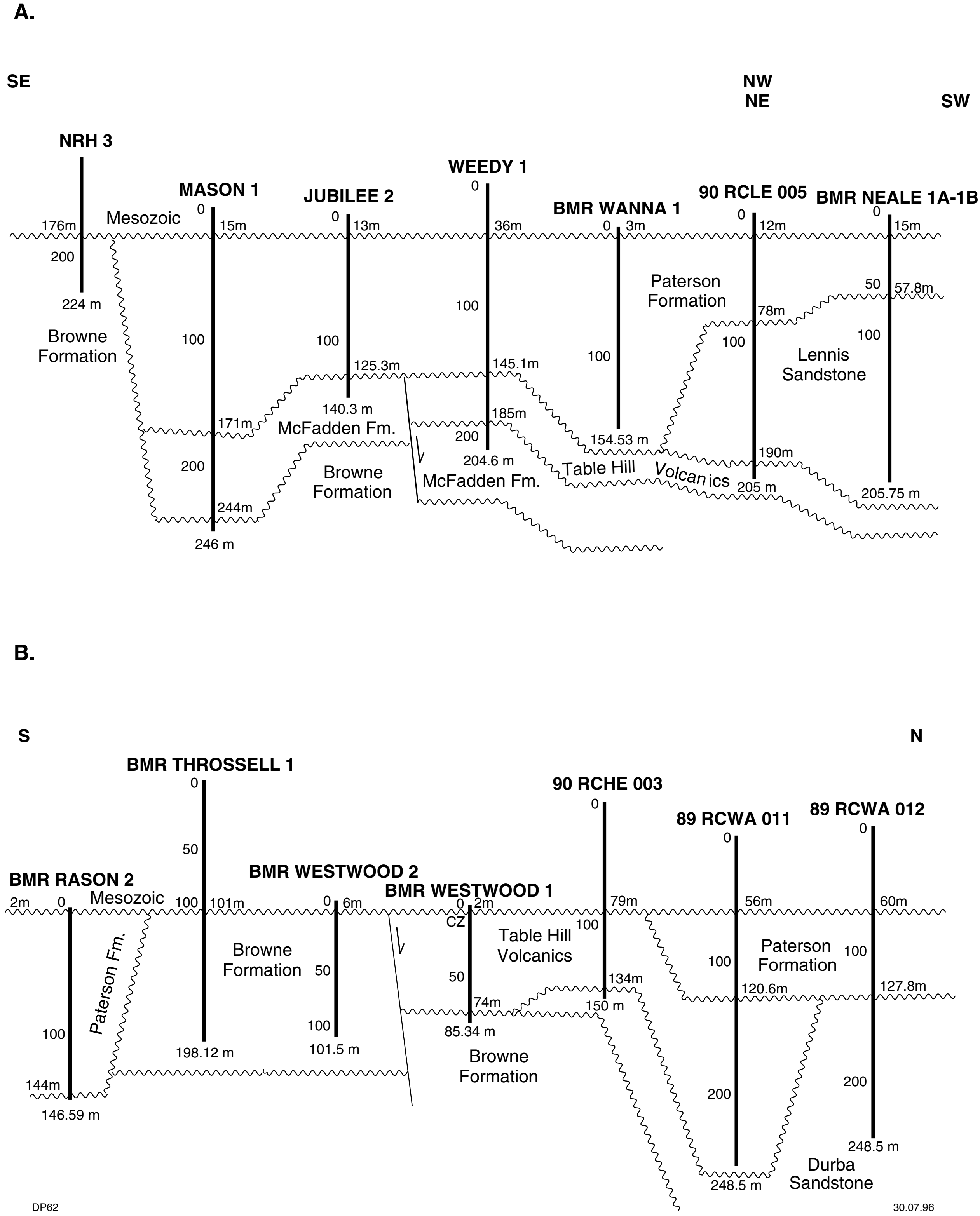


Figure 5. Well correlation: NRH 3, Mason 1, Jubilee 2, Weedy 1, BMR Wanna 1, 90 RCLE 005, BMR Neale 1A, 1B, BMR Rason 2, BMR Throssell 1, BMR Westwood 2, BMR Westwood 1, 90 RCHE 003, 89 RCWA 011 and 89 RCWA 012. Location of well shown in Figure 1. Note that the northeast bounding fault of the Kingston Platform is evident in this correlation. In general the hanging wall contains a thick sedimentary section and the Table Hill Volcanics

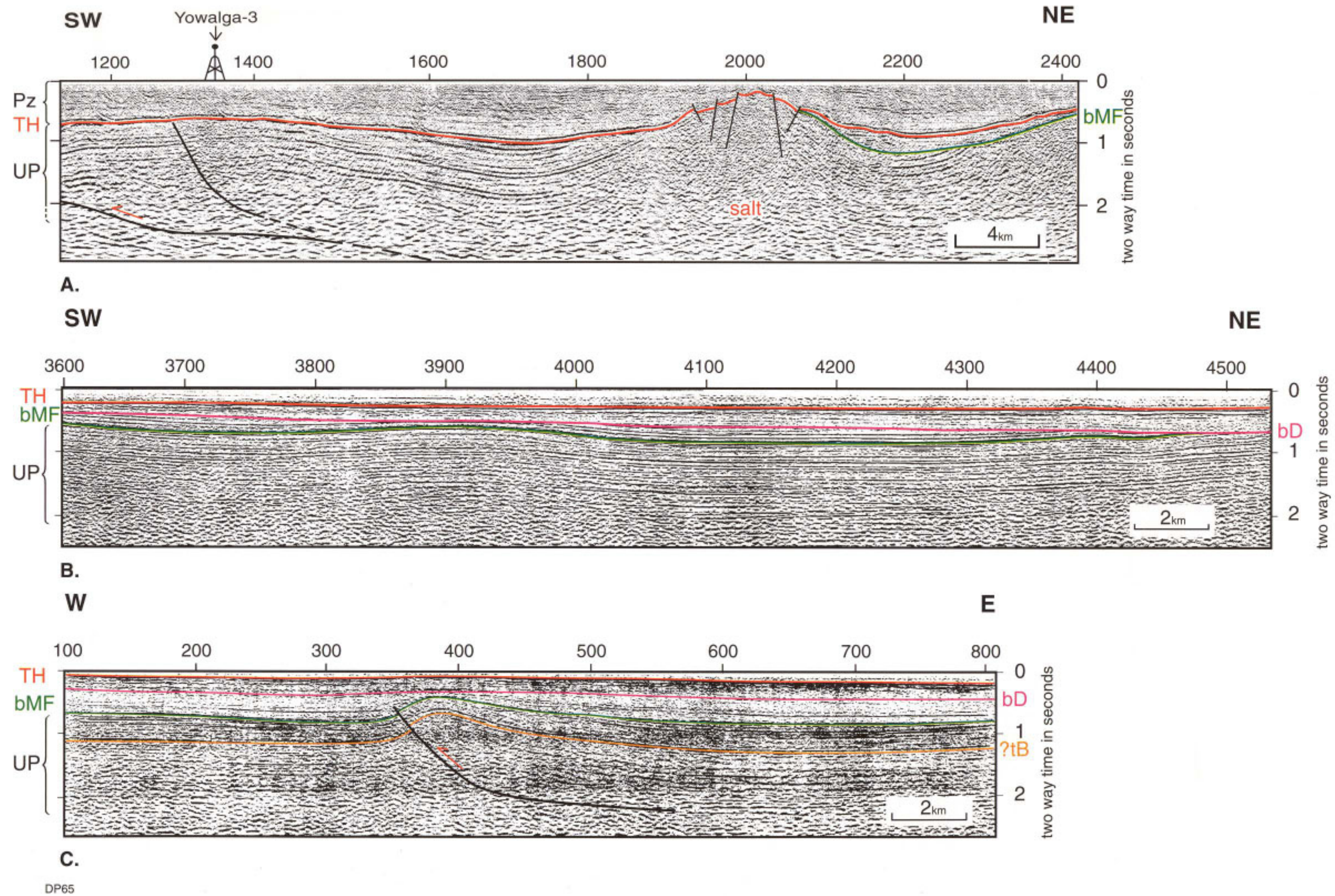


Figure 6. A. Seismic line (migrated) 80-07 showing reactivation of salt movements, probably pre-Late Carboniferous in age that caused folding of the Table Hill Volcanics. Salt pierces the Table Hill Volcanics near sp 2000

B. Seismic line (migrated) N83-11 illustrating broad folding postdated by the basal unconformity of the Durba Sandstone. Note that erosion removed the upper portion of the McFadden Formation but did not affect Supersequence LP1 sediments. Truncation of the pre-Durba Sandstone rock is evident from sp 4400 to sp 4520

C. Seismic line (migrated) N84-12 showing thrusting and folding related to the Petermann Ranges Orogeny which also caused erosion on the crest of this structure (sp 360–470). Following deposition of the McFadden Formation, another tectonic event caused further folding, faulting and extensive erosion of the McFadden Formation on the crest area (sp 380–420). Seismic line also illustrates unconformable relationships of the upper and lower boundaries of the McFadden Formation (Sequence LP4A). UP=Upper Proterozoic (Supersequence LP1), tB=top Browne Formation, bMF=base McFadden Formation (base Sequence LP4A), Pz=Palaeozoic (Lennis Sandstone and Wanna, Paterson Formations), TH=Table Hill Volcanics. Location of seismic line shown in Figure 1 bounding formations, which have been more reliably dated with fossils.

Phillips et al. (1985) believed that the Babbagoola Formation (lateral equivalent of the McFadden Formation) was deposited in a predominantly subaerial environment, in the Gibson Sub-basin. However, a brackish to marine environment of deposition was suggested by Townson (1985) for the remainder of the unit elsewhere in the western Officer Basin.

The McFadden Formation is correlated with the Wirrildar Beds that outcrop near the South Australian border, and with the late Early Cambrian, trilobite-bearing Observatory Hill Formation of the eastern Officer Basin.

The McFadden Formation and Tchukardine Formation are lithologically similar and consist of medium- to coarse-grained sandstone, conglomerate lenses and minor siltstone and shale. A prograding deltaic sequence of the McFadden Formation is a lateral equivalent of the shallow-marine shelf material of the Tchukardine Formation (Williams, 1992).

Durba Sandstone (sequence LP4B)

At present the Durba Sandstone is included in Supersequence LP4 (sequence LP4B), but this needs further investigation. This unit consists predominantly of sandstone, with minor claystone in Hussar 1. Sedimentary structures indicate that this formation was deposited in a fluvial, arid fan environment. The sandstone and claystone between 100 and 465m in Hussar 1 (Figs 1 and 3), previously interpreted as Lennis Sandstone and Wanna Formation, are now assigned to the 'Durba Sandstone'. Seismic interpretation and shallow mineral wells near Hussar 1 (Fig. 5B) show that this unit predates the Table Hill Volcanics (Perincek, 1996), therefore a relative age of middle Cambrian is assigned to the Durba Sandstone. The lower boundary with the McFadden Formation is an angular unconformity (Figs 6B and 6C).

The Durba Sandstone is the youngest unit in the Savory Sub-basin and consists of a clean quartz sandstone with minor basal conglomerate lenses unconformably overlying the McFadden and Boondawari Formations (Williams, 1992). The Durba Sandstone has been interpreted as a fluvial deposit in which palaeocurrents were directed to the north.

Palaeozoic

Sequence Pz1

Table Hill Volcanics

The Table Hill Volcanics consists of porphyritic and amygdaloidal tholeiitic basalts. Basal fluvial sandstones and a sandy, weathered interval between two distinct massive subaerial flows are also present (Phillips et al., 1985; Townson, 1985). This unit outcrops along the southwestern and northeastern margins of the western Officer Basin (Myers and Hocking, 1988). The basalt flows were previously named as the Officer Volcanics in the Western Australian section of the basin (Jackson and van de Graaff, 1981).

Widespread Cambrian basalts cap the prospective Upper Proterozoic to Lower Cambrian sequence in the Yowalga, Lennis, and Waigen Sub-basins and in the southern portion of Gibson Sub-basin (Figs 3, 5 and 6). Several northerly trending feeder dykes are present in the Savory Sub-basin and are here considered to be associated with the Middle Cambrian volcanism. However, owing to subsequent uplift and erosion, flows of the Table Hill Volcanics are absent in the Savory Sub-basin (except a local outcrop of possible Table Hill Volcanics in the northern part of the Poisonbush Range (Fig. 1 — Williams, I. R., 1996, pers. comm.) and most of the Gibson Sub-basin. This erosion occurred prior to deposition of the Paterson Formation as is evident in seismic (Perincek, 1996) and well (Dragoon 1, Hussar 1 and 89RCWA 011, 89RCWA 012) data (Figs 3 and 5B).

The Table Hill Volcanics has been dated as Early or Middle Cambrian (575 ± 40 Ma) (Townson, 1985) and correlated with the Kulyong Volcanics of South Australia and the Antrim Plateau Volcanics of northern Australia (Peers, 1968; Jackson and van de Graaff, 1981). The Kulyong Volcanics has yielded a radiometric date of 485 ± 20 Ma (Peers, 1968), and Moussavi–Harami and Gravestock (1995) have suggested a Middle to Late Cambrian age for the unit. However, the accuracy of both age determinations is questionable, in part due to resetting of crystal ages and uncertainties related to the geochronology. The outcrop of the Table Hill Volcanics in the geological map of the western Officer Basin extends into South Australia and is mapped as Kulyong Volcanics near the state border (Jackson and van de Graaff, 1981). The Wirrildar beds overlie the Upper Proterozoic Punkerri Sandstone and are unconformably overlain by the Lower Cambrian Kulyong Volcanics and Table Hill Volcanics. (Jackson and van de Graaff, 1981). Outcrop, geophysical and petrographic evidence confirm that the Kulyong Volcanics and Table Hill Volcanics constitute a single tholeiitic basalt suite (Townson, 1985). On the basis of seismic (Fig. 6) and stratigraphic correlation (Figs 3, 4 and 5) a Middle to Late Cambrian age is suggested for the Table Hill Volcanics.

Sequence Pz4

Lennis Sandstone, Wanna Formation

The Lennis Sandstone and Wanna Formation consist predominantly of sandstones (Fig. 4) as originally described by Jackson and van de Graaff (1981). These two units were deposited in a shallow-marine environment (Jackson and Muir, 1981).

On the basis of fission-track analysis a Devonian–Carboniferous age is assigned for the Lennis Sandstone (Green and Gleadow, 1984). This age determination is not constrained by fossil evidence: the Lennis Sandstone and Wanna Formation have not yielded any age-diagnostic fossils. Stratigraphically, the age of these units is constrained only by their position between Cambrian volcanics and Upper Carboniferous–Lower Permian sediments (Fig. 4). Correlation with the Cambro-Ordovician of South Australia is suggested without palaeontological support (Jackson and van de Graaff, 1981).

Generally, the Lennis Sandstone and Wanna Formation unconformably overlie the Table Hill Volcanics (Figs 4 and 5A), but these two sedimentary units are missing in the northwestern Officer Basin (Figs 4 and 5B).

Sequence Pz5

Paterson Formation

The Late Carboniferous to Early Permian glacial sediments of the Paterson Formation outcrop over extensive areas and have been identified in most of the wells drilled in the western Officer Basin (Figs 3, 4 and 5). The Paterson Formation consists of interbedded grey to red sandstones, claystone and minor tillite. Based on seismic data, the thickness of the Paterson Formation probably reaches at least 1200 m in the Yowalga Sub-basin (Townson, 1995). The unit has been deposited in a fluvioglacial to lacustrine environment in Western Australia, and a marine section is found in South Australia (Jackson and van de Graaff, 1981; Phillips et al., 1985). A connection between the Canning Basin and the Great Artesian Basin via the Officer Basin was established during the Early Permian (Fitzpatrick, 1966). The Browne and McFadden Formations and the Table Hill Volcanics are unconformably overlain by the Paterson Formation (Figs 3, 4, 5 and 6).

Post-Paterson Formation sedimentary rocks

The Samuel Formation, a thin Cretaceous unit, was deposited in the central and northwestern portion of the basin. This unit consists of interbedded marine sandstones and claystones. A thin sedimentary succession deposited during the Tertiary and Quaternary now forms most of the outcrops in the basin.

Tectonic elements

The structure of the basement appears to be controlled by faults which trend northeast, north, northwest and east-northeast to east. Northeast-trending faults have a right lateral strike-slip component and postdate the northwest-trending fault system (NKF in Fig. 1). The major north-trending fault is the post-Miocene Westwood Fault (WF in Fig. 1). The Warri Gravity Ridge is offset to the south by the northern extent of this fault zone. Several of the interpreted Table Hill Volcanics feeder dykes are also oriented north–south. It is postulated that the northeast- and north-trending fault systems are the products of a northeasterly oriented compressional regime. As a result of post-Cambrian movement along numerous north- and northeast-trending dextral faults in the region, including the northeasterly trending Billiluna Fault of the eastern Canning Basin (ECF in Fig. 1), the Musgrave Complex stepped farther to the south than the Rudall Complex (Perincek, 1996). This event probably initiated the extrusion of the Table Hill Volcanics along the north–south oriented feeder dykes. Geophysical interpretation in the southeastern corner of the Canning Basin has revealed that structural style in the area is consistent with a north–south dominated dextral strike-slip regime (Howell, 1984).

A northwest-trending normal fault (Salvation Fault in Fig. 1) on the northeastern margin of the Earaheedy Basin extends into the Officer Basin (NKF in Fig. 1). This trend is one of the most pronounced on aeromagnetic data. Initial movement on this fault had predated the Neoproterozoic and was later reactivated (Perincek, 1996). Activity of this fault ceased prior to deposition of the Paterson Formation (Fig. 5A). The downthrown block comprises a thick Upper Proterozoic section and the Lennis Formation. However the same section is considerably thinner on the upthrown Kingston Platform (Fig. 1).

Tectonic and structural evolution

Interpretation of the seismic data in the Officer Basin indicates at least nine periods of tectonic activity from the beginning of the Neoproterozoic to the end of the Cretaceous.

The Neoproterozoic–Palaeozoic movements include: 1) An unnamed minor event between LP1A and LP1B; 2) Areyonga Movement (Blake Movement); 3) Souths Range Movement; 4) Petermann Ranges Orogeny; 5) An unnamed minor event between LP4A and LP4B; 6) Delamerian Orogeny; 7) Rodingan Movement; 8) Alice Springs Orogeny.

Post-Permian and Miocene movements are also recorded in the sedimentary section of the Officer Basin.

These tectonic events and their relationship to the stratigraphy are discussed below and their time and stratigraphic position shown in Figure 2.

Sequence LP1A/LP1B tectonic event

The first event followed deposition of the Townsend Quartzite and Lefroy Formation. This minor event is marked by local erosion and an unconformity between the Jilyili and Spearhole Formations in the Savory Sub-basin, and between the Lefroy and Browne Formations in the western Officer Basin (Fig. 2).

Areyonga Movement

The Areyonga Movement between Supersequence LP1 and Supersequence LP2, comprised vertical movements which affected the western Officer Basin and resulted in extensive erosion prior to deposition of the Lupton Formation (Townson, 1985). This event is correlated with the Blake Movement (Williams, 1994) of the Savory Sub-basin (Hocking, 1994; Perincek, 1996).

Souths Range Movement

This third tectonic event is known from the Amadeus Basin. Extensive erosion and a missing section between the third event and the younger Petermann Ranges Orogeny, and the previous Areyonga Movement cause ambiguity in distinguishing the third event from others in the Officer Basin (Fig. 2). However, at this stage, this event in the basin is not detected from the available data.

Petermann Ranges Orogeny

The Petermann Ranges Orogeny disrupted and dismembered the Centralian Superbasin to form the Amadeus, Georgina, Ngalia and Officer Basins (Walter and Gorter, 1994). This compressional event, which separates Supersequences

LP3 and LP4, imparted a northwest-oriented structural grain and initiated thrusting and diapiric movements. The Petermann Ranges Orogeny (570–540 Ma), is the largest tectonic event in the structural evolution of the region.

Seismic sections from the Lennis and Yowalga Sub-basins show that Neoproterozoic, salt-assisted tectonic events resulted in thrusting and uplifting, leading to complex structural styles in the basin. The evidence suggests that this event terminated sedimentation in the Officer Basin by the end of the Neoproterozoic or early Cambrian. An extensive erosional phase was followed by accumulation of the McFadden Formation (previously Babbagoola Formation as defined *in* Perincek, 1996) and lateral equivalents (Sequence LP4A).

One of the thrust slices of Supersequence LP1 in the northern Savory Sub-basin has been named the Yeneena Group (Williams, 1992). Williams (1992) mapped this thrust belt, the Paterson Orogen, on the northeastern portion of the Savory Sub-basin as the surface extension of the fold belt that lies along the northeastern flanks of the Waigen–Yowalga–Gibson Sub-basins. The correlation of tectonic events and stratigraphic evidence suggests that the Petermann Ranges Orogeny and Paterson Orogeny are the same event (Hocking, 1994; Perincek, 1996). However, Myers (1990) suggested that tectonic activity of the Paterson Orogeny occured between 750 and 550 Ma. Williams (1994) proposed an age range of 620–540 Ma for the same orogeny. Myers (1990, 1993), Walter et al. (1994), Williams (1994) and Bagas et al. (1995) all suggested that the Paterson Orogeny appears to be synchronous with the Petermann Ranges Orogeny, for which ages of 550–530 Ma (Maboko et al., 1992) and 560–525 Ma (Camacho and Fanning, 1995) have been reported. Perincek (1996) suggested that the Petermann Ranges Orogeny is postdated by the Tchukardine, McFadden, Observatory Hill, and Narana Formations and the Relief Sandstone (Sequence LP4A), and is predated by the Boondawari, Lupton, Pertatataka, and Julie Formations and the Rodda, and Winnall Beds (Supersequence LP3). Townson (1985) suggested that the Table Hill Volcanics and Kulyong Volcanics of the Officer Basin, and the Antrim Plateau Basalts of the Northern Territory, are all products of the Petermann Ranges Orogeny.

Sequence LP4A/4B tectonic event

The fifth tectonic event is relatively minor and occurred between deposition of the McFadden Formation and Durba Sandstone equivalents (Fig. 2). Seismic lines (Fig. 6B, C) near Hussar 1 show an unconformity (Perincek, 1996) which is also evident in the well.

Delamerian Orogeny

The sixth orogenic event, the Delamerian Orogeny, followed deposition of Supersequence LP4 sediments and appears in seismic data northeast of Lennis 1 (Perincek, 1996).

Reactivation of diapiric movement and folding related to the Delamerian Orogeny followed deposition of the McFadden Formation and Durba Sandstone. Peneplanation was completed prior to the extrusion of the Table Hill Volcanics.

Rodingan Movement

No direct evidence of the seventh event, the Rodingan Movement (400 Ma), has been noted in the Officer Basin.

Alice Springs Orogeny

The Alice Springs Orogeny (Fig. 2) preceded deposition of the Paterson Formation and created folds in the underlying Table Hill Volcanics and Lennis Sandstone in the Yowalga and Lennis Sub-basins (Townson, 1985, fig. 7). The angular unconformity (290 Ma) between the Paterson Formation and underlying units (Perincek, 1996, fig. 7) resulted from this tectonic event. The geological map of the northern Savory Sub-basin (Williams, 1992) shows thrusting over the Tchukardine Formation caused by the same orogeny. The preferred interpretation of these observations is that they are both results of the Alice Springs Orogeny. However, because of the absence of the Lennis Sandstone in these areas, the age of this tectonism is not well constrained and therefore may be related to the Rodingan Movement. Structuring during the Alice Springs Orogeny (or perhaps during the Rodingan Movement) includes reactivation of diapiric movement within the Browne Formation that deformed the Table Hill Volcanics, as seen in Figure 6A.

Post-Permian movements

The ninth tectonic event caused reactivation of the salt-bearing Upper Proterozoic section. Salt movements subsequent to the Alice Springs orogeny have also deformed the Paterson Formation around the Woolnough Hills Diapir (Phillips et al., 1985) and periodically continued into the Mesozoic. Diapiric movement of evaporites began in the Precambrian, continued through the Permian, and caused tilting of Cretaceous rocks, as in the Browne Diapir (Fitzpatrick, 1966). Sedimentation was again interrupted by compressional tectonics possibly related to Late Triassic or Early Jurassic transpressional events in the Fitzroy Graben of the Canning Basin. After deposition of the Jurassic strata, rifting and eventual break-up resulted in an Early Cretaceous transgression in which epeiric seas invaded the Officer and Canning Basins. Fossil evidence indicates that the Canning, Officer, and Eucla Basins were interconnected by the widespread marine transgression during the Aptian (Fitzpatrick, 1966).

The latest phase of tectonism commenced in the Miocene and caused dextral movement along northeast- and north-trending faults in the Officer Basin

Conclusions

A study of the Neoproterozoic sediments and tectonic events within the Officer Basin has resulted in the following conclusions.

There are several formation names defined for the same stratigraphic unit within the western Officer Basin. These differences of nomenclature have been resolved in this paper so that work towards a unified stratigraphy will be more coordinated. Nomenclature proposed in this paper (Fig. 2) should provide a sound basis for future study.

Supersequence LP1 is modified and sub-divided into two sequences. Sequence LP1A includes the Townsend Quartzite, the Heavitree Quartzite, and the Lefroy, and Pindyin Formations. Sequence LP1B includes the Spearhole, Browne, Skates Hills, Hussar, Kanpa, and Steptoe Formations.

The McFadden and Tchukardine Formations postdate the Petermann Ranges Orogeny. These formations and the Durba Sandstone are considered to lie within Supersequence LP4, but the Table Hill Volcanics is excluded from Supersequence LP4 and included in Sequence Pz1.

In the Officer Basin at least nine periods of tectonic activity may be interpreted from existing data. The Areyonga Movement (Blake Movement), Petermann Ranges Orogeny, Delamerian Orogeny, Alice Springs Orogeny, post-Permian and Miocene movements are the major events affecting and recorded in the sedimentary section of the basin.

The Table Hill Volcanics has been removed from the Gibson Sub-basin by subsequent uplift and erosion caused by the Alice Springs Orogeny, or perhaps by the Rodingan Movement, prior to deposition of the Paterson Formation.

The Musgrave Complex stepped farther south in relation to the Rudall Complex, with accommodation along numerous north- and northeast-trending faults. Initial movement of this system probably started as early as the Cambrian and was repeatedly reactivated till post-Miocene.

References

BAGAS, L., GREY, K., and WILLIAMS, I. R., 1995, Reappraisal of the Paterson Orogen and Savory Basin. Western Australia: Western Australia Geological Survey, Annual Review 1994–95, p. 55–63.

CAMACHO, A., and FANNING, C. M., 1995, Some isotopic constraints on the evolution of the granulite and upper amphibolite facies terranes in the eastern Musgrave Block, central Australia: Precambrian Research, v. 71, p. 155–181.

COCKBAIN, A .E., and HOCKING, R .M., 1989, Revised stratigraphic nomenclature in Western Australian Phanerozoic basins: Western Australia Geological Survey, Record 1989/15.

FITZPATRICK, B., 1966, Officer Basin summary, Exoil Pty Ltd: Western Australia Geological Survey, S-series Open File, Item S24 A1 (unpublished).

GRAVESTOCK, D. I., and LINDSAY, J. F., 1994, Summary of 1993 seismic exploration in the Officer Basin, South Australia: PESA Journal, v. 22, p. 65–75.

GREEN, P. F., and GLEADOW, A. J. W., 1984, Fission track analysis of samples from Kanpa 1A and Yowalga 3, Officer Basin. Geotrack Report No. 14 November 1984, prepared for Shell Development (Australia) Pty Ltd University of Melbourne (unpublished).

GREY, K., and COTTER, K., 1996, Palynology in the search for Proterozoic hydrocarbons: Western Australia Geological Survey, Annual Review for 1995–96 p. 70–80.

GREY, K., 1995, Neoproterozoic stromatolites from the Skates Hills formation, Savory Basin, Western Australia, and a review of the distribution of *Acaciella australica*: Australian Journal of Earth Sciences, v. 42, p. 123–132.

HOCKING, R. M., 1994, Subdivisions of Western Australian Neoproterozoic and Phanerozoic sedimentary basins: Western Australia Geological Survey, Record 1994/4, 83p.

HOWELL, E. A., 1984, Petroleum geology of EP's 205 & 252, South Canning Basin, *in* The Canning Basin Western Australia *edited by* P. G. PURCELL: Proceedings of GSA/PESA Canning Basin Symposium, Perth, 1984, p. 148–154.

IASKY, R. P., 1990, Officer Basin, *in* Geology and mineral resources of Western Australia: Western Australian Geological Survey, Memoir 3, p. 362–380.

JACKSON, P. R., 1966, Geology and review of exploration, Officer Basin, Western Australia, Hunt Oil Company Report (unpublished): Western Australia Geological Survey, S-series Open File, Item S26 A1, 91 p (unpublished).

JACKSON, M. J., and MUIR, M. D., 1981, The Babbagoola Beds, Officer Basin, Western Australia: Correlations, micropalaeontology and implications for petroleum prospectivity: BMR Journal of Australian Geology and Geophysics. v. 6, p. 81–93.

JACKSON, M. J., and van de GRAAFF, W. J. E., 1981, Geology of the Officer Basin, Western Australia: Australia Bureau of Mineral Resources, Geology and Geophysics, Bulletin 206.

MABOKO, M. H., McDOUGALL, I., ZEITLER, P. K., and WILLIAMS, I. S., 1992, Geochronological evidence for ~520–550 Ma juxtaposition of two Proterozoic metamorphic terranes in the Musgrave Ranges, central Australia: Australian Journal of Earth Sciences, v. 39, p. 457–471.

MOUSSAVI–HARAMI, R., and GRAVESTOCK, D. I., 1995, Burial history of the eastern Officer Basin, South Australia. APEA Journal, v. 35, p. 307–320.

MYERS, J. S., and HOCKING, R. M., 1988, Geological Map of Western Australia, 1: 2 500 000: Western Australia Geological Survey.

MYERS, J. S., 1990, Precambrian tectonic evolution of part of Gondwana, southwestern Australia: Geology, v. 18, p. 537–540.

MYERS, J. S., 1993, Precambrian history of the west Australian Craton and adjacent orogens: Annual Review of Earth and Planetary Sciences, v. 21, p. 453–485.

PEERS, R., 1968, A comparison of some volcanic rocks of uncertain age in the Warburton Range area: Western Australia Geological Survey, Annual Report 1968, p. 57–61.

PERINCEK, D. P., 1996, The age of Neoproterozoic–Palaeozoic sediments within the Officer Basin of the Centralian Super-Basin can be constrained by major sequence-bounding unconformities: APPEA Journal, v. 36, p. 350–368.

PHILLIPS, B. J., JAMES, A. W., and PHILIP, G. M., 1985, The geology and hydrocarbon potential of the northwestern Officer Basin: APEA Journal v. 25 (1), p. 52–61.

SHAW, R. D., ETHERIDGE, M. A., and LAMBECK K., 1991, Development of the Late Proterozoic to Mid-Palaeozoic, intracratonic Amadeus Basin in central Australia: A key to understanding tectonic forces in plate interiors: Tectonics, v. 10 (4), p. 688–721.

TOWNSON, W. G., 1985, The subsurface geology of the western Officer Basin — results of Shell's 1980–1984 petroleum exploration campaign. The APEA Journal, v. 25 (1), p. 34–51.

WALTER, M. R., and GORTER, J., 1994, The Neoproterozoic Centralian Superbasin in Western Australia, the Savory and Officer Basins, *in* The sedimentary basins of Western Australia *edited by* P.G. and R.R. PURCELL: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1994, p. 851–864.

WALTER, M. R., GREY, K., WILLIAMS, I. R., and CALVER, C. R., 1994, Stratigraphy of the Neoproterozoic to early Palaeozoic Savory Basin and correlation with the Amadeus and Officer Basins. Australian Journal of Earth Sciences, v. 41, p. 533–546

WALTER, M. R., VEEVERS, J. J., CALVER, C. R., and GREY, K., 1995, Neoproterozoic stratigraphy of the Centralian Superbasin, Australia. Precambrian Research, v. 73, p. 173–195.

WILLIAMS, I. R., 1992, Geology of the Savory Basin, Western Australia. Western Australia Geological Survey, Bulletin 141, 115p.

WILLIAMS, I. R., 1994, The Neoproterozoic Savory Basin, Western Australia, *in* The sedimentary basins of Western Australia *edited by* P.G. and R.R. PURCELL: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1994, p. 841–850.

Phase separation (boiling) as a mechanism for deposition of gold in low-iron host rocks, Yarri mining district, Eastern Goldfields Province

by W. K. Witt

Abstract

Gold mineralization in the Yarri and Porphyry mining centres of the Yilgarn Craton is associated with hematitization of granitoid and andesitic host rocks. The low iron content of the granitoid and andesites suggests that a depositional mechanism involving reaction of sulfur in the hydrothermal fluids with iron in the host rocks is inappropriate. An alternative depositional model involving phase separation, accompanied by oxidation of the hydrothermal fluid and destabilization of gold bisulfide complexes, is proposed for the deposits at the Yarri and Porphyry mining centres.

KEYWORDS: Archaean, Yilgarn Craton, Eastern Goldfields Province, Yarri mining area, gold, hydrothermal alteration, phase separation

Alteration assemblages associated with Western Australian, Archaean lode-gold (mesothermal) deposits can be divided into two groups characterized by different fluid fO_2 conditions (Mikucki and Ridley, 1993; Witt, 1993). Most mafic-hosted deposits are zoned from a magnetite-bearing metamorphic assemblage through an outer metasomatic zone in which pyrrhotite is stable to an inner, mineralized, pyritic zone. This zoned sequence of opaque Fe minerals suggests fluid fO_2 conditions on or close to the CO_2/CH_4 buffer, a conclusion supported by the widespread presence of CH_4 and CO_2 in associated fluid inclusions (Ho et al., 1990; Mernagh and Witt, 1994). A second, less common group of mafic-hosted deposits is characterized by mineralized alteration assemblages in which hematite and pyrite are stable. Fluids responsible for these deposits had fO_2 at or close to the $H_2S/\Sigma SO_4^{2-}$ buffer. The origin of these relatively oxidized fluids is contentious. Mikucki and Groves (1990) review some of the models which variously derive these oxidized fluids from specific, oxidized sources or by local processes at or near the site of gold deposition.

Gold deposits with strongly oxidized wallrock alteration assemblages are common in the Porphyry area of the Yarri mining district (Fig. 1). The main host rocks are andesite, quartz monzonite and monzogranite. Table 1 shows that these host rocks have low iron contents compared with those of the fractionated tholeiites (dolerite and basalt) and banded iron-formation, which are preferred host rocks elsewhere in the Yilgarn Craton (Groves et al., 1990; Witt, 1993). It is generally believed that iron in the latter group of rocks reacts with gold bisulfide complexes in hydrothermal fluids to deposit pyrite and gold (Phillips and Groves, 1983).

e. g.

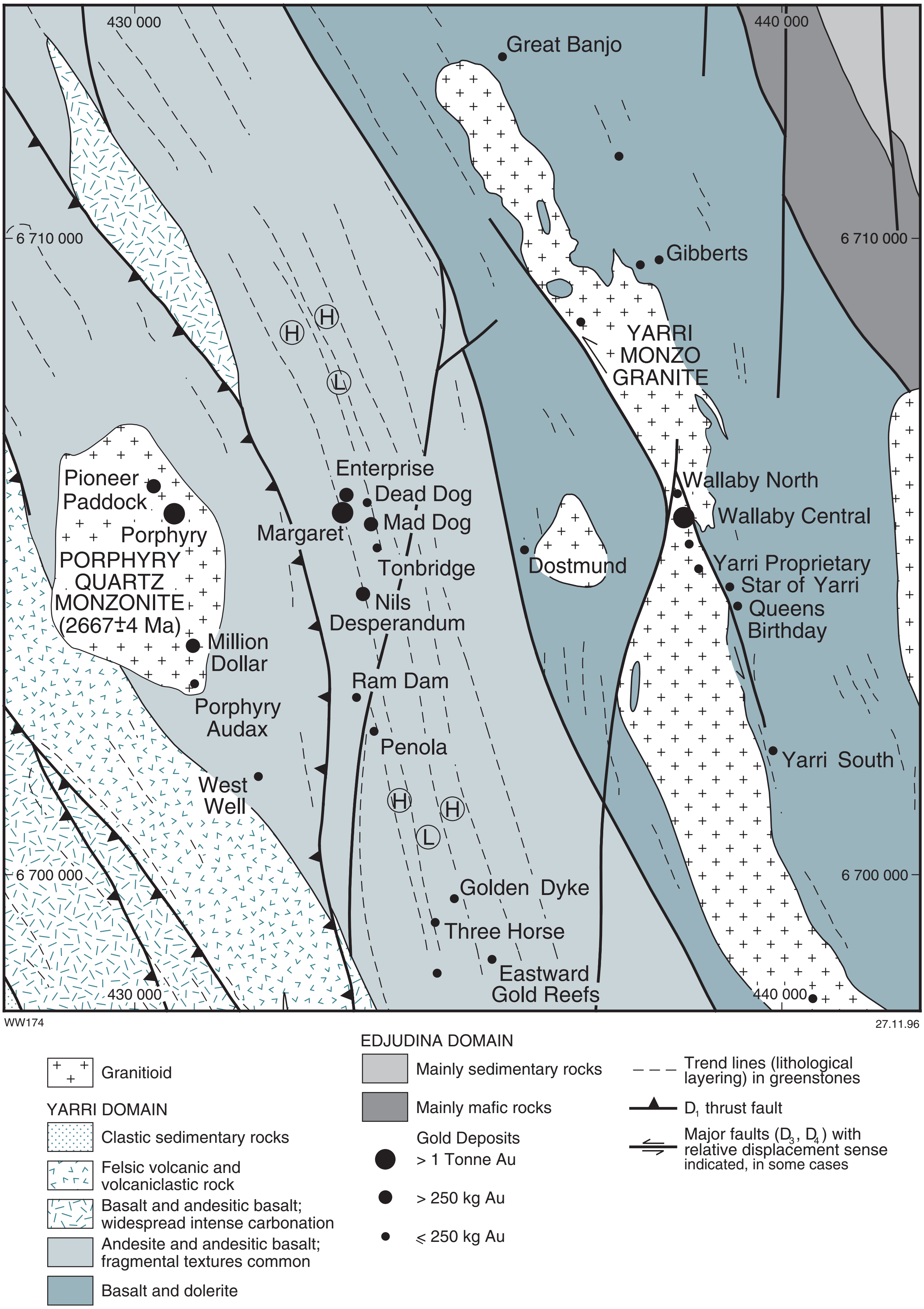
$$Au(HS)_2^- + Fe^{2+} \rightarrow FeS_2 + Au + 2H^+ + e^-$$

There is less agreement about depositional mechanisms in relatively low-Fe rocks. The association between oxidized wallrock assemblages and mineralization in relatively low-Fe host rocks in the Yarri mining district provides an opportunity to examine the role of changes in fO_2 and phase separation as triggers for gold deposition.

Gold deposits in the Yarri mining district

Most gold deposits in the Yarri mining district are found in two main centres (Fig. 1). The Yarri Monzogranite has produced about 460 kg of gold, mainly from the Wallaby Central and Yarri Proprietary mines. Mineralized shear zones in monzogranite are pyritic quartz–muscovite schist with locally abundant hematite and epidote. The second centre of mineralization is at Porphyry. Gold occurs along the eastern margin of the Porphyry Quartz Monzonite and in andesitic rocks to the east of the intrusion (Fig. 1). The Porphyry deposit has produced about 4 tonnes of gold. Unmined resources of 1035 kg and 274 kg of gold have been measured at Margaret and Enterprise respectively. Mineralized rocks in all deposits are characterized by abundant hematite and pyrite.

Most andesite-hosted deposits, including Margaret, occur in two north-trending shear zones. Within the shear zones, metamorphic assemblages (plagioclase–



430 000
440 000
6 710 000
6 700 000
Great Banjo
Gibberts
YARRI MONZO GRANITE
Wallaby North
Wallaby Central
Yarri Proprietary
Star of Yarri
Queens Birthday
Yarri South
Dostmund
Enterprise
Dead Dog
Mad Dog
Margaret
Tonbridge
Nils
Desperandum
Ram Dam
Penola
Golden Dyke
Three Horse
Eastward Gold Reefs
Pioneer Paddock
Porphyry
PORPHYRY QUARTZ MONZONITE (2667±4 Ma)
Million Dollar
Porphyry Audax
West Well
H
L
WW174
27.11.96
Granitoid
YARRI DOMAIN
Clastic sedimentary rocks
Felsic volcanic and volcaniclastic rock
Basalt and andesitic basalt; widespread intense carbonation
Andesite and andesitic basalt; fragmental textures common
Basalt and dolerite
EDJUDINA DOMAIN
Mainly sedimentary rocks
Mainly mafic rocks
Gold Deposits
> 1 Tonne Au
> 250 kg Au
≤ 250 kg Au
Trend lines (lithological layering) in greenstones
D1 thrust fault
Major faults (D3, D4) with relative displacement sense indicated, in some cases

Table 1. Major element chemistry of some host rocks to gold mineralization in the Eastern Goldfields Province

	1	*2*	*3*	*4*	*5*	*6*
SiO_2	55.2	50.0	54.5	57.5	66.4	74.1
TiO_2	2.1	1.4	1.0	0.9	0.4	0.12
Al_2O_3	10.1	13.7	14.9	15.4	16.0	13.5
Fe_2O_3	5.6	3.6	3.3	8.7	3.0	0.64
FeO	12.2	10.7	4.8	-	-	1.05
MnO	0.3	0.3	0.1	0.1	0.0	<0.05
MgO	2.6	3.8	3.8	4.8	0.8	0.31
CaO	5.7	11.8	8.3	10.3	2.3	1.87
Na_2O	3.0	2.7	2.5	1.7	3.9	4.37
K_2O	0.1	0.3	0.4	0.5	3.6	2.79
P_2O_5	0.2	0.1	0.1	0.2	0.2	<0.05
LOI	2.3	1.7	6.9	1.7	1.9	0.94
FeO*/MgO	6.63	3.67	2.04	1.81	1.30	3.96

Notes: FeO^* is total iron = ($FeO + 0.9\ Fe_2O_3$)
1. Unit 8B, Kambalda domain, Golden Mile Dolerite (Travis et al., 1971)
2. Missouri Basalt (GSWA 89969), Ora Banda domain, Kalgoorlie Terrane (Morris et al., 1991)
3. Meta-andesite, carbonated (GSWA 110726), Yarri mining district (Swager, 1995)
4. Meta-andesite, Porphyry mine area (Allen, 1987)
5. Unmineralized Porphyry Quartz Monzonite, Porphyry mine area (Allen, 1987)
6. Unmineralized Yarri Monzogranite (GSWA 115536), Byer Well (Smithies, R. H., 1996, pers. comm.)

amphibole–biotite) have been converted to quartz–plagioclase–chlorite–calcite schist with variable amounts of muscovite and accessory titanite. A striking feature of this schist is the presence of up to 5% subhedral to euhedral porphyroblasts (≤2 mm) of magnetite. Gold is associated with late, steep, commonly sheeted veins that are oriented approximately northwest. Albite in the pyritic albite–ankerite–quartz veins is stained pink with finely disseminated hematite. Pink (hematitic), pyritic alteration selvages are dominated by albite ± ankerite. The Enterprise deposit is a gently plunging array of brittle quartz veining that formed in the lower-strain domain between the two mineralized shear zones. However, in the lower part of diamond drillhole G-94-2, the orebody intersects the western shear zone. Quartz veins and related alteration assemblages (similar to those described above) overprint ductile fabrics and quartz–plagioclase–chlorite–calcite assemblages in the shear zone (Fig. 2). Magnetite is unstable in zones of intense hematite–albite alteration and displays evidence of replacement by pyrite at the margins of intense alteration domains (Fig. 2). Mineral assemblages in unaltered metamorphosed andesite, sheared, carbonated andesite and mineralized andesite are summarized in Table 2.

Figure 1. Map of the Yarri mining district showing location of gold deposits

Fluids

Alteration assemblages at Enterprise allow two distinct hydrothermal fluids to be distinguished. Quartz–plagioclase–chlorite–calcite schist within shear zones contains magnetite and, locally, minor pyrite. The presence of both magnetite and pyrite suggests a relatively low aΣS fluid (Fig. 3). This fluid had a low gold bisulfide-carrying capacity (Fig.3) and the schists are unmineralized.

The second fluid, the ore fluid, was in equilibrium with hematite and pyrite at the time of gold deposition. It was relatively S-rich and more oxidized (Figs 3, 4). This fluid may also have been more acidic but the predominance of albite (and paucity of muscovite) in the veins and alteration selvages imposes a lower pH limit (approximately 5.5). This fluid would also have had a limited gold bisulfide-carrying capacity (Fig. 3).

The ore fluid (hematite–pyrite) cannot have been derived from the earlier carbonating, shear zone fluid (magnetite ± pyrite; field 1 in Fig. 3) unless aΣS was increased. There is no readily apparent mechanism for doing this.

Depositional mechanisms

Mineralization at Enterprise and other andesite-hosted deposits of the Yarri mining district is clearly associated with oxidation of magnetite-bearing wallrocks. A similar reaction has been documented at several deposits in the Tennant Creek district, Northern Territory. Gold would have been transported as chloride complexes in the relatively saline fluids (20 wt% equivalent) at Tennant Creek, and Huston et al. (1993) interpreted gold deposition to have resulted from reduction of oxidized fluids (Fig. 4). This mechanism is inappropriate for Archaean mesothermal deposits where gold was transported as bisulfide complexes in low-salinity fluids (Seward, 1984). In this case, reduction of oxidized fluids will increase the solubility of gold (Fig. 4). Therefore other mechanisms for gold deposition must be sought.

Carbonation of wallrocks may acidify the oxidized hydrothermal fluid. A lowering of pH along the pyrite–hematite equilibrium curve will decrease gold solubility but the solubility curves are widely spaced (Fig. 4) making this mechanism inefficient at concentrating gold. Furthermore, there is relatively little carbonation associated with the mineralizing fluids and the pH is constrained to a relatively small range by the magnetite–hematite–pyrite triple point and the albite–muscovite equilibrium (pH ≈ 5–5.5, slightly lower than the K-feldspar–muscovite equilibrium shown in Figure 4).

A more effective gold depositional mechanism is the lowering of aΣS in the fluid, thereby destabilizing $Au(HS)_2^-$ complexes (Fig. 3). These processes may be initiated by (i) reaction of gold bisulfide complexes with iron in the wallrocks to precipitate gold and pyrite, (ii) mixing with a relatively S-depleted fluid, or (iii) phase separation (boiling). It is not yet possible to choose between these three possibilities. However, phase

Table 2. Metamorphic and metasomatic assemblages in andesitic rocks, Enterprise deposit, Porphyry area

Metamorphism	*Ductile deformation*		*Brittle deformation*
Metamorphic assemblage	*Moderate deformation/ metasomatism*	*Intense deformation/ metasomatism*	*Late vein-realted alteration*
Plagioclase	**Plagioclase**	**Quartz**	**Albite**
Amphibole	**Chlorite**	**Carbonate**	**hematite**
Biotite	**Calcite**	**Muscovite**	**Ankerite**
Ilmenite	**Quartz**	Magnetite	**Muscovite**
	Muscovite	Titanite	Rutile
	Magnetite	Pyrite	Pyrite
	Titanite		Chalcopyrite

Note: Major mineral components are shown in **bold**
Minor mineral components are shown in plain

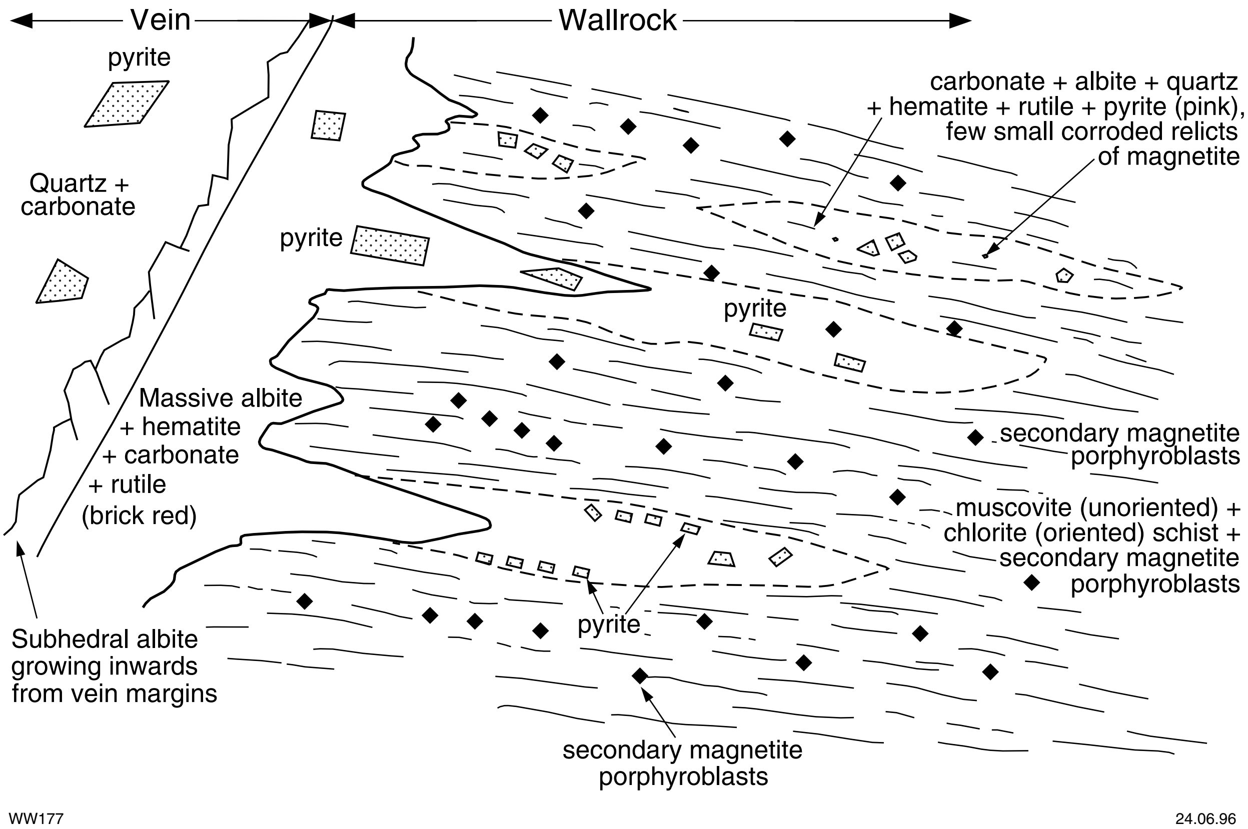


Figure 2. Sketch of microtextural and microstructural relationships in GSWA 130684 from diamond drillhole G-94-2, Enterprise deposit

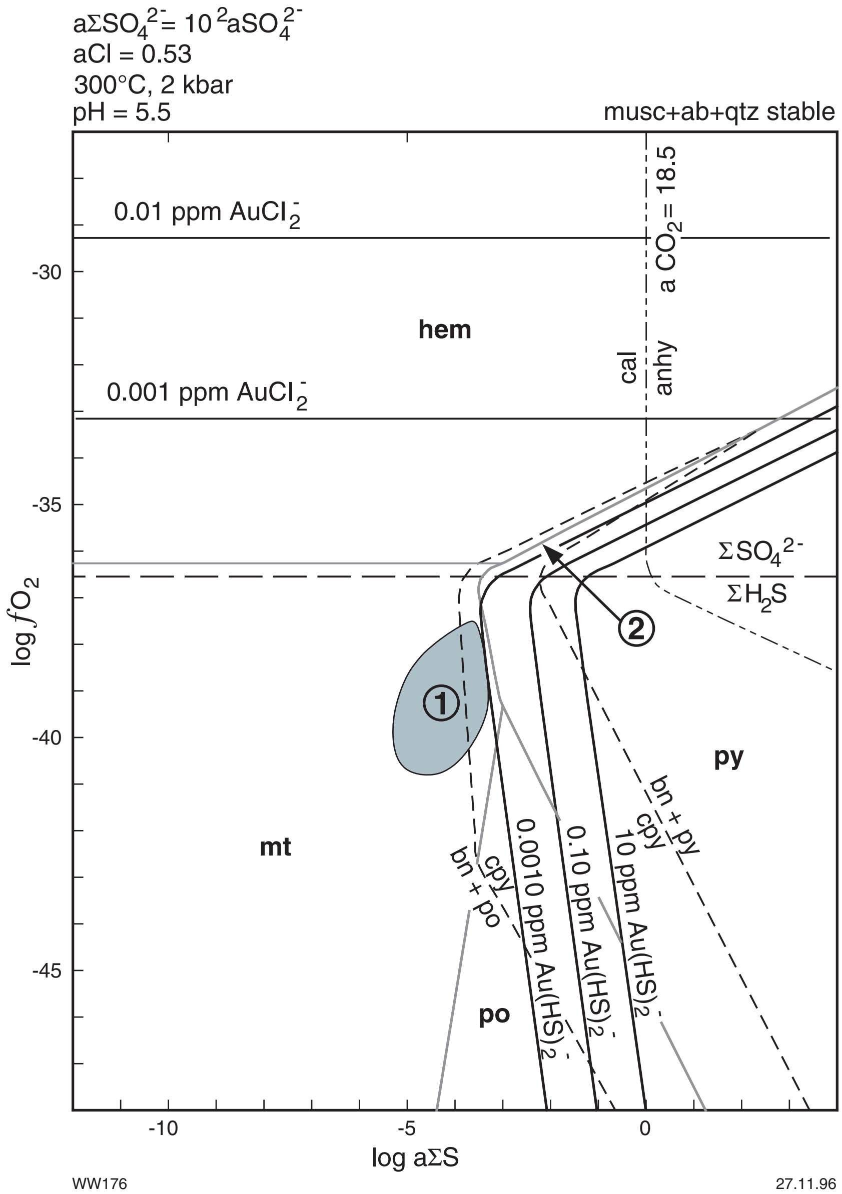


Figure 3. Fe–S–O relations as a function of fO_2 and aΣS showing solubility contours for gold as i) chlorite complexes and ii) bisulfide complexes (from *Mikucki and Groves, 1990). Field 1 shows the approximate location of the hydrothermal fluid responsible for carbonation of andesites in shear zones. Arrow marked 2 shows hypothetical path of the ore fluid at Enterprise following phase separation (boiling)*

separation and fluid mixing are especially attractive precipitation mechanisms because they do not require Fe-rich host rocks.

During phase separation, reduced species such as H_2S, CH_4 and H_2 are preferentially partitioned into the vapour phase, leaving a relatively oxidized fluid (Drummond and Ohmoto, 1985). The change in aΣS and fO_2 attendant upon phase separation may have shifted the hydrothermal fluid from the pyrite stability field to the pyrite–hematite equilibrium curve (Figs 3, 4). These changes will be accompanied by a rapid decrease in the solubility of gold. The decrease in gold solubility owes more to decreasing aΣS than to increased fO_2 because the steep solubility gradient in Figure 4 lies within the hematite-only stability field, whereas fluid conditions at Enterprise are constrained by the hematite–pyrite equilibrium curve. Nevertheless, in the wider context, widespread and intense hematitization of wallrocks may record a phase separation event in hydrothermal fluids with implications for gold deposition.

Allen (1987) suggested that gold deposition in quartz monzonite at Porphyry was related to fluid/wallrock reaction with Fe/Fe+Mg of the host rock being more important than total iron. This

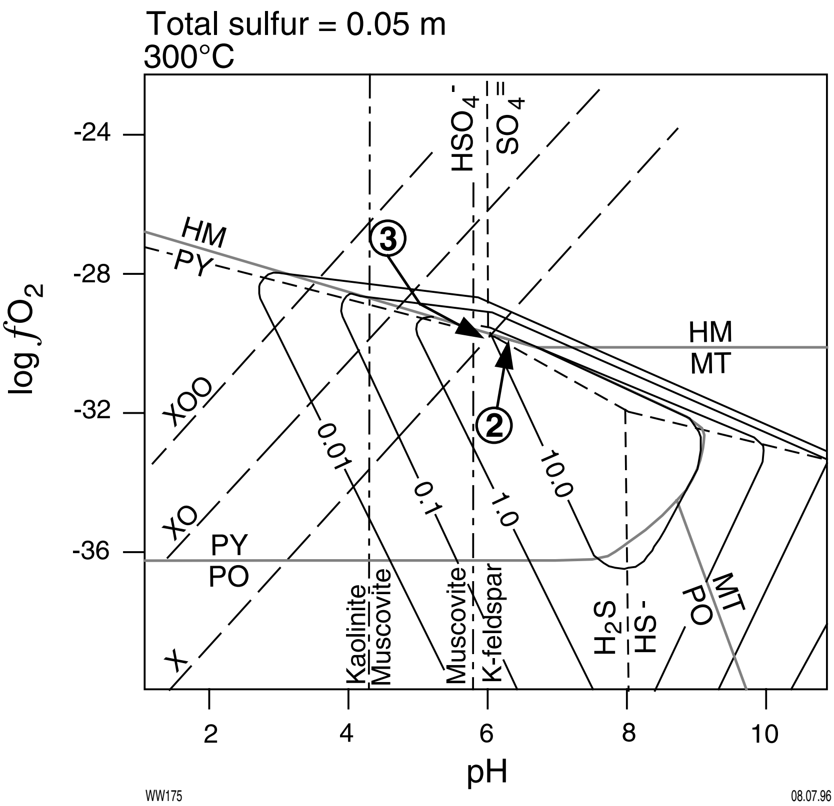


Figure 4. Fe–S–O relations as a function of fO_2 and pH showing solubility contours (solid lines marked 0.01, 0.1, 1.0 and 10.0 ppm Au) for gold bisulfide complexes **(from** *Roberts (1988)). Gold chloride complex solubility contours (dashed lines marked X00, X0 and X are approximate only and in ppb Au) are taken* **from** *Huston et al., 1993). Arrow 2 as above; arrow 3 is the evolutionary path for hydrothermal fluids at Tennant Creek (Huston et al., 1993)*

argument presumes that carbonate will compete with sulfur for iron in rocks with low Fe/Fe+Mg (Bohlke, 1988). However, carbonate addition to the host rocks is very limited at both Porphyry and Enterprise. Furthermore, FeO*/MgO ratios for mineralized units shown in Table 1 are not uniformly high. Therefore, other gold depositional mechanisms such as phase separation should be considered.

The consistent and widespread association of gold mineralization with oxidized vein and alteration assemblages in the Yarri mining district suggests a common hydrothermal fluid and depositional mechanism. Thus, phase separation may be more widely applicable as an effective mechanism for gold deposition in felsic granitoid as well as andesitic host rocks, neither of which have high iron contents.

Conclusions

Wallrock oxidation and sulfidation of low- to moderate-iron host rocks is a characteristic feature of most gold deposits in the Yarri mining district. Gold deposition occurred in response to a decrease in aΣS of the hydrothermal fluid, possibly accompanied by an increase in fO_2. These changes in fluid chemistry could be induced by phase separation which might be a more generally applicable mechanism for gold deposition in low-iron host rocks. Fluid inclusion studies are required to confirm the role of phase separation as a trigger for gold deposition in the Yarri mining district.

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References

ALLEN, C. A., 1987, The nature and origin of the Porphyry gold deposit, Western Australia, *in* Recent advances in understanding Precambrian gold deposits *edited by* S. E. HO and D. I. GROVES: Geology Department and University Extension, University of Western Australia, Publication 11, p. 137–145.

BOHLKE, J. K., 1988, Carbonate–sulphide equilibria and 'stratabound' disseminated epigenetic gold mineralization: a proposal based on examples from Alleghany, California, U.S.A.: Applied Geochemistry, v. 3, p. 499–516.

DRUMMOND, S. E., and OHMOTO, H., 1985, Chemical evolution and mineral deposition in boiling hydrothermal systems: Economic Geology, v. 80, p. 126–147.

* (FeO) = (FeO + 0.9 Fe_2O_3)

GROVES, D. I., KNOX-ROBINSON, C. M., HO, S. E., and ROCK, N. M. S., 1990, An overview of Archaean lode-gold deposits, *in* Gold deposits of the Archaean Yilgarn Block, Western Australia: nature, genesis and exploration guides *edited by* S. E. HO, D. I. GROVES, and J. M. BENNETT: Geology Department (Key Centre) and University Extension, University of Western Australia, Publication 20, p. 2–18.

HO, S. E., BENNETT, J. M., CASSIDY, K. F., HRONSKY, J. M. A., MIKUCKI, E. J., and SANG, J. H., 1990, Fluid inclusion studies, *in* Gold deposits of the Archaean Yilgarn Block, Western Australia: nature, genesis and exploration guides *edited by* S. E. HO, D. I. GROVES, and J. M. BENNETT: Geology Department (Key Centre) and University Extension, University of Western Australia, Publication 20, p. 198–211.

HUSTON, D. L., BOLGER, C., and COZENS, G., 1993, Comparison of mineral deposits at the Gecko and White Devil deposits: implications for ore genesis in the Tennant Creek District, Northern Territory, Australia: Economic Geology, v. 88, p. 1178–1225.

MERNAGH, T. P., and WITT, W. K., 1994, Early, methane-rich fluids and their role in Archaean gold mineralisation at the Sand King and Missouri deposits, Eastern Goldfields Province, Western Australia: AGSO Journal of Australian Geology and Geophysics, v. 15, p. 297–312.

MIKUCKI, E. J., and GROVES, D. I., 1990, Mineralogical constraints, *in* Gold deposits of the Archaean Yilgarn Block, Western Australia: nature, genesis and exploration guides *edited by* S. E. HO, D. I. GROVES, and J. M. BENNETT: Geology Department (Key Centre) and University Extension, University of Western Australia, Publication 20, p. 212–220.

MIKUCKI, E. J., and RIDLEY, J. R., 1993, The hydrothermal fluid of Archaean lode-gold deposits at different metamorphic grades: compositional constraints from ore and wallrock assemblages: Mineralium Deposita, v. 28, p. 469–481.

MORRIS, P. A., PESCUD, L., THOMAS, A., GAMBLE, J., TOVEY, E., and MARSH, N., 1991, Major element oxide, trace and rare earth element concentrations in Archaean mafic and ultramafic volcanic rocks from the Eastern Yilgarn Craton, Western Australia: Western Australia Geological Survey, Record 1991/8, 78p.

PHILLIPS, G. N., and GROVES, D. I., 1983. The nature of Archaean gold-bearing fluids as deduced from the gold deposits of Western Australia: Australian Journal of Earth Sciences, v. 30, p. 25–39.

ROBERTS, R. G., 1988, Ore deposits #11. Archean lode gold deposits: Geoscience Canada, v. 14, p. 37–52.

SEWARD, T. M., 1984, The transport and deposition of gold in hydrothermal systems, *in* Gold '82: the geology, geochemistry and genesis of gold deposits *edited by* R. P. FOSTER, Rotterdam, A. A. Balkema, p. 165–182.

SWAGER, C. P., 1995, Geology of the Edjudina and Yabboo 1:100 000 sheets: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes, 34p.

TRAVIS, G. A., WOODALL, R., and BARTRAM, G. D., 1971, The geology of the Kalgoorlie goldfield: Geological Society of Australia, Special Publication 3, p. 175–190.

WITT, W. K., 1993, Gold mineralization in the Menzies–Kambalda region, Eastern Goldfields, Western Australia: Western Australia Geological Survey, Report 39, 165p.

Mesoproterozoic and Phanerozoic sedimentary basins in the northern Halls Creek Orogen: constraints on the timing of strike-slip movement on the Halls Creek Fault system

by A. M. Thorne and I. M. Tyler

Abstract

Fault patterns in the northeastern Halls Creek Orogen reflect large-scale (~90 km displacement) sinistral wrench faulting. Previous interpretations suggest much of this movement was coeval with deposition of the Mesoproterozoic Carr Boyd Group. This view is not supported by recent mapping, which shows that details of Carr Boyd Group sedimentation and stratigraphy are inconsistent with deposition in a strike-slip setting. Instead, most of the post-Palaeoproterozoic sinistral faulting occurred after deposition of the Carr Boyd Group, the principal movements having occurred in the post-Duerdin Group – pre-Antrim Plateau Volcanics interval, and also during the late Palaeozoic. The latter event has exerted a major influence on the development of upper Devonian (Frasnian) sedimentary basins in the northern Halls Creek Orogen.

KEYWORDS: Halls Creek Orogen, Carr Boyd Group, strike-slip faulting, Devonian sedimentary basins

Fault patterns in the northeastern Halls Creek Orogen (Fig. 1) are consistent with large-scale sinistral wrench faulting. The northeast-trending Dunham–Ivanhoe Fault system in the west and the Halls Creek Fault in the east are first-order faults linked by synthetic second-order structures, including the Carr Boyd, Glenhill, and Revolver Creek Faults. A complex network of smaller scale (third-order) faults, including synthetic and antithetic strike-slip shears, and both normal and reverse faults, occur between the main structures.

Attempts to determine the amount and timing of sinistral strike-slip movement along the Halls Creek Fault have been hampered by the paucity of suitable markers that can be matched on either side of this structure. Tyler et al. (1995) calculated a sinistral displacement of 90 km on the Halls Creek Fault, based on the offset of the Angelo and Osmond Faults. Support for this estimate comes from the recognition of similar magmatic-hydrothermal alteration associated with the McHale Granodiorite northwest of the Osmand Range and in the Angelo Granite south of Halls Creek (Witt and Sanders, 1996). Plumb et al. (1985) estimated the total accumulative left-lateral displacement of all faults in the Halls Creek System as approximately 200 km, although the details of how this value was obtained were not given.

Plumb et al. (1985) interpreted the Carr Boyd Group as having been deposited during a protracted period of strike-slip faulting in the Mesoproterozoic. This interpretation has been taken to represent a major constraint on the timing of tectonism in the Halls Creek Orogen (Tyler and Griffin, 1994). Here we discuss the timing of strike-slip faulting in the Halls Creek Orogen in the light of new information obtained during remapping of the LISSADELL* 1:250 000 map sheet.

Carr Boyd Group

The Mesoproterozoic Carr Boyd Group is exposed in the Carr Boyd and Pincombe Ranges in the northeastern part of the Halls Creek Orogen (Fig. 1)., and was first described by Dow et al. (1964), Dow and Gemuts (1969), Plumb (1968), Plumb and Veevers (1971), and Plumb and Gemuts (1976). The group unconformably overlies Palaeoproterozoic metasedimentary and igneous rocks of the Lamboo Complex and Kimberley Basin, and is in turn overlain unconformably by Neoproterozoic glacial deposits of the Duerdin Group. The Carr Boyd Group has been subject to very low-grade metamorphism.

No single complete section of the Carr Boyd Group is known because it has been disrupted extensively by faulting. However, six formations which together total ~4.4 km in thickness are recognized. These are (in ascending order): Hensman Sandstone, Golden Gate Siltstone, Lissadell Formation, Glenhill

* Capitalized names refer to standard map sheets.

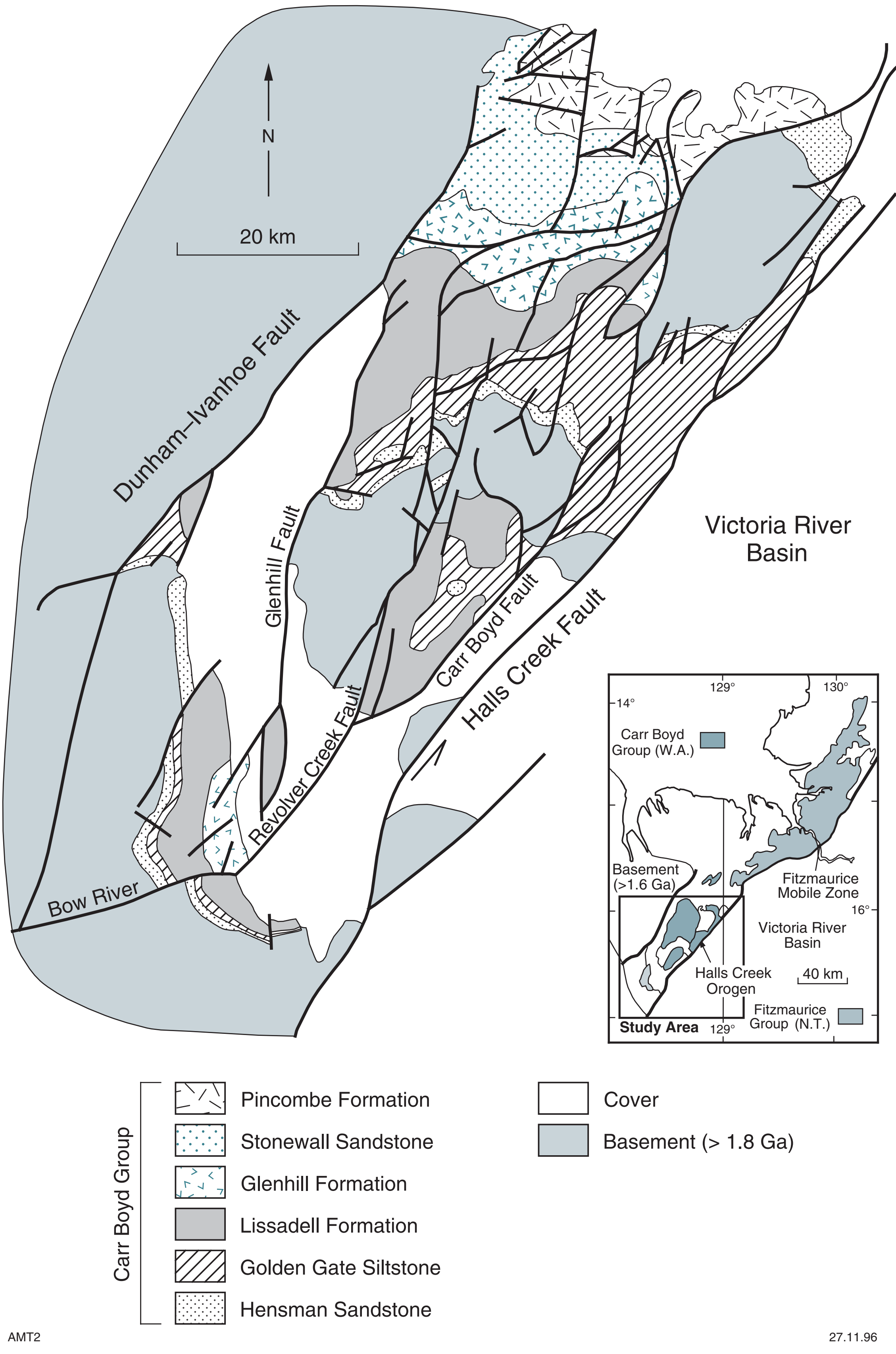


Figure 1. Carr Boyd Group outcrop and stratigraphy

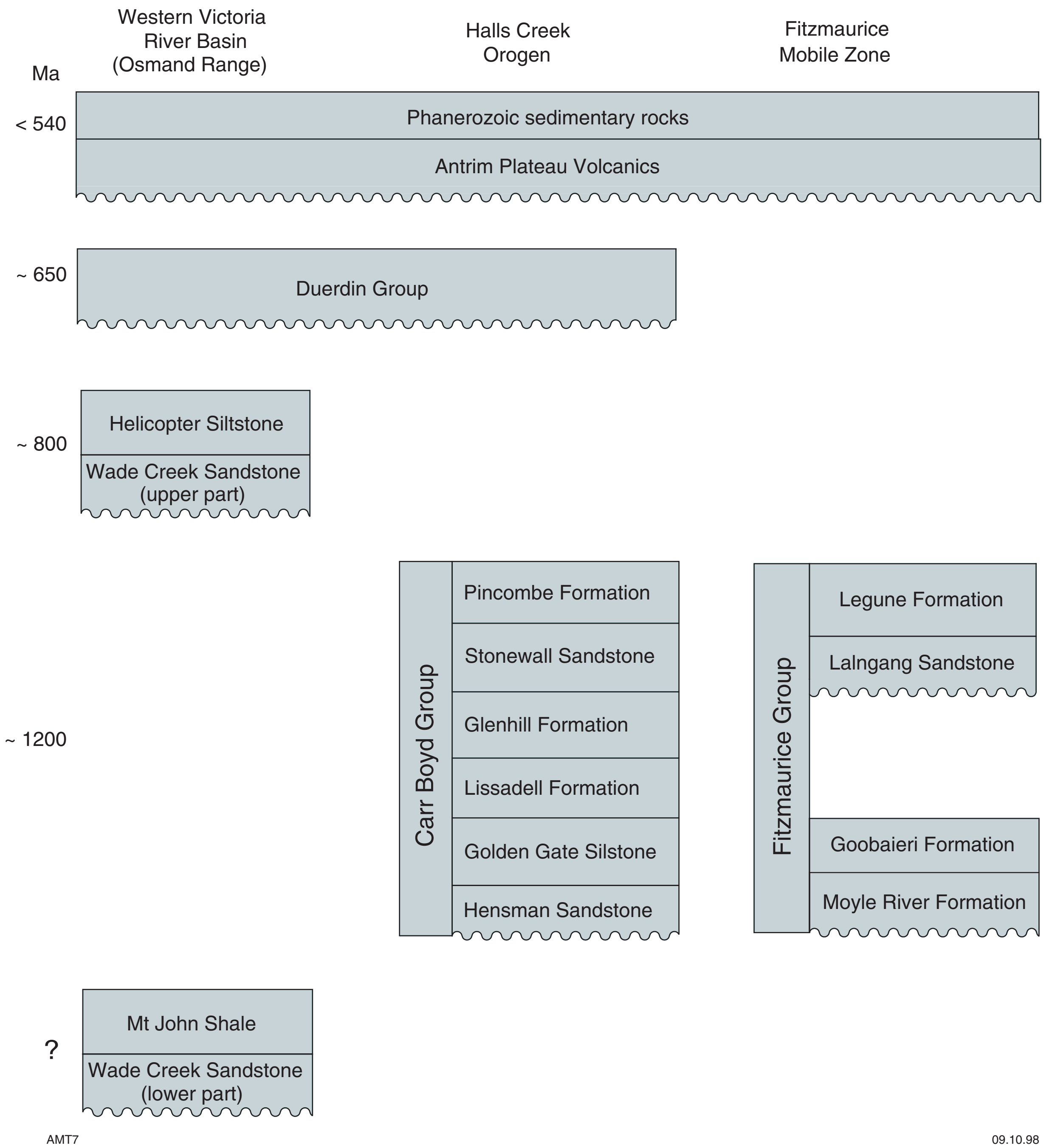


Figure 2. Regional correlation of the Carr Boyd Group

Formation, Stonewall Sandstone, and Pincombe Formation (Fig. 1). All formations are dominated by siliciclastic sedimentary rocks, comprising fine- to coarse-grained quartz sandstone, argillite, and minor lithic sandstone and conglomerate. These rocks have been interpreted as alluvial fan, fluvial, and shallow-marine shelf deposits that were laid down in an active strike-slip setting. (Plumb et al., 1985).

Previous workers recorded the presence of angular and erosional unconformities at the bases of the Lissadell and Glenhill Formations, and the Stonewall Sandstone (Dow et al., 1964; Dow and Gemuts, 1969; Plumb and Gemuts, 1976). Subsequent mapping (Thorne et al., in prep.) does not confirm the presence of these stratigraphic breaks and most discordant boundary relationships and anomalous thickness variations can be more readily attributed to post-Carr Boyd Group faulting.

Age of the Carr Boyd Group

The age of the Carr Boyd Group is loosely constrained by Rb–Sr whole rock dates of 1158 ± 123 Ma, 1057 ± 80 Ma, and 891 ± 149 Ma obtained from shales within the Golden Gate Siltstone, Glenhill Formation, and Pincombe Formation respectively (Bofinger, 1967, recalculated *by* Plumb et al., 1981). However, these ages are younger than the values of 1178 ± 47 Ma (Rb–Sr whole rock) or 1238 ± 12 Ma (K–Ar, phlogopite) reported from the Argyle lamproite diatreme (Pidgeon et al., 1989), which post-dates the Lissadell Formation (Boxer et al., 1989).

Regional correlation

The Fitzmaurice Mobile Zone forms the northeastern continuation of the Halls Creek Orogen into the Northern Territory. Here, the Lalngang Sandstone and Legune Formation in the upper part of the Fitzmaurice Group (Fig. 2) are correlated directly with the Stonewall Sandstone and Pincombe Formation respectively of the upper Carr Boyd Group (Sweet, 1977; Plumb and Gemuts, 1976). Older formations in the Carr Boyd and Fitzmaurice Groups cannot be correlated directly, although correlations (Fig. 2) have been made on the basis of inferred relations with the Angalarri Siltstone (Auvergne Group) in the Victoria River Basin (Sweet, 1977; Plumb and Gemuts, 1976; Plumb et al., 1985). However, a Rb–Sr whole-rock age of 838 ± 142 Ma from the Angalarri Siltstone (Webb and Page, 1977) and comparison with the Centralian Superbasin succession (Walter et al., 1995) suggests that the Auvergne Group and its Osmand Range equivalents (upper Wade Creek Sandstone and Helicopter Siltstone) are younger than the Carr Boyd Group.

Carr Boyd Group sedimentation

The Carr Boyd Group stratigraphy (Fig. 6) records the evolution of a sandy, braided delta complex and the adjacent siliciclastic marine shelf. Four broad facies associations are recognized and are interpreted to represent three major environments: wave-influenced shallow-marine shelf, delta front, and braided delta-plain.

Wave-influenced shallow marine shelf: mudstone–siltstone and siltstone–sandstone associations

Four major lithofacies make up these associations: laminated mudstone, graded siltstone–mudstone couplets, sandstone–siltstone, and cross-laminated siltstone and sandstone. The laminated mudstone facies is interpreted as the product of suspension fallout during periods of fair weather, whereas graded siltstone–mudstone couplets suggest an alternation of suspension fallout and weak gravity-flow depositional processes. Graded sandstone and siltstone layers represent deposition from stronger, storm-induced currents and gravity flows. Here, the presence of wave-ripple bedforms indicates that upper parts of the deposit were commonly modified by wave processes. Amalgamated units of cross-laminated siltstone and sandstone were laid down during relatively sustained periods of wave activity.

Delta front: complexly cross-stratified quartz sandstone association

This association is dominated by fine- to medium-grained quartz sandstone and comprises five lithofacies: parallel-planar stratified sandstone, low-angle planar stratified sandstone, undulatory cross-stratified sandstone, trough and planar tabular cross-stratified sandstone, ripple-laminated sandstone and siltstone. Palaeocurrent data from this facies are variable, the principal transport directions being toward the northwest, southeast and southwest (Fig. 3).

This association is dominated by moderate- to high-energy wave- and current-generated sedimentary structures that are typically found today on shoreface to foreshore environments (McCubbin, 1982; Harms et al., 1982; Elliott, 1986). Cosets of parallel planar cross-stratification are interpreted as swash stratification, formed in a foreshore setting. Trough and planar cross-stratification, parallel planar stratification and undulatory stratification record dune migration and storm deposition on the upper and lower shoreface. Thin interbeds of ripple-laminated sandstone and siltstone probably represent bar-top or bottomset deposits; thicker accumulations probably formed in a distal shoreface setting.

Braided delta-plain: medium and large-scale cross-stratified sandstone association

This association (Fig. 4) comprises thick, planar beds of medium-to coarse-grained or pebbly quartz sandstone. Internal structure consists of 0.5–1.0 m thick cosets of medium-scale trough cross-strata, and planar bounded sets of asymptotic trough cross-strata, 0.3–1.2 m thick. Fine-to medium-grained sandstone, which in places contains abundant argillite clasts, caps the tops of some beds. Upper bedding planes may preserve straight-crested symmetrical or asymmetrical ripples. Palaeocurrent data from the troughed portions are unimodal with low dispersion and indicate sediment transport was toward the northeast.

The dominance of large-scale trough cross-stratification, planar bedding, and unimodal palaeocurrent data suggest that this association represents the vertical infilling of broad, shallow channels by subaqueous dunes. The presence of wave ripples and mud flakes on upper bedding surfaces suggests periods of streamflow sedimentation. These were separated by intervals characterized by wave rippling and current reworking of channel sands and nearby slackwater deposits.

Depositional model and basin evolution

The proposed model for Carr Boyd Group deposition is shown in Figure 5. This reconstruction takes into account some 100 km of post-Carr Boyd Group sinistral strike-slip movement along the Halls Creek Fault system (*see* next section). The central feature of the model is a sandy braided-delta complex which progrades north and northeast-wards over a low-gradient, wave-influenced shallow-marine shelf. The fine grain size and compositional maturity of the sediment indicates the principal source area probably lay several hundred kilometres to the south and

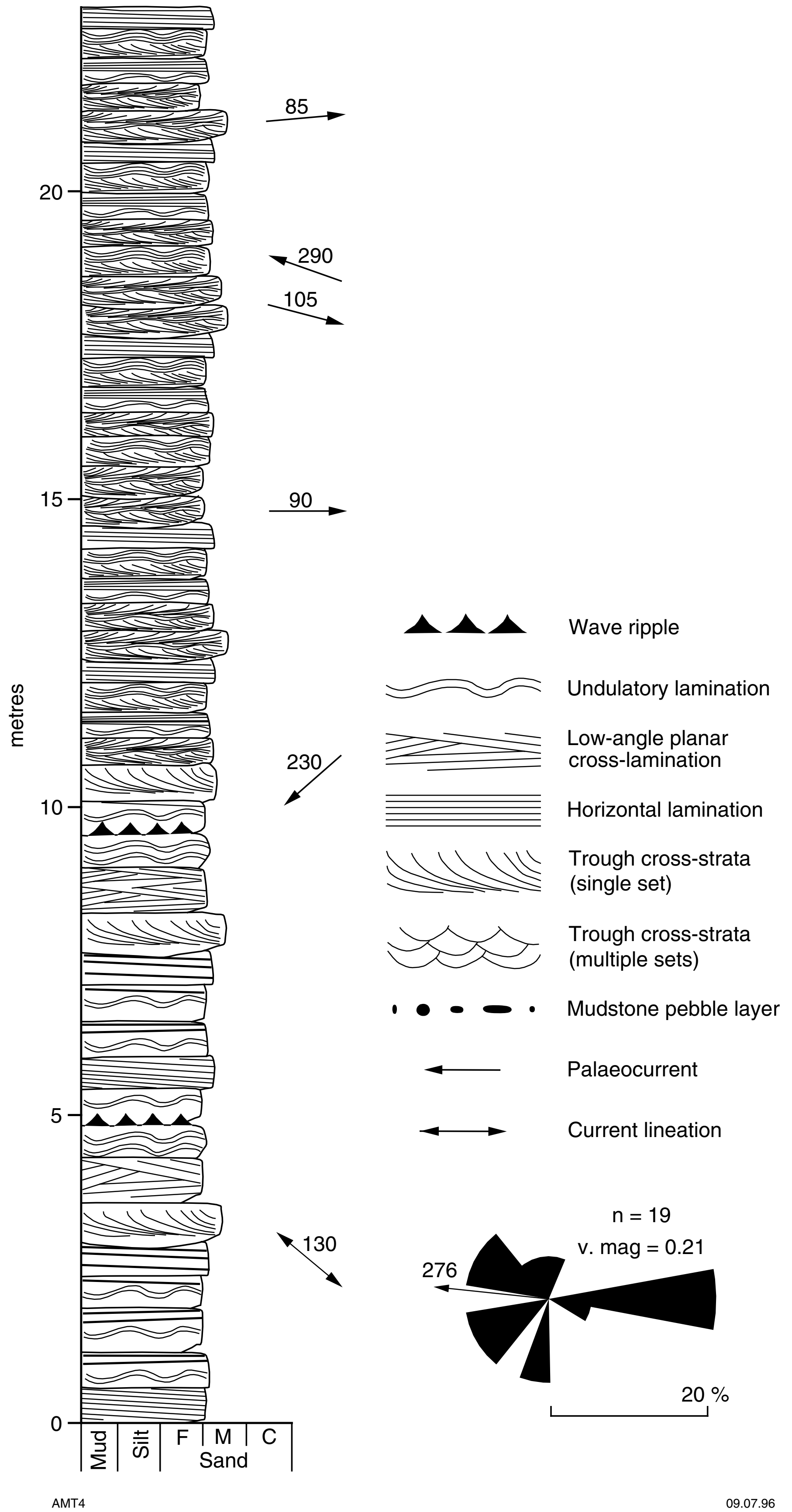


Figure 3. Vertical profile through the delta front facies association summarizing major rock types and internal structure

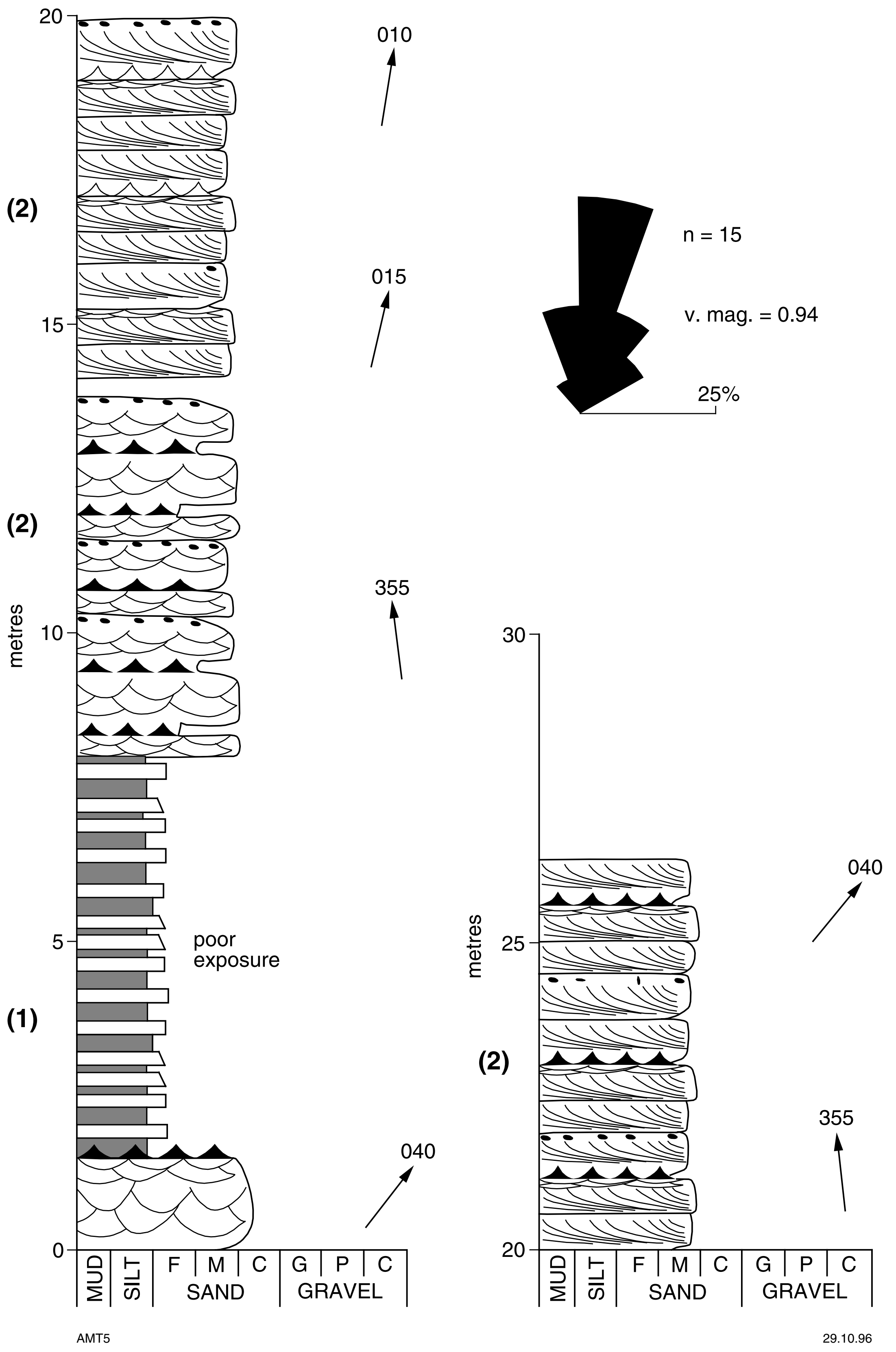


Figure 4. Vertical profile through the braided delta plain and delta front facies associations summarizing major rock types and internal structure. (1) delta front siltstone and sandstone, (2) delta plain sandstone. Symbols as for Figure 1

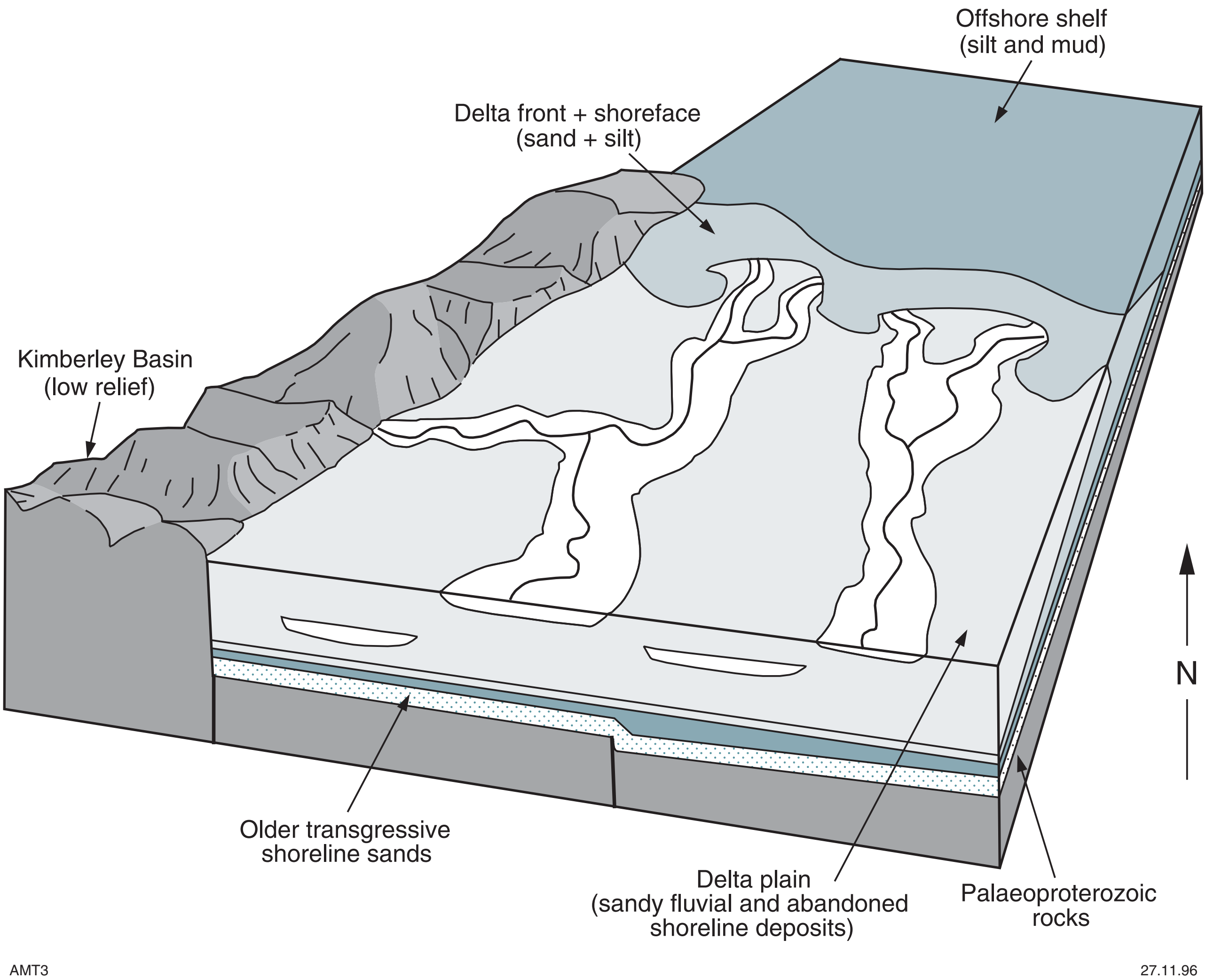


Figure 5. Depositional model for the Carr Boyd Group during delta progradation

southwest. Quartz sand was transported to the shelf by a system of shallow braided channels, and redistributed at the delta front by waves and longshore currents. Mud, silt, and sand were transported further offshore by storm-generated currents and weak sediment-gravity flows.

The Carr Boyd Group stratigraphy records an initial period of marine transgression during which shoreface sands (Hensman Sandstone) followed by finer grained offshore shelf deposits (lower Golden Gate Siltstone) were deposited over an eroded surface of Palaeoproterozoic rocks (Fig. 6). This initial flooding event was followed by four major cycles of braided-delta progradation and retreat (upper Golden Gate Siltstone to Pincombe Formation). The maintenance of deltaic and shallow-marine shelf (<100 m deep) sedimentation throughout this time implies that depositional rates generally kept pace with overall rates of basin subsidence.

Estimates of the former extent of the Carr Boyd depositional system depend upon the reliability of correlations with the Fitzmaurice Group and Victoria River Basin succession of the Northern Territory. Direct correlations between the Stonewall Sandstone and Pincombe Formation, and the Lalngang Sandstone and Legune Formation (Fitzmaurice Group) suggest the basin extended at least 200 km northeastwards into the Fitzmaurice Mobile Zone (Sweet, 1977; Plumb and Gemuts, 1976; Plumb et al., 1985). The southward extension of the basin is unknown because of the difficulty in correlating the Carr Boyd Group with the Victoria River Basin succession on the southeast side of the Halls Creek Fault.

Timing of strike-slip fault movement

Mesoproterozoic and Neoproterozoic

Plumb et al. (1985) considered that Carr Boyd Group deposition was strongly influenced by major strike-slip movements along the Halls Creek Fault system. However, much of the evidence that was used to support this concept, including the presence of synsedimentary faults and localized unconformities within

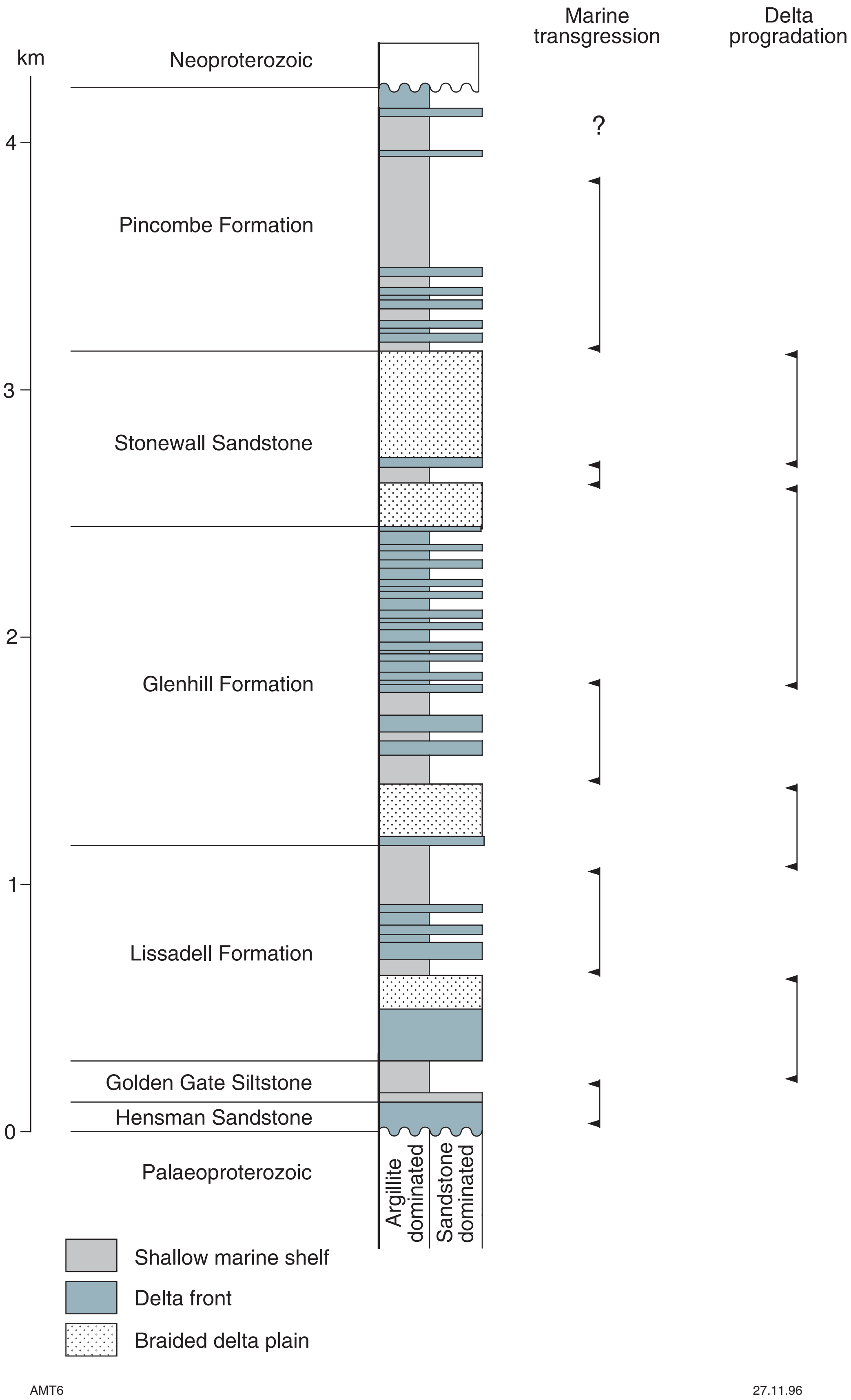


Figure 6. Depositional history of the Carr Boyd Group showing major episodes of delta progradation and marine transgression

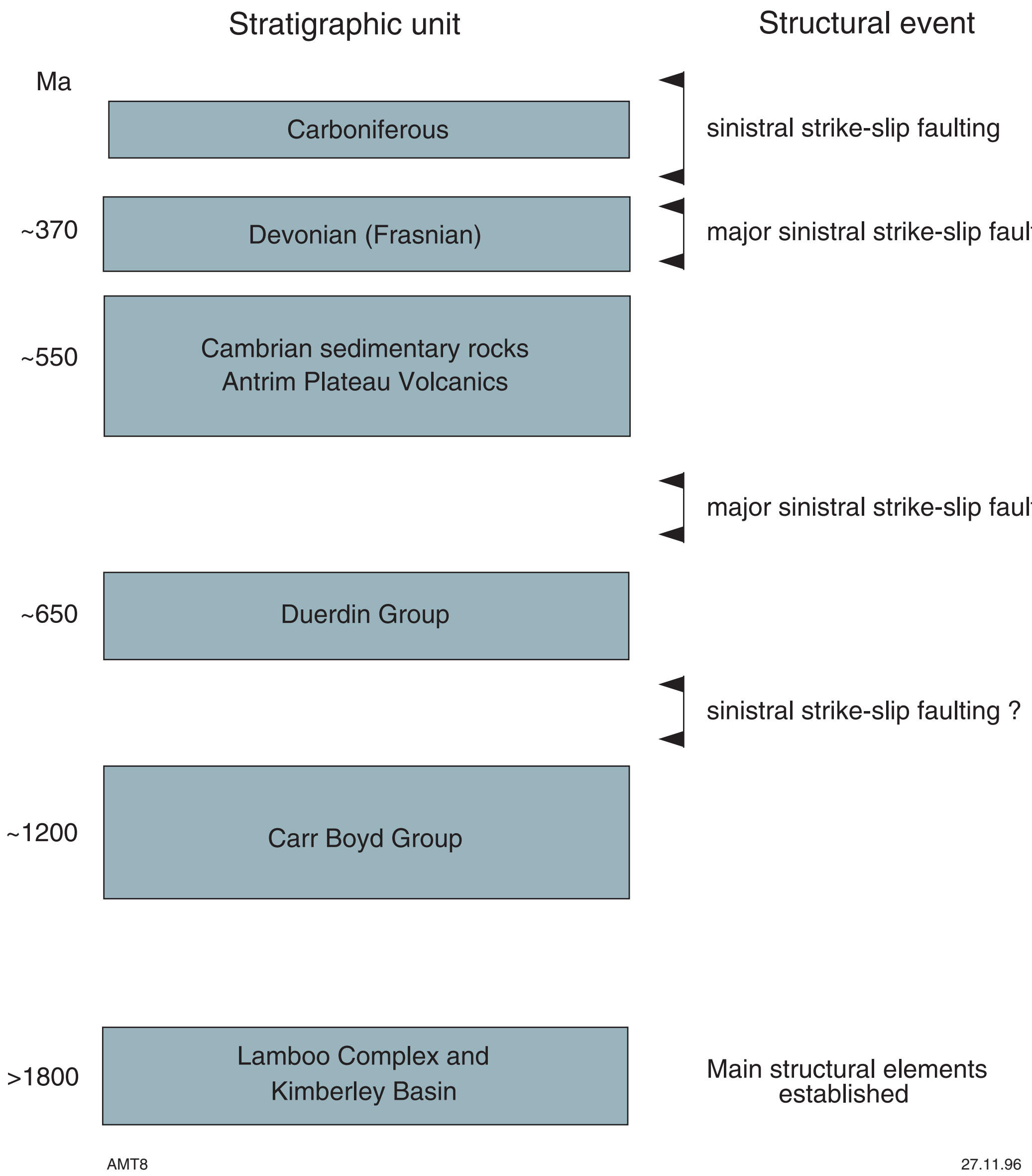


Figure 7. Timing of Mesoproterozoic to Phanerozoic fault movements in the northern Halls Creek Orogen

the Carr Boyd Group (Plumb, 1968; Plumb et al., 1985), has not been borne out by subsequent mapping (Thorne et al., in prep.). In addition, the Carr Boyd Group lacks most of the features normally associated with deposition in strike-slip settings (*see* Christie-Blick and Biddle, 1985; Nilsen and Sylvester, 1995). Specifically, the fine-grained (sand and argillite) character of the Carr Boyd Group, its uniform style of deposition (both spatially and temporally), and the lack of evidence for localized syndepositional uplift and adjacent rapid subsidence, are inconsistent with this interpretation. Instead, the overall character of the Carr Boyd Group suggests deposition probably took place within an intracratonic basin which formed following amalgamation of the North, West, and South Australian Cratons at about 1300 Ma (Myers, 1990; Myers et al., 1994).

Although there appears to be little evidence for major strike-slip movement having occurred along the Halls Creek Fault system during Carr Boyd Group deposition, the considerable thickness of the Carr Boyd Group, when compared with the total thickness of Mesoproterozoic sedimentary successions in the Victoria River Basin, suggests there may have been considerable (1–2 km) downward movement of the west block along this fault line during Carr Boyd Group deposition.

The high degree of brittle deformation that has affected both the Carr Boyd Group and the glacigene rocks of the Neoproterozoic Duerdin Group (Thorne et al., in press), combined with the problems experienced in correlating these units across the Halls Creek Fault, implies post-Carr Boyd Group faulting (Fig. 7) may account for much of the sinistral displacement in the Halls Creek Orogen. These movements took place through the reactivation of major basement structures that formed initially during the Palaeoproterozoic orogeny (Tyler et al., 1995).

Post-Duerdin Group – pre-Antrim Plateau Volcanics faulting and tilting indicates a major period of strike-slip movement took place during the Neoproterozoic, between about 650 and 550 Ma. This event may correlate with a phase of contractional tectonism in the King Leopold Orogen c. 560–530 Ma (Shaw et al., 1992a) and north– south compression in the Paterson and Petermann Orogens (Myers et al., 1994). In the east Kimberley, there is little evidence in the stratigraphic record for an earlier period of sinistral movement which would correlate with the c. 1000 Ma Yampi Orogeny in the King Leopold Orogen (Shaw et al., 1992a).

Palaeozoic

Upper Devonian (Frasnian) sedimentation in the northern Halls Creek Orogen (Mory and Beere, 1988) shows many of the features associated with active strike-slip sedimentation (Christie-Blick and Biddle, 1985; Nilsen and Sylvester, 1995).

- Sedimentation took place in isolated basins which are today bounded on one or more sides by strike-slip faults (Fig. 8)
- Basin margins were sites of conglomeratic alluvial-fan sedimentation; e.g. Ragged Range, Galloping Creek, and Cockatoo sub-basins
- Basin fill was derived from multiple basin-margin sources
- There is clear evidence of intraformational unconformities and syndepositional faulting within the basin fill (Mory and Beere, 1988)
- Basin fill is often very thick (up to 2.7 km, Mory and Beere, 1988) relative to basin size and it is characterized by abrupt facies changes
- They contain upward-coarsening sequences (Mory and Beere, 1988) that developed in response to tectonically induced basin deepening.

In addition, there is evidence of mismatched source areas north of Glenhill where alluvial-fan deposits on the western side of the Glenhill Fault show an easterly source and are juxtaposed against similar facies on the eastern side of the fault which show a westerly source (Mory and Beere, 1988, fig. 58). The most likely explanation for these relationships is that post-depositional sinistral strike-slip movement has displaced the basin on the western side of the Glenhill Fault a minimum distance of 10 km south relative to the basin on the eastern side of this fracture

Most of the Devonian sedimentary basins (here referred to as sub-basins) in the northern Halls Creek Orogen have the structural characteristics of either stepover or transpressional strike-slip basins (Nilsen and Sylvester, 1995). Examples of the former include the Optic Hill sub-basin, located in the extensional stepover zone between the Dillon Spring and Dunham Faults and the Halls Creek Fault, and the Burt Range sub-basin, which developed in an extensional setting between the Halls Creek Fault and a synthetic splay from the Ivanhoe Fault. Elongate transpressional basins such as the eastern Cockatoo sub-basin (Fig. 8) formed next to uplifted and overthrust fault blocks along the Cockatoo Fault. Here, subsidence has resulted from the flexural loading of Precambrian basement adjacent to the uplifted blocks.

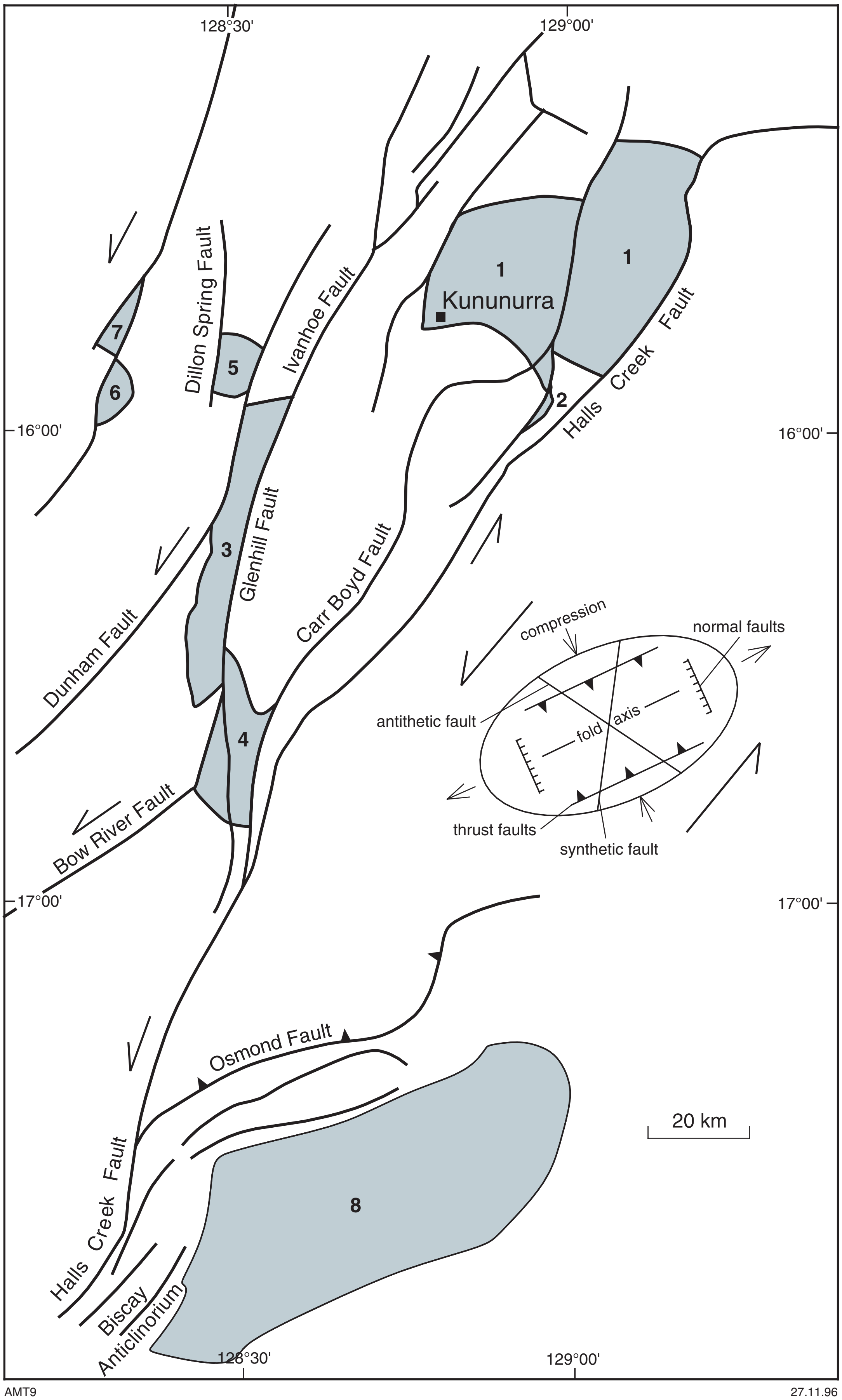
The Hardman sub-basin, 60 km southeast of Warmun, is another major Late Devonian depocentre which formed as a result of strike-slip deformation. Here, north-northwest – south-southeast compression, associated with Devonian sinistral movement on the Halls Creek Fault was responsible for thrust movement on the north-dipping Osmond Fault. The resultant folding and uplift in the Osmand Range was accompanied by flexural subsidence and the formation of the Hardman sub-basin in the area immediately to the south (Fig. 8). Subsidence along the western margin of this sub-basin was also enhanced by west-northwestward transpression against the Biscay Anticlinorium. Upward-coarsening fluvial to alluvial-fan deposits of the Frasnian Glass Hill Sandstone and Boll Conglomerate were deposited in the Hardman sub-basin, their presence reflecting sustained, coeval uplift in the Osmand Range to the north (Mory and Beere, 1988).

Sinistral strike-slip movement continued in the Halls Creek Orogen until the end of the Carboniferous and resulted in the reactivation of sub-basin boundary faults and associated splays, and development of large-scale open folds (e.g. Hardman Syncline). Post-Frasnian faults are associated locally with a steeply dipping Palaeozoic succession. On the western limb of the Hardman Syncline, the regional transpression has resulted in local overturning of the Cambrian Headleys Limestone. The sedimentary responses to post-Frasnian tectonism, though significant, were not as marked as during the Frasnian and resulted mainly in the development of local unconformities and syndepositional fault scarps within the Fammenian and Lower Carboniferous succession (Mory and Beere, 1988).

Large-scale Devonian to Carboniferous sinistral movement along the Halls Creek Fault coincides with a major period of north-northeasterly sinistral strike-slip faulting and transtension in the Pillara Range in the Canning Basin (Dorling et al., 1996). This deformation may reflect a widespread north–south compressive event that was felt throughout much of northern Australia during the 400–300 Ma Alice Springs Orogeny (Shaw and Black, 1991; Shaw et al., 1992b).

Conclusions

Details of Carr Boyd Group sedimentation and stratigraphy are inconsistent with deposition in an active strike-slip setting. Most of the post-Palaeoproterozoic sinistral faulting in the Halls Creek Orogen took place after deposition of the Carr Boyd Group. The principal fault movements occurred in the



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Ivanhoe Fault
Glenhill Fault
Carr Boyd Fault
Dunham Fault
Bow River Fault
Halls Creek Fault
Osmond Fault
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post-Duerdin Group – pre-Antrim Plateau Volcanics interval and also during the late Palaeozoic. The latter event has exerted a major influence on the development of upper Devonian (Frasnian) sedimentary basins in the northern Halls Creek Orogen.

Figure 8. Structural setting of upper Devonian sedimentary basins in the northern Halls Creek Orogen:
1. Burt Range sub-basin,
2. east Cockatoo sub-basin,
3. Ragged Range sub-basin,
4. Galloping Creek sub-basin,
5. Optic Hill sub-basin,
6. Mount Rob sub-basin,
7. Gap Point sub-basin,
8. Hardman sub-basin

References

BOFINGER, V. M., 1967, Geochronology of the east Kimberley area of Western Australia: Australian National University, PhD thesis (unpublished).

BOXER, G. L., LORENZ, B., and SMITH, C. B., 1989, Geology and volcanology of the Argyle (AK1) lamproite diatreme, Western Australia, *in* Kimberlites and related rocks, Vol. 1, Their composition, occurrence, origin, and emplacement *edited by* J. ROSS: Geological Society of Australia, Special Publication no. 14, p. 140–152.

CHRISTIE-BLICK, N., and BIDDLE, K. T., 1985, Deformation and basin formation along strike-slip faults, *in* Strike-slip deformation, basin formation, and sedimentation *edited by* K. T. BIDDLE and N. CHRISTIE-BLICK, Society of Economic Geologists and Mineralogists, Special Publication no 37, p. 1–34.

DORLING, S. L., DENTITH, M. C., GROVES, D. I., PLAYFORD, P. E., VEARNCOMBE, J. R., MUHLING, P., and WINDRIM, D., 1996, Heterogeneous brittle deformation in the Devonian carbonate rocks of the Pillara Range, Canning Basin: implications for the structural evolution of the Lennard Shelf: Australian Journal of Earth Sciences, v. 53, p. 15–29.

DOW, D. B., and GEMUTS, I., 1969, Geology of the Kimberley region, Western Australia — The East Kimberley: Western Australia Geological Survey, Bulletin 120 (also published as Australia BMR, Bulletin 106), 135p.

DOW, D. B., GEMUTS, I., PLUMB, K. A., and DUNNET, D., 1964, The geology of the Ord River region, Western Australia: Australia BMR, Record 1964/104 (unpublished).

ELLIOTT, T., 1986, Siliciclastic shorelines, *in* Sedimentary environments and facies *edited by* H. G. READING: Oxford, Blackwell Scientific Publications, p. 155–188.

HARMS, J. C., SOUTHARD, J. B., and WALKER, R. G., 1982, Structures and sequences in clastic rocks: Society of Economic Palaeontologists and Mineralogists, Short Course no. 9 Lecture Notes.

McCUBBIN, D. G., 1982, Barrier-island and strand-plain facies, *in* Sandstone depositional environments *edited by* P. A. SCHOLLE and D. SPEARING, American Association of Petroleum Geologists, Memoir 31, p. 247–279.

MORY, A. J., and BEERE, G. M., 1988, Geology of the onshore Bonaparte and Ord Basins in Western Australia: Western Australia Geological Survey, Bulletin 134, 184p.

MYERS, J. S., 1990, Precambrian tectonic evolution of part of Gondwana, southwestern Australia: Geology, v. 18, p. 537–540.

MYERS, J. S., SHAW, R. D., and TYLER, I. M., 1994, Proterozoic tectonic evolution of Australia: 12th Australian Geological Convention, Perth, Geological Society of Australia, Abstracts, no. 37, p. 312.

NILSEN, T. H., and SYLVESTER, A. G., 1995, Strike-slip basins, *in* Tectonics of sedimentary basins *edited by* C. J. BUSBY and R. V. INGERSOLL: Cambridge, Blackwell, p. 425–457.

PIDGEON, R. T., SMITH, C. B., and FANNING, C. M., 1989, Kimberlite and lamproite emplacement ages in Western Australia, *in* Kimberlites and related rocks; vol. 1, their composition, occurrence, origin, and emplacement *edited by* J. ROSS: Geological Society of Australia, Special Publication, no. 14, p. 369–381.

PLUMB, K. A., 1968, Lissadell, W.A.: Western Australia Geological Survey, 1:250 000 sheet Geological Series Explanatory Notes.

PLUMB, K. A., ALLEN, R., and HANCOCK, S. L., 1985, Excursion guide — Proterozoic evolution of the Halls Creek Province, Western Australia: Conference on tectonics and geochemistry of Early to Middle Proterozoic fold belts, Darwin, N. T., 1985, Excursion Guide, Australia BMR, Record 1985/25 (unpublished).

PLUMB, K. A., DERRICK, G. M., NEEDHAM, R. S., and SHAW, R. D., 1981, The Proterozoic of northern Australia, *in* Precambrian of the Southern Hemisphere — developments in Precambrian geology *edited by* D. R. HUNTER: Amsterdam, Elsevier, v. 2, p. 205–307.

PLUMB, K. A., and GEMUTS, I., 1976, Excursion guide — Precambrian geology of the Kimberley Region, Western Australia: 25th International Geological Congress Sydney, N.S.W., 1976, Excursion Guide, no. 44C, 72p.

PLUMB, K. A., and VEEVERS, J. J., 1971, Cambridge Gulf, W.A.: Western Australia Geological Survey, 1:250 000 sheet Geological Series Explanatory Notes.

SHAW, R. D., and BLACK, L. P., 1991, The history and tectonic implications of the Redbank Thrust Zone, central Australia, based on structural, metamorphic and Rb–Sr isotopic evidence: Australian Journal of Earth Sciences, v. 38, p. 307–332.

SHAW, R. D., TYLER, I. M, GRIFFIN, T. J., and WEBB, A., 1992a, New K–Ar constraints on the onset of subsidence in the Canning Basin, Western Australia: BMR Journal of Australian Geology and Geophysics, v. 13, p. 31–35.

SHAW, R. D., ZEITLER, P. K., McDOUGALL, I., and TINGATE, P. R., 1992b, The Palaeozoic history of an unusual intracratonic thrust belt in central Australia based on ^{40}Ar–^{39}Ar, K–Ar and fission track dating: Journal of the Geological Society of London, v. 149, p. 937–954.

SWEET, I. P., 1977, The Precambrian geology of the Victoria River region, Northern Territory: Australia BMR, Bulletin 168, 73p.

THORNE, A. M., SHEPPARD, S., and TYLER, I. M., in prep., Lissadell, W.A., (2nd edition): Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

TYLER, I. M., and GRIFFIN, T. J., 1994, The Yampi Orogeny in the Kimberley region of Western Australia: an intracratonic response to the assembly of Proto-Gondwanaland: 12th Australian Geological Convention, Perth, Geological Society of Australia, Abstracts, no. 37, p. 436.

TYLER, I. M., GRIFFIN, T. J., PAGE, R. W., and SHAW, R. D., 1995, Are there terranes within the Lamboo Complex of the Halls Creek Orogen?: Western Australia Geological Survey, Annual Review for 1994–95, p. 37–46.

WALTER, M. R., VEEVERS, J. J., and GREY, K., 1995, Neoproterozoic stratigraphy of the Centralian Superbasin, Australia: Precambrian Research, v. 73, p. 173–179.

WEBB, A. W., and PAGE, R. W., 1977, Geochronology of glauconitic sandstone and shale beds in the Victoria River region, Northern Territory, *in* Precambrian Geology of the Victoria River Region, Northern Territory *by* I. P. SWEET: Australia BMR, Bulletin 168, p. 68–72.

WITT, W. K., and SANDERS, T., 1996, Magmatic–hydrothermal breccia dykes and hydrothermal alteration in the McHale Granodiorite, Halls Creek Orogen: A possible porphyry system: Western Australia Geological Survey, Annual Review 1995–96, p. 104–110.

A geostatistical approach to characterizing downslope changes in regolith geochemistry: a case study

by A. G. Subramanya and A. J. Sanders

Abstract

Changes in regolith chemistry have been modelled as a function of distance and degree of alteration compared with the source rock from which the regolith was derived. A primary requirement for such a study is the availability of a chemically well-characterized and uniform source rock and a statistically significant population of regolith samples derived from, and downslope from, the source rocks.

The Narracoota Formation in the Glengarry Basin was chosen for this study because of the availability of geochemical and mineralogical data, both for the rocks themselves and the regolith derived from these rocks.

Rock chemistry was used as control data and regolith samples downslope from the source rocks were identified by catchment analysis using satellite imagery, digital elevation data, GIS and discriminant analysis. Statistical methods were used to quantify changes in regolith chemistry as material moved progressively downslope. These changes indicate possible processes responsible for regolith formation and account for element variation under these conditions of weathering and transport.

The regolith largely reflects the composition of the rock it was derived from and, in areas of extensive cover, can be used to predict the underlying geology. Patterns of change in the chemistry of the regolith are not always uniform for all elements but overall trends are similar.

KEYWORDS: Peak Hill, Narracoota Volcanics, regolith, geochemistry, weathering, geostatistics, GIS

The lack of readily available, complementary bedrock and regolith geochemical data makes it difficult to assess the effects of bedrock erosion and weathering. Neither geochemical trends in the regolith, nor processes which influence chemistry, can be identified unless the source material and the derived regolith are similarly characterized.

The regional geochemical mapping of the regolith on the PEAK HILL*, GLENGARRY, and ROBINSON RANGE 1:250 000 map sheets and the recent detailed regional geological mapping of the Glengarry Basin by the Geological Survey of Western Australia (GSWA) presented an opportunity to carry out a comparative study of the regolith and its source rock. The lithological unit chosen for study was the Narracoota Formation, which forms continuous and distinctive outcrops of mafic and ultramafic rocks that are readily delineated on satellite imagery. This made it easy to select catchment areas where the relationships of regolith and host rock, for which geochemical analysis was available, could be established with some certainty. The sampling density of the regional geochemical mapping program ensured that there was a significant number of samples from different regolith units downslope from the source rock.

The Narracoota Formation is a new name (Pirajno and Occhipinti, 1995; Pirajno and Occhipinti, in prep.) which includes most of the Narracoota Volcanics as defined by Gee (1987, 1990) and Gee and Grey (1993). The new formation differs from the original Narracoota Volcanics in the exclusion of the suite of mafic rocks, found in the southeast corner of the Peak Hill 1:250 000 map sheet, which is now included in the Killara Formation (Dawes and Le Blanc Smith, 1995). The Narracoota Formation consists of metamorphosed mafic and ultramafic volcanic rocks now preserved as tremolite–actinolite and chlorite schists (Hynes and Gee, 1986). They are largely tholeiitic with some subvolcanic high-Mg cumulates reported by Pirajno and Davy (1996) and Pirajno and Occhipinti (in prep.).

The aim of the study is to identify chemical trends resulting from the weathering and downslope movement of bedrock from which

* Capitalized names refer to standard map sheets.

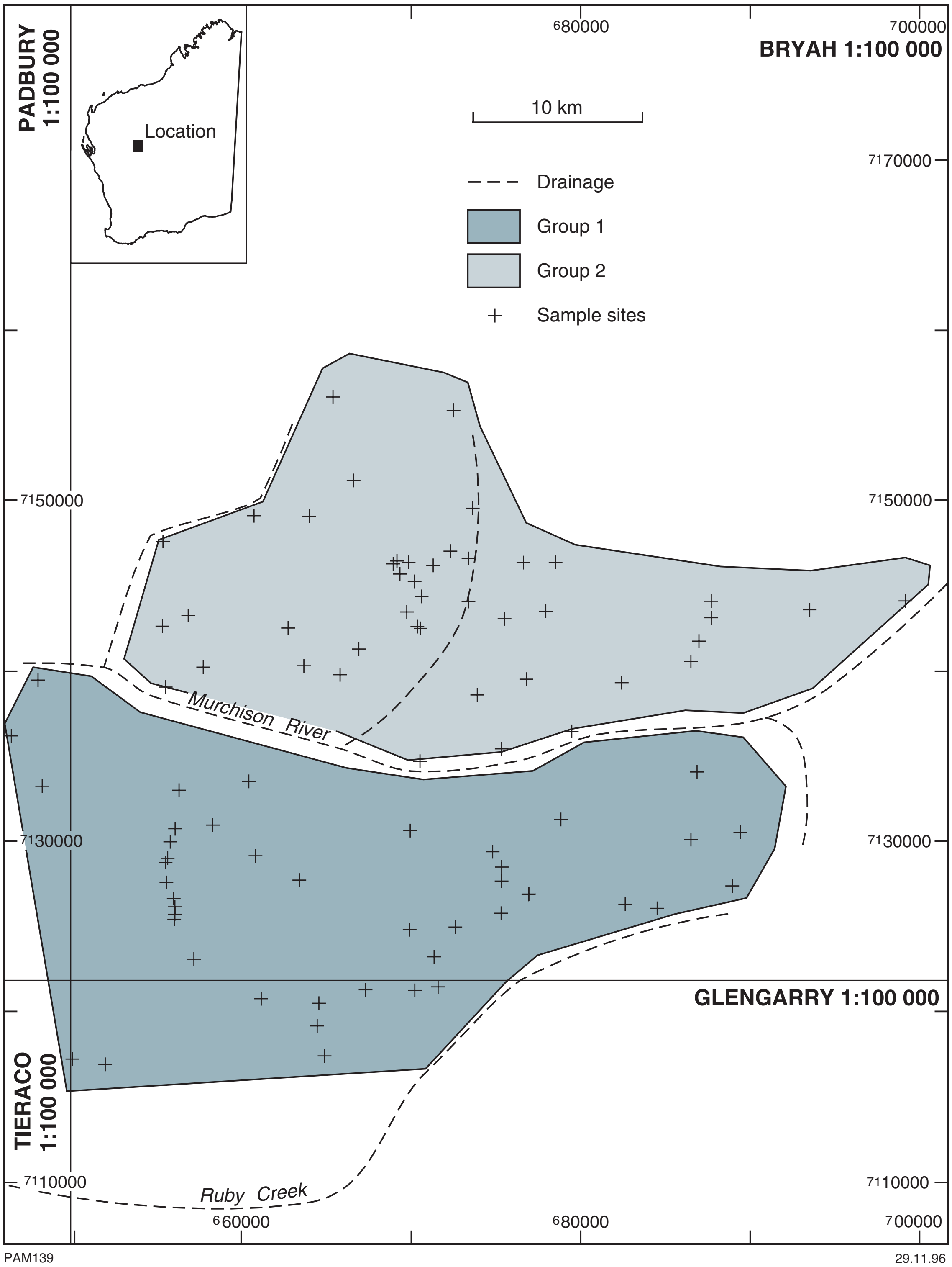


Figure 1. Location diagram of the sample groups

the regolith is produced. This is possible in areas where bedrock samples have been collected and analysed, along with regolith samples derived from the outcrop and extending downslope to an area of active drainage. The region from the outcrop to the active drainage is defined as a catchment group.

Figure 1 outlines the area of this study, which includes all the volcanic rocks from the Narracoota Formation south of the Robinson Ranges. Most of the area consists of flat to gently undulating colluvial plains and low hills and is arid, with low and irregular rainfall (averaging about 200 mm per year). The area north of the Murchison River is largely composed of extensive, gently sloping flood plains that drain to the south. Outcrops of the Narracoota Formation are isolated and the regolith is more 'mature' and ferruginized than those to the south of the river, where the outcrops are continuous and form an elongated range of low hills trending easterly. These form a divide with the northern flanks and slopes draining into the Murchison River and streams on the southern side draining south. In many places the volcanics have been ferruginized where they are exposed.

Regolith classification

Regolith units used here are classified under three regimes: relict, erosional and depositional (Anand et al., 1993). Each of these regimes is subdivided into units based on position in the landform and the nature of the material which makes up the regolith. The relict regime essentially consists of products which are a result of weathering and erosion of bedrock in situ. As no relict units were encountered in the area under study these will not be discussed any further.

The erosional regime is represented by material which has not been transported far from its source, and which has undergone various degrees of mechanical and chemical alteration. This regime is divided into three units, E1, E2 and E4, which represent increasing distance downslope from the source rock. The E1 unit corresponds to a mottled zone, or saprolite, and is best exposed in deeply incised areas or below breakaways. The E2 unit corresponds to areas of prominent outcrop or extensive subcrop that are actively shedding material. The regolith here consists predominantly of partly weathered bedrock overlying and intermixed with locally derived sand and sandy clay. E2 typically occurs in areas of high topographic relief. The E4 unit covers erosional areas of moderate to low relief and is generally downslope from unit E2. E4 is characterized by a lag of partly ferruginized lithic fragments and outcrops are less evident.

The depositional regime is one in which there is net material gain and dominantly chemical (rather than mechanical) alteration of sediments. The depositional regime is divided into two subcategories based on whether the material is predominantly colluvial (DC) or alluvial (DA). As the alluvial units generally represent highly mixed sediment sources, they have not been considered in this study.

The colluvial units are divided into DC1, DC2, DC3, and DC3f based on the nature of the material and position downslope of the source rocks. DC1 consists of colluvium that is relatively close to its source and normally downslope to E4. It marks the change from an erosional to a predominantly depositional regime. DC2 is generally composed of relatively mature, fine- to medium-grained, commonly ferruginized material. The unit contains mainly sheetwash-derived sediments in areas of low relief. DC2 is normally downslope to DC1 and E4 and is topographically higher than DC3. The DC3 unit forms low-angled, wide sheetwash fans occupying broad valleys that finally merge into alluvial plains or major drainage floors. The most abundant material is fine clay and sand. The unit DC3f consists of fine, non-lithic ferruginous detritus overlying red sandy clay.

Methodology

Regolith samples of the Narracoota Formation were selected from the GSWA regional geochemical mapping of the PEAK HILL (Subramanya et al., 1995), GLENGARRY (Crawford et al., 1996), and ROBINSON RANGE (Bradley et al., in prep.) 1:250 000 mapsheets. Bedrock samples were selected from the metavolcanic rocks of the Narracoota Formation, collected and analysed (Pirajno, F., 1996, pers. comm.) during the regional mapping of the BRYAH (Pirajno and Occhipinti, 1995), DOOLGUNNA (Adamides, 1995) and PADBURY (Occhipinti et al., in prep.) 1:100 000 sheets.

Sample selection

Defining catchment areas

Geologically discrete areas that would be unaffected by mixing of volcanic, granitic or sedimentary detritus were selected for analysis. An area of regolith derived from volcanic rocks was identified by analysing the outcrop and drainage pattern of the BRYAH 1:100 000 Landsat TM image. This area was further subdivided into two groups based on internal catchment boundaries (Fig. 1). These catchment boundaries were checked against stereo photography and digital elevation data to ensure the sampling areas were self-contained and represented only the metavolcanic rocks of the Narracoota Formation and regolith material derived from it.

Checking the catchment areas using discriminant analysis and GIS

Discriminant analysis of the PEAK HILL, ROBINSON RANGE and GLENGARRY regolith samples was carried out to check the chemistry of the catchment boundaries. This technique was used in the geochemical mapping of the GLENGARRY 1:250 000 sheet (Crawford et al., 1996) to define the extent of regolith derived from specific parent rocks. The process assigns samples to various geological units based on their chemistry. All regolith samples in the southwest quadrant of the PEAK HILL 1:250 000 sheet were classified and then gridded using the ARC/INFO GRID package. The grid was overlain with the generalized geology and the sample point locations map as a further check that the selected catchment boundaries lay in a representative area of the Narracoota Formation.

Valid samples

Owing to the sampling density of the regolith geochemical mapping project and the occurrence of granitic, volcanic and sedimentary rocks in some areas, only two catchment groups containing only the volcanics of the Narracoota Formation could be identified. Within these groups the Rock, E2, E4, DC1, DC2, and DC3 samples where separated and processed. Because of a statistically insignificant number of samples, the E2 category was eliminated from both the groups and the DC3 category was eliminated from one of the groups.

Statistical methods

A subset of rock samples from the Narracoota Formation was constructed from an initial set of 109 analyses of 35 major and/or trace elements. Catchment Groups 1 and 2 comprise 21 and 20 bedrock samples respectively, from which the average composition of the rocks for each group was calculated. Regolith samples were collected from the area surrounding the bedrock samples and extending downslope to the active drainage. Overall statistics for each group were tabulated excluding MnO, Na_2O, P_2O_5, Ag, Au and Bi which were too close to their lower detection limits.

Summary statistics were calculated for each catchment group. Geometric means (GM) for all elements from the bedrock and regolith units have been tabulated (Tables 1 and 2) and form the basis of comparison within and between the catchment groups. Geometric means are used in all comparisons to minimize the effects of extreme ranges in value.

The geometric means of all elements in the regolith units were divided by the geometric means for the same elements in rocks of that group. This normalizes the data, allowing comparison of major and trace elements. This operation also permits the inference that any element in the regolith with a value greater than rock normal has been enriched by the weathering process, and any element less than rock normal has been depleted relative to rock.

Table 1. Geometric means for bedrock and regolith from Group 1

	Rock	*E4*	*DC1*	*DC2*
n	*18,21*	*11*	*10*	*6*
		weight percent		
SiO_2	53	46	54	56
TiO_2	0.93	0.94	0.72	0.84
Al_2O_3	13	9.8	10	7.3
Fe_2O_3	11	26	18	19
MgO	6.4	0.31	0.37	0.28
CaO	4.9	0.21	0.22	0.09
K_2O	0.20	0.32	0.53	0.35
LOI	3.8	5.4	6.2	4.4
		parts per million		
As	2.9	17	13	14
Ba	121	99	166	141
Ce	0.88	12	18	13
Cr	153	803	766	1 004
Cu	120	71	60	48
Ga	13	23	21	19
La	0.88	4.8	6.8	5.3
Mo	0.58	1.7	2.2	1.7
Nb	1.6	7.8	11	8.1
Ni	110	76	88	76
Pb	4.6	18	21	18
Rb	2.2	11	16	16
Sb	0.49	1.6	0.84	1.0
Sc	12	14	25	22
Sn	1.1	2.1	2.3	1.9
Sr	51	14	19	12
Th	0.63	5.9	7.0	7.3
U	0.18	1.6	2.2	1.8
V	246	407	292	329
Y	21	7.5	7.0	5.1
Zn	91	53	55	43
Zr	69	85	103	92

Normalization procedure used was:

[GM element (x) from regolith unit of Group (n)/ GM element (x) from rock of Group (n)] × 100

e.g. $$\frac{(Fe_2O_3)\text{ E4 Group 1}}{(Fe_2O_3)\text{ Rock Group 1}} \times 100$$

Discussion

Mineralogical studies using X-ray diffraction (Subramanya et al., 1995) and petrographic studies (Pirajno and Occhipinti, in prep.) show that chemical rather than mechanical weathering is the dominant process in the formation of the regolith derived from the volcanics of the Narracoota Formation. The bedrock is composed primarily of plagioclase feldspar, amphibole, chlorite, epidote, and minor zeolite and carbonate. There is a rapid breakdown of these minerals to produce quartz, iron hydroxides (goethite) and oxides (hematite) and clay minerals (kaolin). Only trace quantities of feldspar, and weathering products of refractory oxides (anatase) can be found in the lower reaches of the catchment area. The occurrence of quartz, goethite, hematite, kaolin and anatase in the depositional units of the regolith are expected products of weathering from mafic volcanic rocks (Loughnan, 1969).

Rock geochemistry

Rock geochemistry for the Narracoota Formation was obtained from the Glengarry Basin regional mapping team (Pirajno, F., 1996, pers. comm.). The two groups (1 and 2) are representative of the mafic metavolcanic rocks of the Narracoota Formation which, in themselves, show some chemical diversity.

Geometric means indicate that the significant difference between the rocks of Groups 1 and 2 is the inclusion in Group 2 of high-Mg metavolcanics compared with the more Fe-enriched rocks of Group 1. The Group 2 rocks are correspondingly higher in CaO, MgO, As, Ce, Cr, Mo, Nb, Ni, and Sb and lower in TiO_2, K_2O, Ba, Cu, Ga, Pb, Rb, Sc, Y, Zn, and Zr.

Overall chemistry of the two groups is similar despite differences in absolute values; this is evident from Figure 2 which plots the geometric means of all elements from the two bedrock groups.

Regolith geochemistry

Subramanya et al. (1995) in a study of the PEAK HILL 1:250 000 map sheet found that on a regional scale the most significant factor influencing the chemistry of the regolith was the underlying geology. General trends for the rocks of the Narracoota Formation included increasing Zr and decreasing Ni with distance from source. The regolith sourced from the Narracoota volcanics shows consistent trends between E4 and DC2 and a distinct change in trend for some elements in DC3. The regolith derived from the metavolcanics is distinguished from surrounding regolith derived from other lithological units by generally higher Cr, Ni, Cu, and Pb values. Regional regolith data also reflected the chemical variability of

Table 2. Geometric means for bedrock and regolith from Group 2

	Rock	*E4*	*DC1*	*DC2*	*DC3*
n	*18,20*	*11*	*6*	*5*	*11*
			weight percent		
SiO_2	49	51	38	53	48
TiO_2	0.30	0.65	0.94	0.87	0.89
Al_2O_3	11	10	11	9.1	10
Fe_2O_3	9.0	20	35	26	25
MgO	10.0	0.72	0.30	0.32	0.71
CaO	10	0.39	0.07	0.05	0.25
K_2O	0.03	0.33	0.38	0.35	0.42
LOI	4.6	5.3	6.9	6.0	7.6
			parts per million		
As	3.2	15	37	28	26
Ba	50	128	231	187	212
Ce	2.1	15	12	14	18
Cr	781	1 159	1 367	1 207	1 900
Cu	44	44	47	43	55
Ga	5.8	20	31	28	31
La	1.4	5.9	4.5	5.8	7.3
Mo	1.6	1.7	3.2	2.7	2.8
Nb	2.4	8.6	13	12	13
Ni	322	154	94	62	138
Pb	2.9	17	36	29	31
Rb	0.98	15	18	20	18
Sb	0.80	0.90	2.6	2.0	1.8
Sc	7.2	26	26	25	32
Sn	1.5	1.6	3.1	2.9	2.9
Sr	39	27	11	13	19
Th	0.72	5.5	8.3	10	9.2
U	0.35	1.7	2.7	2.7	2.7
V	165	295	405	401	429
Y	12	7.7	3.7	4.7	6.8
Zn	56	50	43	42	51
Zr	20	69	119	118	119

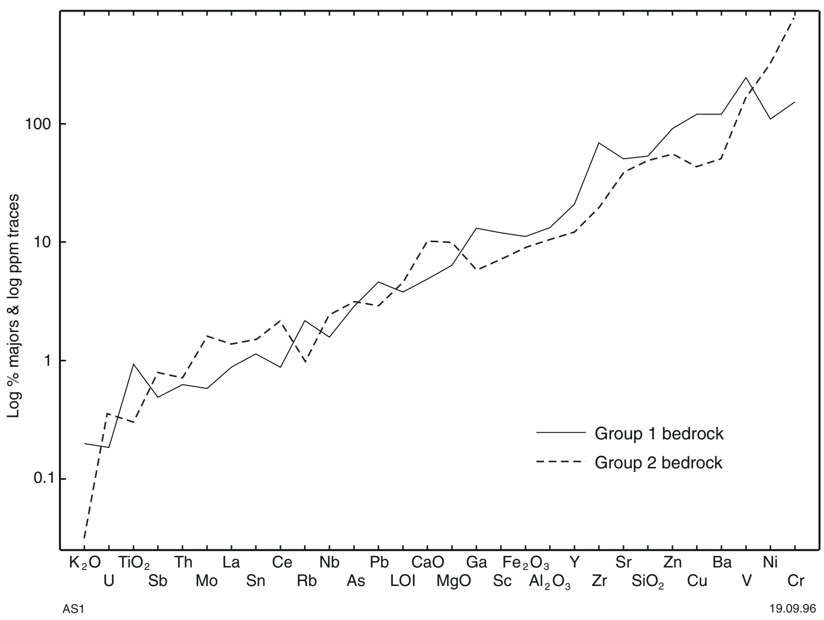


Figure 2. Geometric means of mafic rocks from Group 1 and 2

the source rocks within the Narracoota Formation.

Intragroup variations

Figures 3 and 4 show the variation of elements in different regolith units from the two groups as normalized to rock of that group. The order in which the elements are presented has no significance and has been used only to highlight the 'depletion' and 'enrichment' trends relative to source rock.

Silica remains almost constant in E4 and DC1 for Group 1 with a slight increase in DC2. There is a large decrease in MgO and CaO in all the regolith units, and CaO drops sharply in DC2. This trend is consistent with the early breakdown of silicate minerals such as amphiboles and feldspars to give rise to iron oxides and clay and the release of Ca, Na, and Mg into solution. Aluminium remains relatively immobile. The clays would be rapidly transported, breaking down further in the process.

Among the trace elements, Mo, Sn, Sb, Cr, As, Nb, U, Th and Ce show an appreciable increase in the regolith unit compared with that in the source rocks. These elements are probably carried along with the clays and other sheet silicates and in resistate minerals such as chromite, zircon and oxides of titanium.

In Group 2, there is a similar sharp depletion in MgO and CaO in the regolith units with significant decrease for DC1 and DC2. Both the oxides show relative enrichment again in DC3, possibly due to precipitation of carbonates from solution. Elements such as Al_2O_3, TiO_2, Ba, Cu, Ga, Mo, Nb, Pb, Sc, V, Zn, and Zr show a consistent enrichment trend from rock to DC1, a slight fall in concentration in DC2, and then an increase in DC3. This seems to indicate a relative enhancement of these elements caused by the early loss of CaO, MgO and Na_2O due to the breakdown of primary silicate minerals. The increased chemical weathering in the relatively more stable DC2 regime would cause further breakdown of secondary silicate and oxide minerals, which are then deposited in the most stable depositional regime, the DC3 unit.

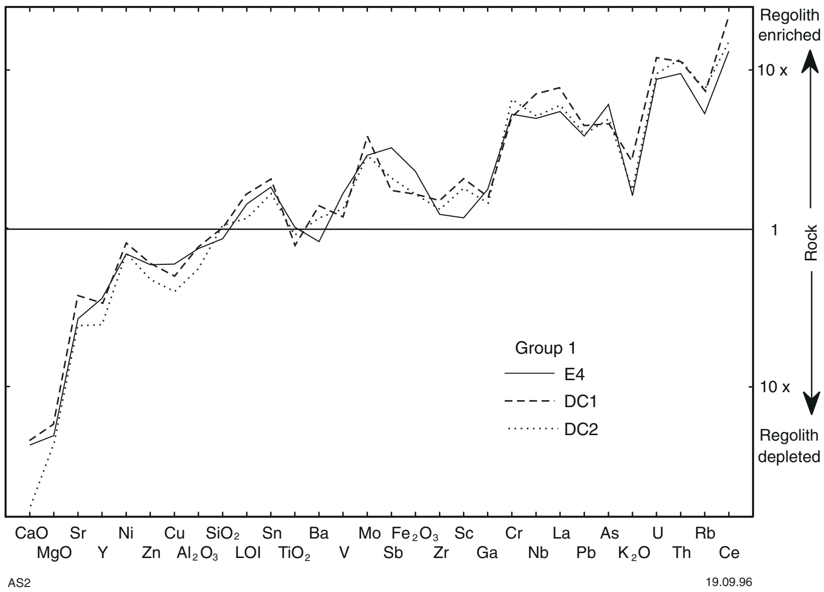


Figure 3. Regolith chemistry normalized to source rock: Group 1

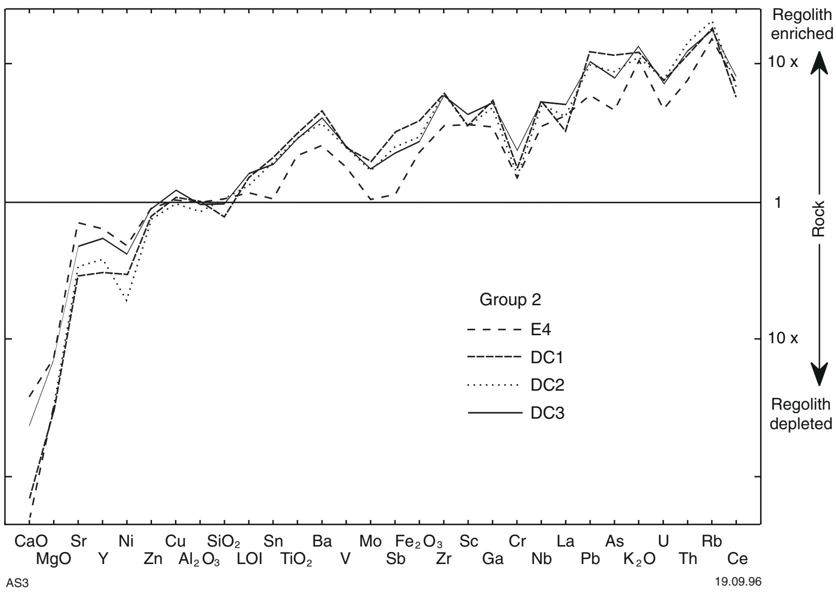


Figure 4. Regolith chemistry normalized to source rock: Group 2

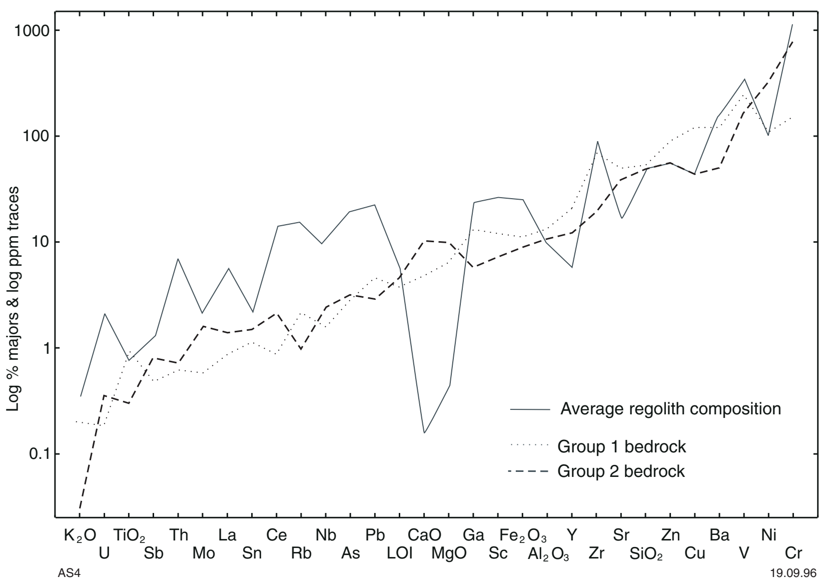


Figure 5. Geometric means of rocks from Groups 1 and 2 superimposed on compositional range of regolith units from the two groups (shaded areas)

All regolith units show K_2O enrichment even though K_2O values in the rock itself are less than the lower detection limit. There is also a corresponding increase in Rb. It is suggested that the high potassium content could be due to 'fixing' in sheet silicates and a contribution from biotite. Extensive shearing, accompanied by metasomatism expressed by the formation of biotite, phlogopite and ankerite, has been recorded in the area covered by Group 2 (Pirajno et al., 1995; Pirajno and Occhipinti, in prep.)

Intergroup variations

As, Ce, Cr, Mo, Nb, Sb, Sn, and U in Group 2 show relatively lower degrees of enrichment compared with their behaviour in Group 1. This is despite the fact that most of these elements have higher concentrations in the rocks of Group 2 compared with those in the rocks of Group 1. These could be explained by the presence of metasomatic minerals such as phlogopite from the shear zones in the regolith units of Group 2, which offsets the enrichment trends seen in Group 1.

There is consistent downslope enrichment of elements such as Cr, Zr, and Th, which probably reside in those minerals more resistant to weathering. Cerium, Ni, Rb, Sb, and Sr do not show consistent trends across groups.

Conclusions

A careful use of geochemical and remotely sensed data and relevant statistical analysis can be developed into a valuable tool in exploration and mapping.

Overall trends in both the groups are similar for most elements, irrespective of regolith unit. As can be seen from Figures 3 and 4, even though absolute values of different elements vary between groups and regolith units, relative proportions commonly remain virtually constant. This indicates that through both the weathering process and the change in mineralogy, the overall chemistry closely reflects that of the parent rock. Figure 5 shows the plot of the geometric means of the two rock groups with the average combined regolith composition. As is evident from this figure, although there is obvious enrichment or depletion of different elements, the general trend of elements mimics that of the parent rock.

An understanding of weathering patterns, coupled with geochemical and mineralogical data, would create the capability to predict behaviour patterns of elements in different environments. This would be useful in areas of extensive cover or poor outcrop where the chemistry of the regolith could be used to determine the underlying geology. Further studies need to be conducted on other lithological units to determine whether such relationships are common.

References

ADAMIDES, N. G., 1995, Doolgunna, W.A. (preliminary edition): Western Australia Geological Survey, 1:100 000 Geological Series.

ANAND, R. R., CHURCHWARD, H. M., SMITH, R. E., SMITH, K., GOZZARD, J. R., CRAIG, M. A., and MUNDAY, T. J., 1993, Classification and atlas of regolith-landform mapping units: CSIRO/AMIRA Project P240A, Exploration and Mining Restricted Report 440R.

BRADLEY, J. J., FAULKNER, J. A., and SANDERS, A. J., in prep., Geochemical mapping of the Robinson Range 1:250 000 sheet: Western Australia Geological Survey, Geochemical Series Explanatory Notes.

CRAWFORD, R. A., FAULKNER, J. A., SANDERS, A. J., LEWIS, J. D., and GOZZARD, J. R., 1996, Geochemical mapping of the Glengarry 1:250 000 sheet: Western Australia Geological Survey, Geochemical Series Explanatory Notes, 90p.

DAWES, P., and Le BLANC SMITH, G., 1995, Mount Bartle, W.A. (preliminary edition): Western Australia Geological Survey, 1:100 000 Geological Series.

GEE, R. D., 1987, Peak Hill, W.A. (2nd edition): Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

GEE, R. D., 1990, Nabberu Basin, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 202–210.

GEE, R. D., and GREY, K., 1993, Proterozoic rocks on the Glengarry 1:250 000 sheet — stratigraphy, structure and stromatolite biostratigraphy: Western Australia Geological Survey, Report 41, 33p.

HYNES, A., and GEE, R. D., 1986, Geological setting and petrochemistry of the Narracoota Volcanics, Capricorn Orogen, Western Australia: Precambrian Research, v. 31, p. 107-132.

LOUGHNAN, F. C., 1969, Chemical weathering of silicate minerals: Amsterdam, Elsevier.

OCCHIPINTI, S., SWAGER, C. P., and MYERS, J. S., in prep., Padbury, W.A.: Western Australia Geological Survey, 1:100 000 Geological Series.

PIRAJNO, F., ADAMIDES, N. G., OCCHIPINTI, S., SWAGER, C. P., and BAGAS, L., 1995, Geology and tectonic evolution of the Early Proterozoic Glengarry Basin, Western Australia: Western Australia Geological Survey, Annual Review 1994–95, p. 71–80.

PIRAJNO, F., and DAVY, R., 1996, Mafic volcanism in the Palaeoproterozoic Glengarry Basin, Western Australia, and implications for its tectonic evolution: 13th Australian Geological Convention, Canberra, Geological Society of Australia, Abstracts no. 41, p. 343.

PIRAJNO, F., and OCCHIPINTI, S., 1995, Bryah, W.A. (preliminary edition): Western Australia Geological Survey, 1:100 000 Geological Series.

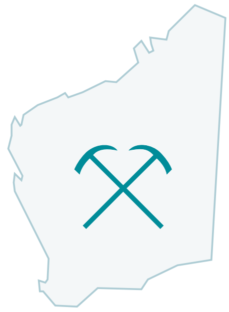
PIRAJNO, F., and OCCHIPINTI, S., in prep., Geology of the Bryah 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

SUBRAMANYA, A. G., FAULKNER, J. A., SANDERS, A. J., and GOZZARD, J. R., 1995, Geochemical mapping of the Peak Hill 1:250 000 sheet: Western Australia Geological Survey, Geochemical Series Explanatory Notes, 59p.

Program review

Program 3
Subprogram 3102
MINERALS AND PETROLEUM RESOURCE STUDIES

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 55-page volume listing whole-rock major, trace and rare-earth element analyses of felsic igneous rocks (granitoids, porphyries and felsic volcanic rocks) from the southwest Eastern Goldfields Province was published as GSWA Record 1995/2. A map showing the interpreted granitoid geology of the southwest Eastern Goldfields Province will be published in September, 1996 followed by a report describing the geology and geochemistry of the granitoids.

Ravensthorpe greenstone belt

The 1:100 000 geological maps of Cocanarup and Ravensthorpe are expected to be published in early 1996–97 with publication of the Explanatory Notes later in that year. Initial conclusions concerning the tectonic evolution and origin of mineralization in the greenstone belt are summarized in the Annual Review 1994–95. A more complete description of the geology and mineralization of the greenstone belt, including the geochemistry of the tonalite and calc-alkaline volcanic rocks at Ravensthorpe, will be completed in September, 1996, for publication in 1997–98.

Kanowna–Kurnalpi–Pinjin regional gold project

Fieldwork in areas east of Kalgoorlie (roughly equivalent to the Edjudina and Kurnalpi 1:250 000 sheets) has been completed with over 600 deposits visited. A report is being compiled that will contain formal descriptions of approximately 200 deposits, each with production exceeding 5 kg of gold, and descriptions of all unmined resources that appear on the GSWA MINEDEX database. The report will follow the format of GSWA Records 1993/13, 1993/14 and 1993/15 and will be accompanied by a 1:250 000-scale solid-geology map that shows the location of the deposits described. The report will include a list of AMG coordinates of all the deposits described. These data will help to constrain exploration models for mesothermal gold deposits in the Yilgarn Craton. The report and map will be completed in September, 1996, and publication can be expected in 1997–98.

Significant results to emerge from this project include:

- Relative abundance of mineralized felsic rocks
- Widespread hematitization in gold deposits (*see*, for example, Witt, this volume).
- Recognition of calc-silicate alteration at several mining centres (previously unrecognized or under-appreciated)
- Recognition of possible epithermal and porphyry styles of gold mineralization
- Improved understanding of structural controls on gold mineralization (particularly D_1 faults)
- Appreciation of potential for syenitic intrusions to host gold mineralization (syenitic intrusions not as late as previously thought)
- Potential clarification of the relationship between late-tectonic uplift and gold mineralization, and the role of late extension.

Mineral occurrences in the Halls Creek Orogen

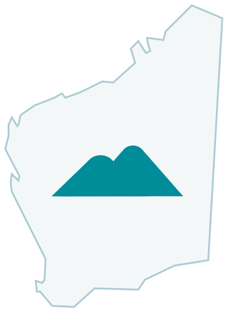
Approximately 300 mineral occurrences in the Halls Creek Orogen that are referred to in the WAMEX database have been documented in the field. Formal descriptions of the occurrences are contained in a report that is currently being compiled. The report also attempts to relate the occurrences to the new regional geological framework that has emerged from the recent 1:100 000 geological mapping carried out by GSWA and AGSO, under the NGMA. A draft report is expected to be completed in September, 1996 and will be completed following compilation of an interpretative regional geology map of the Halls Creek Orogen. Publication of the report and map is expected in 1997–98. Some preliminary results are given *in* Witt and Sanders (this volume).

Volcanological facies and alteration mapping in the Kanowna–Gindalbie area

During 1996–97, fieldwork will commence for a project that undertakes to produce a new style of map in the Eastern Goldfields Province. It is intended to show the distribution of primary depositional facies for felsic and mafic volcanic rocks, and the subsequent styles of regional- and district-scale alteration. It is hoped that this approach will help to identify environments that are suitable for more-detailed exploration for epithermal and volcanogenic massive sulfide base- and precious-metal deposits. If this initial project is successful, it is intended to extend the maps north and south along the Gindlabie Terrane (*see* Witt et al., this volume).

W. K. Witt

Industrial minerals studies



Objectives: *Compilation of commodity Bulletins, preparation of commodity Reports as required for Commonwealth and State departments, continuation of the GSWA/MGMR Research Project, preparation of the 'Australian Uniform Code of Nomenclature for Reporting Production of Industrial Minerals', continuation of resource advice to industry, government, and public, and the provision of geoscientific advice on Mining Act matters.*

An important objective of the GSWA is to provide advice to Government, industry, and the public on prospectivity, geology, and distribution of industrial minerals in Western Australia. Accordingly, important and relevant projects on industrial minerals are identified and implemented by the Industrial Minerals Group. The main projects completed during 1995–96 were the compilation of three commodity bulletins and one report.

Commodity bulletins

As planned, three commodity bulletins were compiled and submitted for publication. These are entitled: Talc, Pyrophyllite, and Magnesite in Western Australia; Barite and Fluorite in Western Australia; and Limestone Resources in Western Australia. The first bulletin is likely to be published in early 1997, and the others later in that year. These three 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 of these bulletins are:

***Talc, pyrophyllite and magnesite*:** Western Australia has produced over 3 Mt of talc from 1940 to 1994 and is currently the largest producer of this mineral in Australia. Talc in Western Australia is produced from two mines, at Three Springs and Mount Seabrook, and the total identified talc resource in the State is approximately 11 Mt. The most prospective areas yet to be explored in Western Australia are the regions of Proterozoic dolomite intruded by mafic dykes, such as those in the Moora Belt. Other prospective areas for talc in the State are discussed in the Bulletin.

The only known deposit of pyrophyllite of potential commercial interest is at Pinnacle Well, where an inferred resource of 10 Mt has been calculated. The Kangaroo Bore area is also considered to be prospective for pyrophyllite.

The last recorded production of magnesite in Western Australia was 16 729 t in 1984, valued at $ 215 936, from deposits at Bandalup near Ravensthorpe where the largest known deposits in Western Australia are located. The total resource in the Bandalup area is around 1.6 Mt. A large deposit of magnesite also occurs at Bulong. The Bulletin discusses many other prospective localities for magnesite in Western Australia.

***Barite and fluorite*:** From 1946 to 1990, Western Australia produced 138 697 t of barite valued at six million dollars. The biggest deposit, North Pole, produced 129 505 t during this period with grades varying from 65.5 to 97.4% $BaSO_4$, and of specific gravity from 3.86 to 4.27. From 1990, no production was recorded in Western Australia. The total barite resource available in the State is considered to be several million tonnes although published figures account for only 1.3 Mt. Other prospective areas for barite are discussed in the Bulletin.

Western Australia has no recorded production of fluorite, but contains two large deposits at Speewah and Meentheena. The deposit at Speewah contains a measured resource of 1.87 Mt at 25.8% CaF_2, an indicated resource of 0.41 Mt at 24.2% CaF_2 and an inferred resource of 1.59 Mt. Fluorite mineralization at Meentheena is mainly in the form of veins in faulted volcanic rocks. It is estimated that the deposit contains over 132 kt of fluorite at 80% CaF_2 from all veins mined to a depth of 17 m. There are a number of other prospective areas for fluorite in the State discussed in the Bulletin.

Limestone: Large deposits of limestone and limesand occur along the coastal belt from Dampier in the north to the Eucla Basin in the south. High quality, metallurgical grade limestone occurs at Cape Range and also 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 Dampier Archipelago. Many of these deposits contain in excess of a few hundred million tonnes of high-grade limestone and limesand. Limestone Resources in Western Australia provides information on the quality and resources of major limestone deposits in the State. The report also contains information on the mode of occurrence and end-uses of limestone.

Commodity reports

The Shark Bay Basic Raw Materials Report was completed and submitted for publication. Some highlights of this reports are:

Shark Bay basic raw materials: Most construction works in the Shark Bay World Heritage Area are to support the tourist industry, currently estimated at 100 000 persons per year together with a permanent population of less than 2000. Road construction is the biggest consumer of basic raw materials in the World Heritage Area, and it has been estimated that over the next 30 to 40 years, approximately 500 000 loose cubic metres of materials will be required for the repair and upgrade of the bitumen road between the Overlander Roadhouse, on the North West Coastal Highway, and Monkey Mia. Although there is no shortage of road materials, transportation costs will increase as current deposits closer to tourist facilities are exhausted. Edel Land, in the west, has the greatest potential for reasonable quality deposits.

GSWA/MGMR Research Project

This project was initiated last year under a Memorandum of Understanding of a Government-initiated Sister-State Agreement with the Department of Geology and Mineral Resources (MGMR) of the Zhejiang Province in the People's Republic of China. Part of the agreement was for the provision of experts in industrial minerals from MGMR to assist in a research project in Western Australia relating to a number of currently unexploited industrial mineral deposits that indicate an enhanced potential for development. Completion of this project is behind schedule owing to delays in obtaining an English translation of the technical report produced by the MGMR. However, GSWA staff have completed report sections on Marchagee Talc, Gabbin Clay, and Warriedar Tourmaline Deposits. The final report should be completed by mid-1996.

Australian Uniform Code of Nomenclature

This project is a voluntary and co-operative arrangement between Commonwealth, State and Territory Departments which have a close liaison with the mining industry. The purpose of the code is to provide a generally acceptable framework for the reporting of individual industrial mineral production figures in a consistent way, based on the end-uses of the minerals. The final report 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.

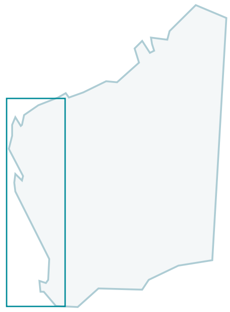
Other activities

A considerable amount of time was spent in carrying out the ongoing responsibilities of resource advice to industry, government and public. Administrative matters such as the provision of geoscientific advice relating to the Mining Act were also carried out during the year.

Three weeks fieldwork was undertaken in different parts of the State gathering data for the Limestone Bulletin. Fieldwork related to the other two commodity Bulletins had been carried out before the current review period. Preparation of the report on Shark Bay Raw Materials necessitated ten days fieldwork. Other field trips involved the inspection of pegmatites in the Mukinbudin area and the micaceous iron oxide deposit at Mount Gould.

P. B. Abeysinghe

Petroleum studies, Western Margin



Objective: *To stimulate and encourage petroleum exploration activities in 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 and open-file industry data.*

The Western Margin Project encompasses the series of onshore sedimentary basins that lie to the west of the Yilgarn Craton and stretch north–south over 1500 km (Fig. 1) from the Bunbury Trough of the southern Perth Basin to the northern onshore limits of the Carnarvon Basin in the vicinity of the Onslow township.

The sedimentary sequences are Permian to Jurassic within the Perth Basin, Silurian to Permian with a veneer of Cretaceous and Tertiary within the Southern Carnarvon Basin, and Palaeozoic to Tertiary within the North West Cape promontory and the Peedamullah Shelf. The Mount Horner oilfield, Dongara gas- and oilfield, and the Beharra Springs, Yardarino, Mondarra, and Woodada–East Lake Logue gasfields have been discovered within the northern Perth Basin. The Tubridgi gasfield and Rough Range oilfield have been discovered within the Peedamullah Shelf and Rough Range areas. Large parts of the Perth and Carnarvon Basins, however, are virtually unexplored: this research aims to encourage industry to invest in those unexplored areas that possess hydrocarbon potential. The development of a gas discovery in the onshore Carnarvon Basin and northern Perth Basin are greatly facilitated by the presence of the Dampier–Perth–Pinjarra and Dongara–Perth gas pipelines. Currently, Western Australia produces more than 50% of the nation's oil and gas from offshore areas. The potential for increasing this share with additional onshore discoveries is rated highly.

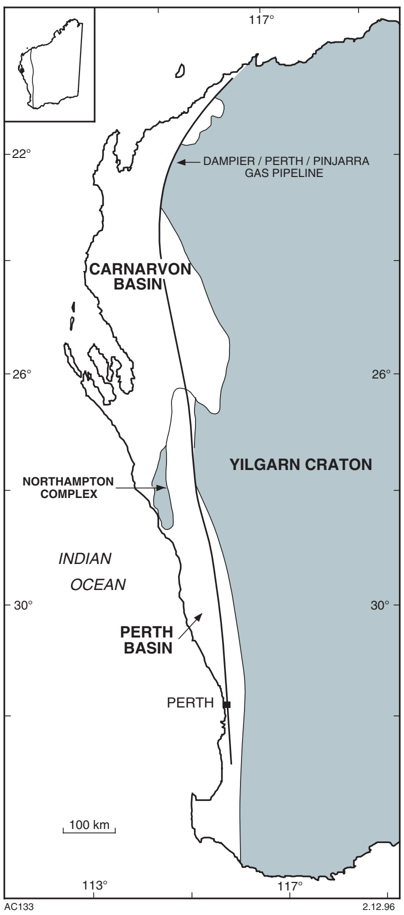


Figure 1. Location of the basins included in the Western Margin Project

Highlights and activities

A number of major data acquisition projects were completed within budget during 1995–96. These included the acquisition of the 45 000 km Merlinleigh aeromagnetic and radiometric survey; the 4100 station Merlinleigh helicopter-supported gravity survey and the continuously cored Gneudna 1 (492 m) and Ballythanna 1 (446 m) stratigraphic boreholes.

Processed images of the aeromagnetic and gravity surveys have been released for sale at nominal cost in both hard copy and digital format to industry and the public. These potential-field data have been integrated with seismic survey, surface geological and other subsurface borehole data to generate regional subsurface-structure maps, at various stratigraphic levels, for the Merlinleigh Sub-basin. These maps are one of the essential components, in conjunction with petroleum geochemical, maturation and timing parameters, to establish lower risk areas for the discovery of hydrocarbon accumulations. The report on the structure, stratigraphy and geochemistry of the Merlinleigh Sub-basin, scheduled to be published in 1996–97, will document these findings.

The objective of the Gneudna and Ballythanna stratigraphic coreholes was to further evaluate the source potential and maturation levels of Devonian and Permian units within the Merlinleigh and northern Byro Sub-basins. Existing subsurface control from petroleum and mineral boreholes is limited and samples from shallow mineral boreholes are often unsuitable as they do not penetrate below the weathered layer.

The Gneudna 1 corehole was inclined at 55° to be perpendicular to the outcropping (Devonian) type section. The well reached a total depth of 492 m in granitic basement. Subsequent geochemical analyses of carbonaceous shale horizons gave positive results for specific intervals, indicating that thicker developments of these facies could be expected in a more basinward position. This concept will be pursued in the forthcoming 1996–97 Mooka 1 and Barrabiddy 1 corehole programs in the Gascoyne platform.

The Ballythanna 1 corehole was designed to evaluate the source potential of the Permian Callytharra formation. This vertical stratigraphic corehole achieved the planned stratigraphic objectives by intersecting a complete Callytharra section with excellent 98% core recovery. The evaluation of the source potential of this predominantly shelfal limestone sequence was marred by the presence of an unexpected sandstone member which replaced much of the Callytharra interval. The name 'Ballythanna sandstone member' has been assigned to this new unit. Geochemical analyses indicate the Callytharra limestone and the associated sandstone member have limited source potential in this area.

However, highly encouraging and positive analyses were obtained from core samples selected from other mineral and petroleum bores. All these geochemical and stratigraphic results for the Merlinleigh and Byro Sub-basins are summarized in recently published GSWA Records.

Similar reports on the structural interpretation, hydrocarbon potential and exploration of the Giralia and North West Cape areas in the Carnarvon Basin have been prepared after a comprehensive analysis and review of existing subsurface and surface data.

To address the questions of reservoir quality and the diagenetic factors that influence reservoir performance, a study on the reservoir quality of the Lower Permian Moogooloo Sandstone was undertaken. The Moogooloo Sandstone is the primary potential reservoir in the basin. To assess and predict the distribution of reservoir quality, a petrophysical database was established for the Moogooloo Sandstone in the Merlinleigh Sub-basin, and its laterally equivalent Keogh Formation in the Byro Sub-basin. This work included the integration of existing industry data on core porosity, permeability, petrology, thermal maturity and wireline porosity from archival core and statutory report sources with new analyses and thin-section data. Results from this study and modelling work enable explorers to predict Moogooloo Sandstone porosity and permeability parameters throughout the sub-basin by referring to a series of maps and crossplots.

A pilot seismic reprocessing project, aimed at enhancing 1960s analog-recorded seismic data from the southern Peedamullah Shelf has been initiated. These surveys are the only seismic data ever acquired in this area and were shot as regional grids, providing the only subsurface structured data for the area. Given the anticipated improvements arising from current processing techniques of the digitized data, a number of regional lines will be reprocessed and the structural and stratigraphic information integrated into existing datasets.

Future work

Acquisition of new data during 1996–97 will be limited to the drilling of the 500 m Mooka 1 and 800 m Barrabiddy 1 stratigraphic coreholes. Following the positive Gneudna 1 results, these stratigraphic coreholes will further evaluate the source potential of the Devonian and older units in the Gascoyne platform. Mooka 1 and Barrabiddy 1 are located on the eastern flank of the Gascoyne platform, where the overlying Mesozoic section is thin enough to justify this investigation. Approximately 210 m and 115 m of Mesozoic section will be drilled at Barrabiddy 1 and Mooka 1 respectively prior to entering the Palaeozoic section.

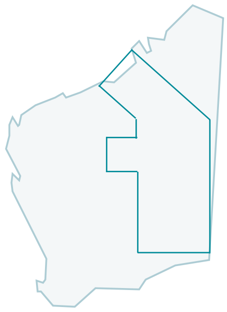
The stratigraphic and analytical geochemical data that arise from these coreholes will be merged with existing and new analyses from mineral and petroleum core data to provide a summary interpretation of the maturation history and source potential of the Gascoyne platform. This report will be complemented by a structural interpretation of the platform utilizing existing seismic, magnetic and gravity data.

A study commenced in late 1995 of the Peedamullah Shelf will extend and complement the existing databases and interpretations of the Cape Range, Giralia and Merlinleigh areas. The relatively high levels of exploration activity in the Peedamullah area have generated significant datasets that are being reviewed, reinterpreted and summarized for inclusion in a series of basic-data and interpretative packages.

These products, in conjunction with a similar range of publications from the Interior Basins project, will make available the geoscientific concepts and data to stimulate additional onshore petroleum exploration within Western Australia.

A. Svalbe

Petroleum studies, 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 underexplored while the recently defined Savory Basin remains unexplored.*

Highlights 1995–1996

- Savory Basin gravity survey
- Trainor 1 stratigraphic coring
- Canning Basin field study
- Officer Basin publication

The Savory Basin gravity survey has been interpreted and results will be published both as a Record of the GSWA and an ASEG paper. These data have enhanced our understanding of the structural and stratigraphic setting of Mesoproterozoic and Neoproterozoic sediments of the Officer Basin. The gravity data have been released to the public.

One 709 m stratigraphic core was completed at Trainor 1. Examination and analysis of sedimentary rocks from this core continue with encouraging data on reservoir quality in the Neoproterozoic and source potential in the Mesoproterozoic of the Officer Basin. The Trainor 1 core has been examined and sampled by a number of oil and mineral exploration companies.

S. Apak's paper, 'Depositional History of the Lower Permian Carolyn Formation and Poole Sandstone in the Northern Canning Basin: Implications for Hydrocarbon Potential' was published as Record 1996/8. This report follows from field studies and leads into detailed seismic stratigraphic interpretation of Permo-Carboniferous sediments in the Barbwire Terrace area.

D. Perincek's paper, 'The age of Neoproterozoic–Palaeozoic sediments within the Officer Basin of the Centralian Super-basin can be constrained by major sequence-bounding unconformities' was published in the APPEA Journal 1996. This paper highlights the continuing improvement in stratigraphic correlation within the Officer Basin through integration of all available data.

Publications in preparation

During the 1995–96 fiscal year the emphasis on work in the Canning and Officer basins has shifted from general review and definition of the datasets and exploration challenges to interpretation of data. Final drafts of the scoping studies for the Canning, Officer and Savory Basins, and the well completion report for Trainor 1 are in preparation. An abstract on interpretation of the Savory Basin gravity survey (G. Carlsen and S. Shevchenko) has been accepted by the ASEG for publication. The first edition of Reservoir Data in the Canning Basin Permo-Carboniferous (P. Havord) has been submitted for internal publication. Two technical articles from the Interior Basins Team are included in this Annual Review. Work programs for the Canning and Officer Basins are listed below and detailed in the following paragraphs.

Intended publications

- Canning Basin scoping study.
- Officer Basin scoping study.
- Savory Basin scoping study.
- Neoproterozoic Reef Plays in the Officer Basin, an untested concept (external publication).
- The Petroleum System of the Lennard Shelf.
- A complete stratigraphic correlation and structural mapping within the Grant Group on the Barbwire Terrace, Canning Basin log cross sections, structure maps and isopachs.
- Second edition of Reservoir Data in the Canning Basin Permo-Carboniferous.
- Reservoir characterization in the Officer Basin Neoproterozoic stratigraphic coring
- Geochemical and thermal maturation modelling for the Officer Basin.
- Palynology in the search for Proterozoic hydrocarbons.
- Recommendation for stratigraphic coring in the Yowalga Sub-Basin including three structural maps and two isopachs including seismic interpretation; geophysical cross-sectional model; five well-correlation cross sections; prognosis of thicknesses and stratigraphy to be cored; a definition of technical objectives for the well and a proposed location.
- Complete outcrop studies in the Officer Basin in support of recommendation for complete stratigraphic coring in the Yowalga Sub-basin to a depth of 1500 m at a cost not to exceed $250 000.

Possible outputs

- Hydrogeology of the Trainor and Bullen sheets.
- Structural analysis and correlation from Trainor 1 dipmeter data to outcrop.

Notes on Canning Basin work program

Stratigraphic correlation and structural mapping within the Grant

Group on the Barbwire Terrace will be completed in mid-1997. This stratigraphic correlation and structural mapping will be extended to the remainder of the Canning Basin Grant Group. Improved palaeontological correlations to aid stratigraphic correlation within the Grant Group will be undertaken. There will be comparison of potential hydrocarbon plays with the commercial discoveries of the Lennard Shelf to establish models for the recognition and prediction of hydrocarbon habitats. Analysis of cores and logs for a more complete reservoir characterization in the Canning Basin Permo-Carboniferous will be undertaken. Geochemical and thermal maturation modelling for the Canning Basin as required will be undertaken following a thorough review of the AGSO studies on Devonian and older sediments of the Canning Basin. Recommendation for the acquisition of new data in the Canning is not expected until the 1997–98 fiscal year. These works will lead to publication of the Canning Basin Permo-Carboniferous Petroleum System Record in 1998. Without a full-time seismic interpreter, the team will not complete a reinterpretation of much of the seismic data before 1999. Publication of a Record on the Petroleum System of the Lennard Shelf will serve to indicate directions for future exploration of the Canning Basin.

Notes on Officer Basin work program

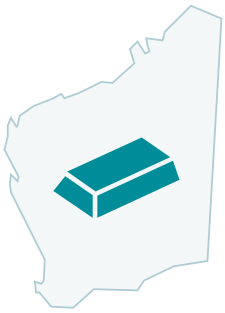
A full technical recommendation for stratigraphic coring in the southern Yowalga or Western Officer Basin has been recently completed. This recommendation is supported by correlation to all relevant bores (five log correlation pairs), interpretation of seismic data providing ties to locate stratigraphic control including structural maps of three horizons and two isopachs. A field study not exceeding two months is planned during which local outcrops will be correlated to the proposed coring location and scouting to the site will be completed. This field trip will include examination of outcrops of the Turkey Hill Beds, Neale Beds, Robert Beds, Woolnough Beds, Madley Beds, Babbagoola Beds, Browne Beds, and Skates Hills Beds. A proposed location and prognosis of thicknesses and stratigraphy to be cored, and a definition of technical objectives for the well will also be submitted. Geophysical modelling will be completed as necessary to assist in the estimation of sedimentary thicknesses and densities at the proposed location. It is anticipated that the proposed location will fully penetrate the Browne Beds in a more marginal setting than previous Yowalga Sub-basin cores, and have a total depth no greater than 1500 m. Based upon tenders received, this core hole can be completed at a cost not exceeding $250 000.

Analysis of cores, cuttings, and logs for a more complete reservoir characterization of Neoproterozoic carbonate and clastic sequences has commenced. Geochemical and thermal maturation modelling for the Officer Basin will be completed and published prior to coring. Stratigraphic correlation based upon palaeontological and palynological studies will be examined and published.

This field work and stratigraphic coring combined with a complete reinterpretation of the seismic data within the Officer Basin will lead to a definitive publication on prospectivity within the basin during 1998.

G. M. Carlsen

Geoscientific advice relating to mining legislation



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 approximately 3400 mineral tenements was reviewed during 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 on first-year exploration licences (Table 1). Where appropriate, 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.

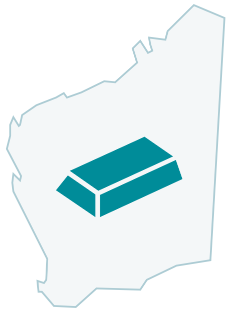
Table 1. Tenement reviews

Geological advice 1995–96	*No. of tenements*
Expenditure exemption 1 year	2 909
Expenditure exemption 2 or more years	95
Extension of term of exploration licence	353
Dealings in first-year exploration licences	36
Total	**3 393**

I. Ruddock

Resource studies (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 1995–96, ongoing data capture formed a large part of the function, together with ongoing advice to a wide range of customers. Early in 1996–97, non-confidential digital data from MINEDEX, including information on mineral resource and mine locations, commodities, ownership, and development status, will be released to the public. A report, which has been prepared to accompany data release, describes terminology used in the database.

An atlas of the State's mineral deposits and petroleum fields, which draws on the MINEDEX database, has been released. Resource localities are superimposed on maps showing the geology of the State. Also released was a map showing Pilbara iron-ore geology, resources and tenement holdings.

Development of the MINEDEX database continued during the year, with provision being made to incorporate details of State production of mineral resources. This will allow current resources and historical production to be linked to provide total in-ground resources for known individual deposits and hence for the whole State.

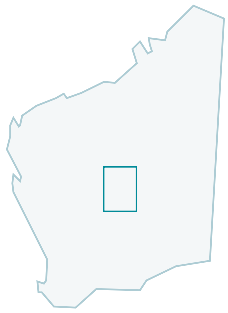
A quarterly update of mineral exploration activity was produced during the year. This revealed that there was a continuing high level of mineral-exploration expenditure in Western Australia, led predominantly by the gold sector. Western Australia is maintaining its dominant share (55%) of Australia-wide exploration expenditure, but the rate of overseas activities by Australian companies is increasing.

W.A. Preston

Subprogram 3103
REGIONAL GEOSCIENCE MAPPING

Eastern Goldfields Project

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



Summary of activities 1995–96

First edition maps of Sir Samuel, Darlot and Duketon (1:100 000 sheets) were released in early 1996, and field mapping was completed on Wiluna and Millrose (1:100 000 sheets). A preliminary interpretation of Wiluna (1:100 000) was presented in the 1994–95 Annual Review, and a summary of the geology of Millrose (1:100 000) is given below. Some new field mapping has been carried out for new editions of Menzies, Edjudina, Sir Samuel, Duketon and Wiluna (1:250 000 sheets).

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.

SHRIMP U–Pb zircon ages have been obtained for a variety of granitoid, gneissic, metasedimentary, and metamorphosed felsic volcanic rocks from SIR SAMUEL and DUKETON (1:250 000 sheets) collected in early 1995. These include a date for the Jones Creek Conglomerate on SIR SAMUEL (1:100 000) that indicates a depositional age younger than 2645 Ma. A date of 2697 ± 6 Ma for felsic gneiss from DUKETON (1:100 000) is the oldest yet documented for gneissic rocks in the Eastern Goldfields. A further sampling program was undertaken in 1996 and more geochronological data will be forthcoming.

Release of information from earlier phases of the Eastern Goldfields mapping program continued with the release of an interpretative map of the Geology of the Kurnalpi–Edjudina Greenstone Terranes (1:250 000) and the geological map of RIVERINA (1:100 000).

New magnetic-features maps covering DUKETON and WILUNA (1:250 000 sheets) are available in hardcopy and digital formats. In addition, there are new processed images of the 1:100 000 sheets which compose the SIR SAMUEL, DUKETON and WILUNA 1:250 000 sheets (Fig. 2). AGSO has flown a new airborne geophysical survey over NABBERU (1:250 000) and images will be available shortly.

An industry trial of a digital index map of open-file WAMEX data covering SIR SAMUEL (1:100 000) was well received and comments and suggestions have been taken into account in designing the final product. The first general release of this product will take place during 1996–97. Index maps covering the rest of SIR SAMUEL, DUKETON and WILUNA (1:250 000 sheets) will follow in quick succession.

The Kalgoorlie Office of the GSWA continues to provide geological information and advice to both the local community and visitors from outside the region. Officers based in Kalgoorlie are actively involved

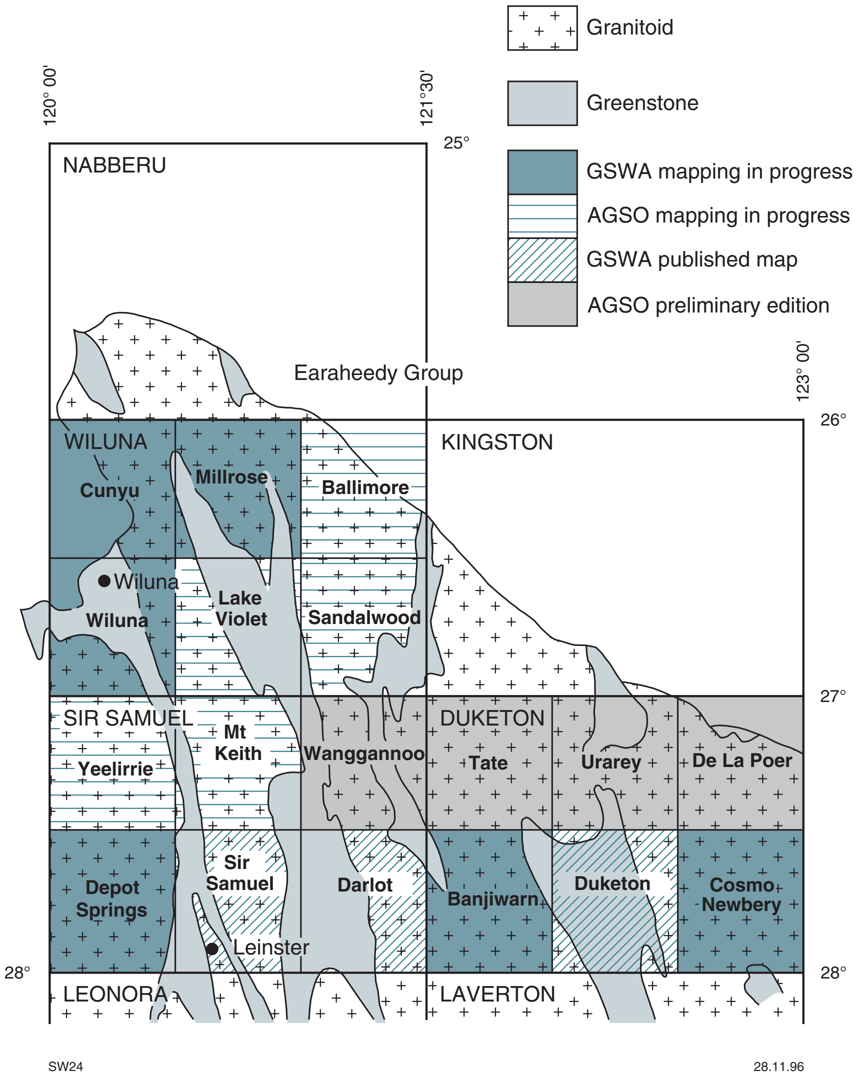


Figure 2. Simplified geology of the northern part of the Eastern Goldfields showing the study areas of the 1:100 000 mapping program

in regional mapping and gold mineralization studies.

The NGMA Eastern Goldfields Project continued with AGSO geologists carrying out field mapping on WILUNA and SIR SAMUEL (1:250 000 sheets). AGSO released preliminary editions of a number of 1:100 000 sheets generated during earlier phases of the mapping program. These include sheets from within the SIR SAMUEL, DUKETON and LAVERTON 1:250 000 sheet areas. AGSO and GSWA conducted a very successful Eastern Goldfields Mapping Expo at the WMC Conference Centre in Kalgoorlie in September. The display was subsequently mounted in the foyer of Mineral House in Perth. A poster featuring an interpretation of the SIR SAMUEL, DUKETON and WILUNA (1:250 000) sheets was presented at the 13th Australian Geological Convention in Canberra in February. GSWA has been involved in preliminary planning with AGSO for a deep-crustal seismic traverse proposed for the northern part of the Eastern Goldfields in 1997.

A regolith map and associated geochemical maps and data for SIR SAMUEL (1:250 000 sheet) have been published as hardcopy and in digital form. A similar product for NABBERU (1:250 000) will be published in the coming year. A detailed study of the regional setting of gold deposits in the Kanowna–Kurnalpi–Pinjin region is nearing completion.

MILLROSE (1:100 000)

Greenstone sequences in the western and eastern parts of MILLROSE (Fig. 3) are separated by areas of granitoid rock and quartzofeldspathic gneiss. The two major sequences, which coalesce to the south on LAKE VIOLET (1:100 000), make up the northern extension of the Yandal belt, a greenstone sequence that has received much publicity as a result of a number of major gold discoveries over the past few years. One of these gold deposits is currently being mined on MILLROSE at Nimary and Jundee. The discovery of this deposit, along with those at Bronzewing and Mount McClure to the south, has generated considerable exploration activity throughout the region.

The lack of good outcrop and the deep weathering profile have meant that much of the geology on MILLROSE has been interpreted from aeromagnetic data and information obtained from mineral exploration drillholes. The better exposed western sequence includes the Jundee–Nimary gold mine. Here the limited outcrop and intensive exploration drilling has allowed some indication of regional stratigraphy and structure to emerge. This sequence appears to have an overall west facing, indicated by sedimentary structures in diamond drillcore from Jundee, and pillow-lava structures in metamorphosed high-Mg basalts along the eastern side of the belt. The base of the sequence is dominated by high-Mg basalt and ultramafic rocks, and grades upwards to a mixed metasedimentary and mafic sequence at Jundee. Farther to the west is a thick sequence of metamorphosed felsic volcanic and sedimentary rocks. A suite of mafic–ultramafic rocks containing a prominent unit of banded iron-formation (BIF) marks the western side of this greenstone belt. If the whole belt represents one greenstone succession, then this BIF must lie near the top of the preserved sequence. Although there is strong deformation in high-strain zones at granite–greenstone contacts, rocks within the sequence away from these contacts are generally little deformed.

The eastern sequence, which extends northwest and south from Millrose homestead, is generally much less well exposed than the western

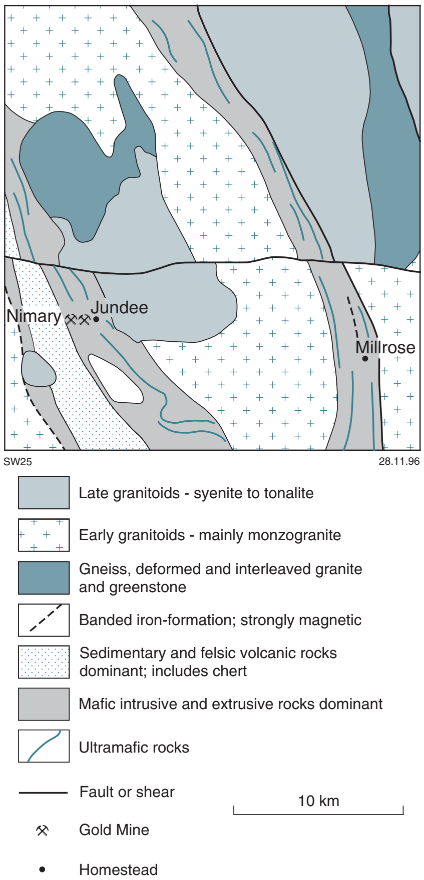


Figure 3. Simplified geology of the MILLROSE 1:100 000 sheet

sequence and all surface exposures are deeply weathered. The Millrose sequence is dominated by mafic and ultramafic rocks with subordinate metamorphosed felsic and sedimentary rocks including quartz–muscovite schist, shale, and chert. Recrystallized, laminated quartz–magnetite rock from a drillhole north of Millrose Homestead may represent a thin unit of banded iron-formation. Some deeply weathered mafic rocks are probably deformed mafic metasedimentary rocks. The eastern sequence is generally more strongly deformed than the western sequence and the deep weathering, strong deformation, lack of facing indicators and poor outcrop make it difficult to establish a stratigraphic succession for this belt. The eastern contact of this sequence is marked by a major shear zone, which is the northern extension of the structure that bounds the Yandal greenstone belt to the south. This structure has been named the Ninnis Fault on DARLOT to the south and was formerly known as the Celia Lineament.

The metamorphic grade is generally low although, as in other parts of the Eastern Goldfields, there are local areas of higher grade rocks along granite–greenstone contacts. Structure within the greenstone sequences is difficult to determine owing to the lack of exposure. The dominant structures are the major shear zones along the granite–greenstone contacts that are correlatable with the D_3 shear zones elsewhere in the Eastern Goldfields.

Away from the greenstone sequences, there is a wide variety of granitoid rocks ranging from diorite to syenite. Emplacement of most of the granitoid rocks appears to predate the latest movement on the major shear zones.

Areas of gneiss to the north of Jundee and north of Millrose Homestead are dominated by quartzofeldspathic gneiss with a minor amphibolite component. The area of gneiss that lies north of Millrose Homestead contains some recrystallized BIF. These gneissic rocks have generally metamorphosed at a higher grade than the greenstones and appear to have a more complex structural history. They may represent an earlier felsic-dominated supracrustal succession.

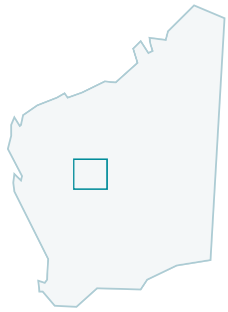
WILUNA (1:100 000)

The article published in the 1994–95 Annual Review gave an overview of the Archaean structural and stratigraphic history of WILUNA. Fieldwork in the Proterozoic strata of WILUNA has allowed correlations to be made with the detailed mapping undertaken in the adjacent Glengarry Basin. The Finlayson Range in the northwestern part of WILUNA is dominated by the clastic Finlayson Member of the Juderina Formation, overlain by chert-rich rocks of the Bubble Well Member. Around the Mount Wilkinson and Mount Lawrence Wells, in the west of WILUNA, there is an angular unconformity between cherts and chert breccias of the Bubble Well Member and the overlying, poorly bedded, horizontal strata of the cherty and clastic Yelma Formation.

S. Wyche

Glengarry Basin Project

Objective: *To increase geoscientific knowledge of the Early Proterozoic Glengarry 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 petrology, geochemistry, geophysics, remote sensing, geochronology and metallogeny.*



Work done and results during 1995–96

Fieldwork was completed on MILGUN, PADBURY, GLENGARRY, MOOLOOGOOL and THADUNA, and parts of MARYMIA, JAMINDI and YANGANOO 1:100,000 map sheets (Fig. 4). Photoscale compilation of the above map sheets was also completed. The final geological maps of BRYAH, DOOLGUNNA and MOUNT BARTLE, which were published as preliminary plots last year, are currently being prepared. These are expected to be completed early in 1997.

A Paradox database was established to detail field locality, petrology and geochemistry of all samples collected by the mapping team members. A total of 2253 samples has been collected and studied since October 1993. Of these, 208 samples were analysed for major and/or trace elements and 1389 thin sections cut for petrological studies. Four samples were dated by the high-precision U–Pb zircon method. Geophysical interpretation, based on the aeromagnetic data obtained during 1994, of the PADBURY and MILGUN sheets was carried out in house. An external contractor is currently working on the remainder of the map sheets completed during this field season.

During the year, team members presented papers on aspects of the geology of the Glengarry Basin at two conferences. Also, six interim reports on the geology, stratigraphy and tectonic evolution of the Glengarry Basin have been presented in GSWA Annual Reviews, including this volume.

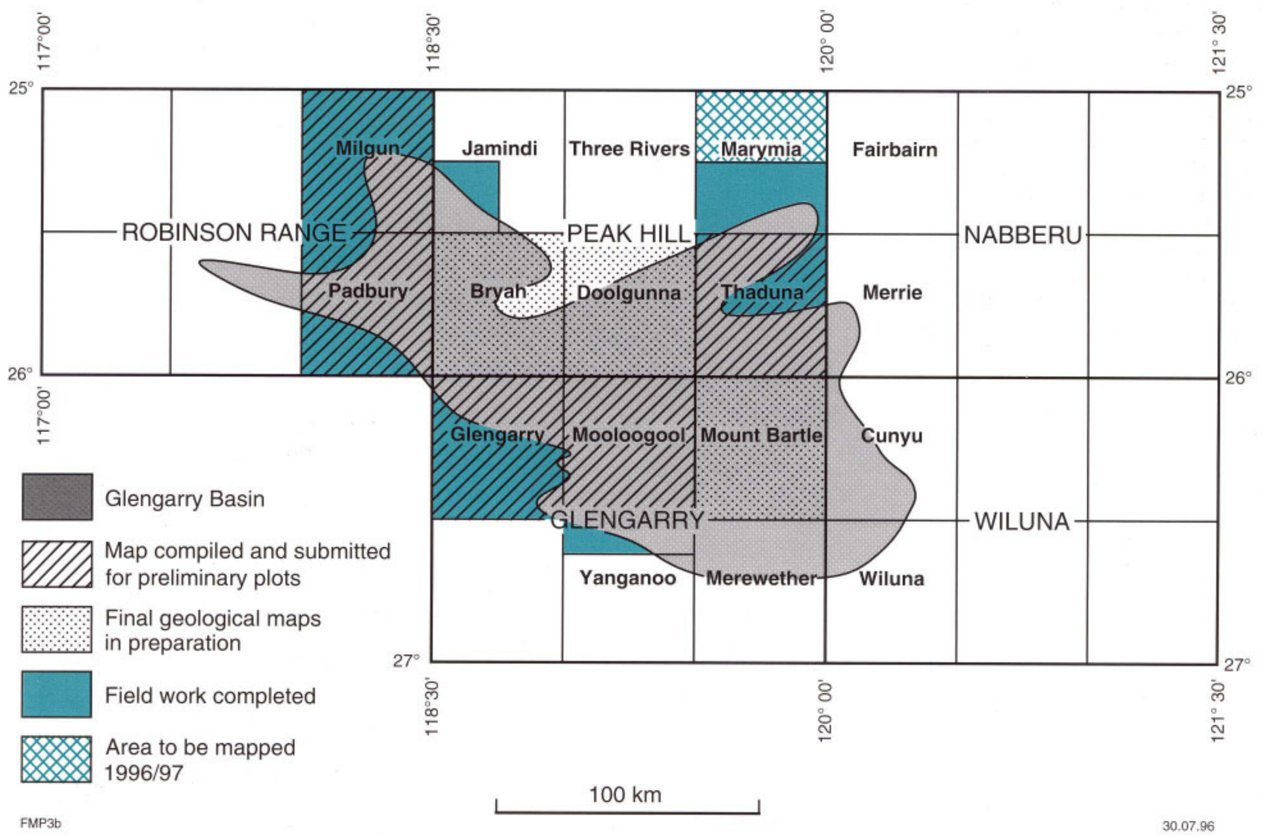


Figure 4. GSWA mapping projects in the Glengarry Basin

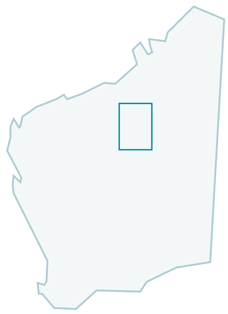
Explanatory Notes for the BRYAH, DOOLGUNNA, MOUNT BARTLE, PADBURY and MILGUN 1:100 000 map sheets are being compiled. These are expected to be completed by late 1996.

Also, during the year a new stratigraphy was established for the Glengarry Basin and a comprehensive document giving details of this stratigraphy is being prepared for publication. The new stratigraphy recognizes that the Glengarry Basin, as originally defined by previous GSWA workers, can be subdivided into three lithostratigraphic domains, representing three separate basins and three different groups, namely: Yerrida, Bryah and Padbury (*see* papers by Pirajno et al., Pirajno, and Occhipinti et al., in this volume). It was also recognized that the Padbury Group was deposited in a separate basin on top of the Bryah Group. A number of new units were recognized, of which two may have metallogenic importance. They are the Bubble Well and Bartle Members. The former is a succession deposited in a tidal–intertidal setting in an epicontinental environment. The Bartle Member is a unit which overlies mafic igneous rocks (Killara Formation) and consists of chemical and evaporitic sedimentary rocks. Samples of Bartle Member rocks contain anomalous gold.

A Bulletin that describes the geology, tectonic development, stratigraphy, geochemistry and economic geology of the Glengarry Basin will be compiled during the next financial year. This work will be significant in improving our understanding of the evolution of Proterozoic basins.

F. Pirajno

Paterson Orogen Project



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

Following completion of fieldwork for the mapping program in 1994–95, work during 1995–96 involved completion of the CONNAUGHTON Explanatory Notes and additions to those for THROSSEL. In addition, POISONBUSH compilation was commenced, and a start made on compilation for a second edition of the RUDALL 1:250 000 map (Fig. 5).

Information gained from the 1:100 000 mapping program on the Paterson Orogen during and prior to the 1994–95 year was collectively assessed, and will be used in a forthcoming report on the RUDALL 1:250 000 sheet. Understanding of the Paterson Orogen has been complemented and greatly advanced by 1:100 000 mapping along the western margin of the orogen in the Gregory Range area to the northwest (*see* review of Pilbara Craton Project).

A. H. Hickman

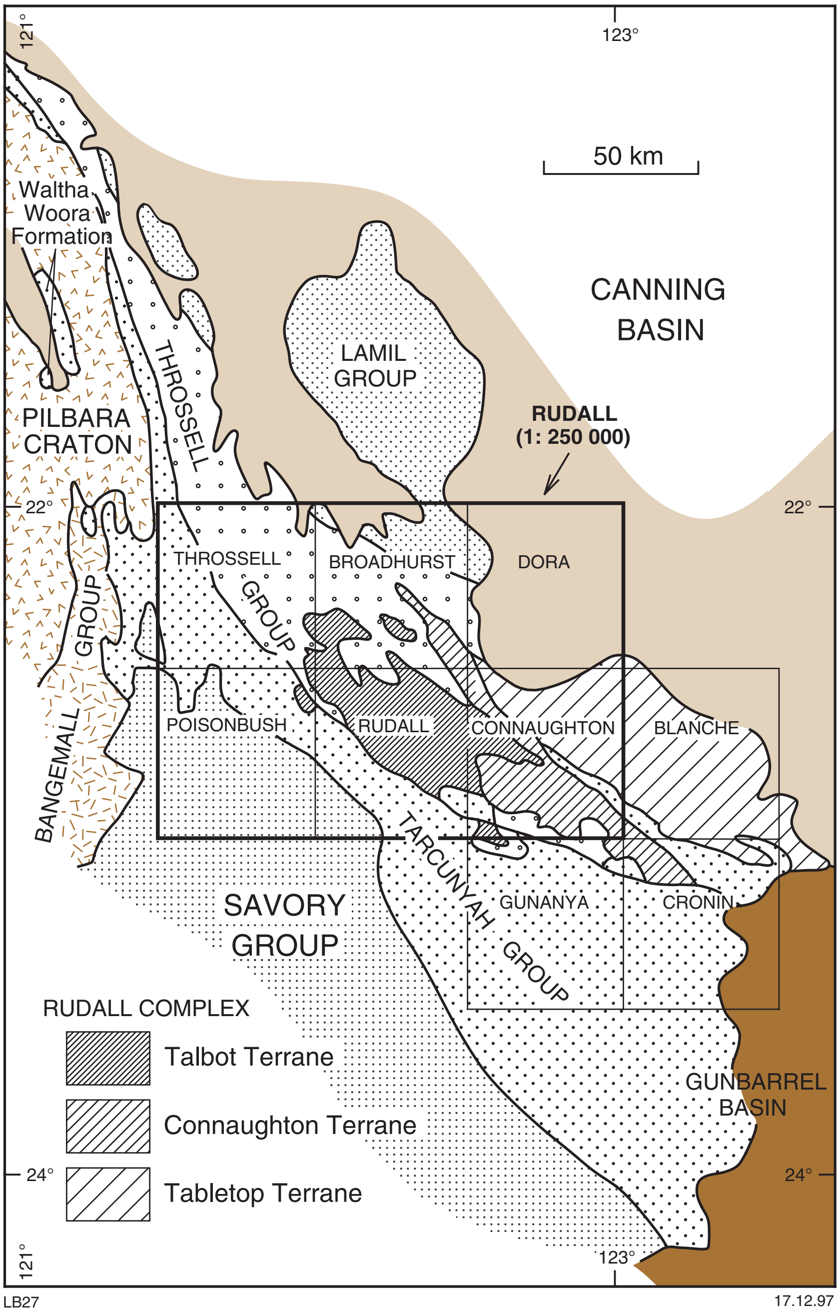
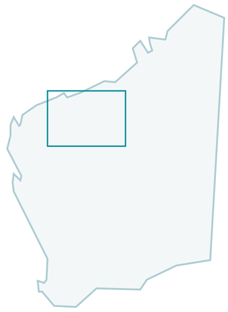


Figure 5. Geological map of the Paterson Range showing the location of mapped sheets

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 petrology, geochronology, geophysics, geochemistry, remote sensing, and metallogeny.*



The Pilbara region, one of the world's greatest mineral producing areas, is an economic and social growth area crucial to Australia's economy. Principal activities are iron-ore mining and the Northwest Shelf gas project. It is forecast that about eight billion dollars will be invested in the Pilbara region over the next ten years in connection with mineral and energy industries.

The Pilbara Craton (Fig. 6) consists of a c. 3500–2800 Ma terrain of granitoids and greenstones unconformably overlain by c. 2770–2300 Ma volcanic and sedimentary rocks of the Hamersley Basin.

Progress summary

The 1995–96 financial year saw the completion of geological mapping projects in the Hamersley Basin, with the publication of the ROCKLEA, ISABELLA, BRAESIDE and PEARANA 1:100 000 maps, and the ROY HILL and MOUNT BRUCE 1:250 000 sheets (Fig. 6). With completion of this work, the mapping effort moved to the North Pilbara granite–greenstone terrane, and GSWA geologists were joined by staff of the Australian Geological Survey Organisation (AGSO) to constitute the North Pilbara National

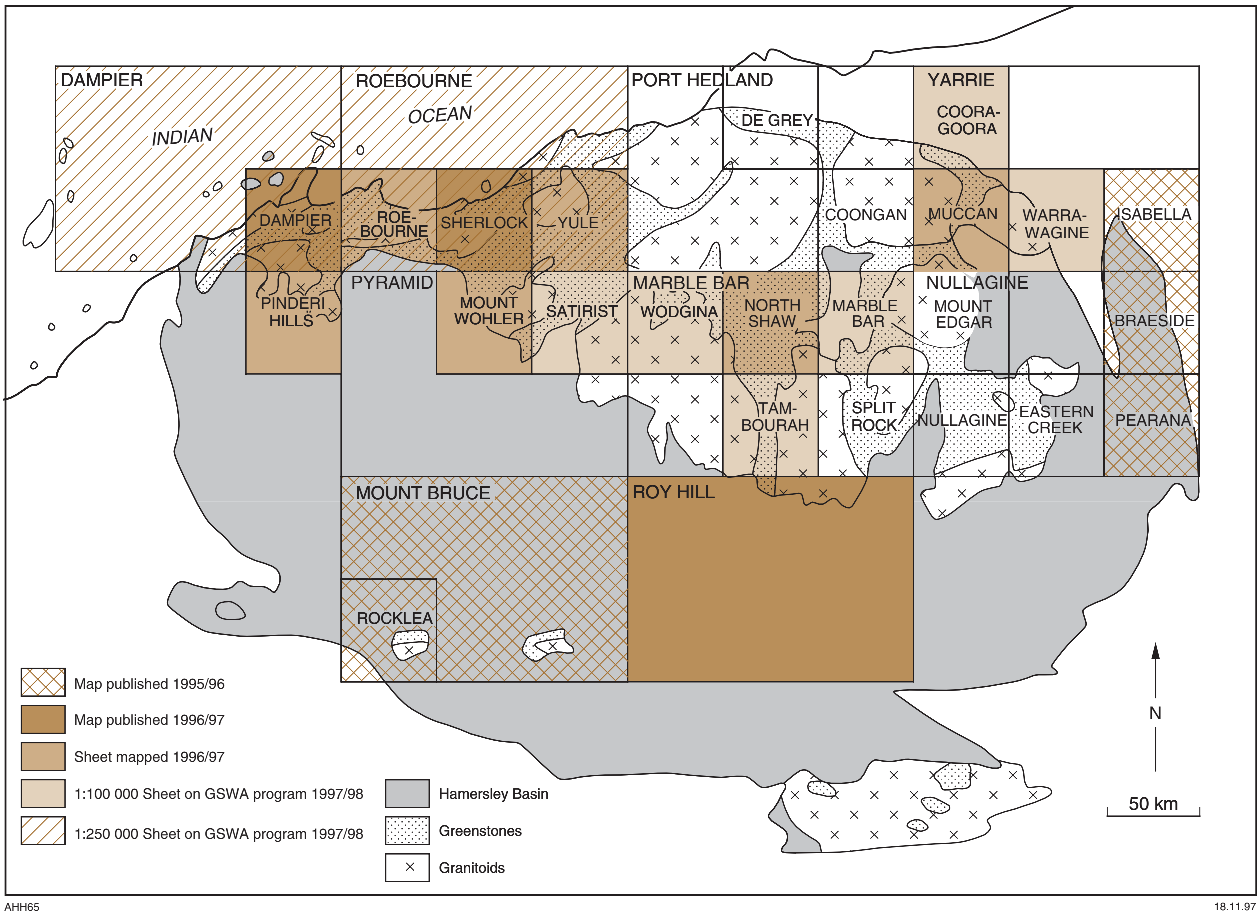


Figure 6. Simplified geology of the Pilbara Craton showing study areas of the mapping program

Geoscience Mapping Accord (NGMA) Project. The combined team, in 1995–96, totalled seven geologists, plus periodic specialist support.

The North Pilbara NGMA project is multidisciplinary, involving an extensive program of geological mapping (eighteen 1:100 000 sheets and seven 1:250 000 sheets), geophysical surveys, mineralization studies, geochemical and geochronological investigations, and compilation of GIS databases. The project will be completed in 2000.

During 1995–96, GSWA staff completed mapping of the DAMPIER and SHERLOCK 1:100 000 sheets, and commenced mapping of ROEBOURNE, PINDERI HILLS, MOUNT WOHLER and MUCCAN (Fig. 6). Aeromagnetic and radiometric surveys of the west Pilbara were flown, and the data and processed images are available for purchase.

DAMPIER 1:100 000 sheet

Background

Previous systematic geological mapping of DAMPIER was limited to reconnaissance-style investigations for the 1964 GSWA DAMPIER and BARROW ISLAND 1:250 000 geological map, and partial cover of the area during a GSWA program of urban geological resource mapping in the late 1970s. A 1:1 000 000-scale geological map of the northern part of the Pilbara Craton, published in 1983, suggested lithostratigraphic correlations between rocks of the Dampier–Roebourne area and more-closely studied greenstones in the east Pilbara. However, these correlations were only tentative because of the lack of conclusive lithological, stratigraphic and structural data from the west Pilbara.

In 1993, an alternative stratigraphic interpretation of the North Pilbara granite–greenstone terrane was published. This was a highly conceptual attempt to apply principles of sequence stratigraphy to essentially the same regional data used in the 1983 lithostratigraphic interpretation. The 1993 interpretation assumes that sequence stratigraphy, normally used in Phanerozoic sedimentary basins, can be reliably applied to structurally complex, dominantly volcanic, mid- to late Archaean successions, and that the latter formed in Phanerozoic-style plate-tectonic environments. Both assumptions are unproven and extremely contentious, and it is clear that a vast amount of additional field data, supported by geophysical interpretation and well-targeted geochronology and geochemistry, are required to significantly advance our understanding of the regional stratigraphy.

Mapping results

Detailed mapping of DAMPIER has revealed that the structural geology of the area is far more complex than previously supposed. The granite–greenstone terrane is bisected by an easterly striking, 0.5 to 2 km-wide mylonite zone, the Sholl Shear Zone. On DAMPIER there is no field or isotopic evidence of any stratigraphic continuity across this tectonic break, although preliminary field evidence from ROEBOURNE suggests that BIF of the northern terrane also occurs south of a branch of the shear zone at Mount Ada. Preliminary SHRIMP U–Pb zircon ages (GSWA and UWA) and Sm–Nd whole-rock isotopic data (AGSO) indicate that the greenstone succession south of the Sholl Shear Zone is approximately 3120 Ma in age. North of the Sholl Shear Zone there are two main greenstone successions separated by a folded, bedding-parallel mylonite zone. This tectonic contact either pre-dates, or is synchronous with, doming of the Karratha Granite, and has been traced around the granite over a total strike length of about 70 km.

The greenstone succession below the folded mylonite zone is a mixed assemblage of ultramafic rocks, mafic amphibolite, chert, clastic sedimentary rocks and minor felsic volcanics, and is intruded by the c. 3260 Ma Karratha Granite. This observation, and preliminary Sm–Nd data indicate that these greenstones are between 3260 and 3420 Ma in age.

The succession above the tectonic break consists of a 1–2 km-thick metabasalt unit conformably overlain by a 0.5–1 km-thick alternating succession of ferruginous chert, BIF, mudstone, and rare tuff, grey-white banded chert, siltstone and intermediate to felsic volcanics. On ROEBOURNE this BIF–mudstone unit (Cleaverville Formation) has been extensively intruded by dolerite sills. Preliminary Sm–Nd data indicate that the upper succession is unlikely to be older than 3310 Ma.

The mylonite zone between the two successions is variously composed of finely layered chert, mafic schist and gneiss, and felsic schist. Where chert is present the rock invariably contains a complex assemblage of isoclinal folds, and it appears that more than one episode of movement is represented.

The new data, outlined above, indicate that none of the previous stratigraphic interpretations on DAMPIER is correct, and a new interpretation is in preparation.

SHERLOCK 1:100 000 sheet

Background

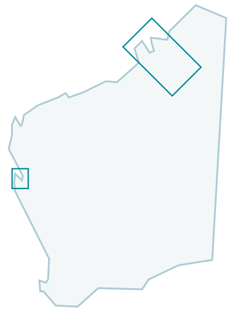
The Archaean geology of SHERLOCK is dominated by the Whim Creek Belt, a well-exposed belt of greenstones striking east-northeast from the southwestern corner of the sheet area. On its northwestern side this belt is flanked by the Caines Well Granite, and to the southeast it is in faulted contact with a major clastic sedimentary unit, the Mallina Formation. The Whim Creek belt is composed of the Whim Creek Group, a c. 3000–2950 Ma predominantly volcanic succession, and overlying mafic volcanic formations, the Louden Volcanics and the Mount Negri Volcanics. However, previous stratigraphic interpretations of the Whim Creek Group have varied considerably, particularly with respect to its relationship to the Mallina Formation, and to its regional distribution. One interpretation has included correlations extending the group 300 km eastwards to MUCCAN (Fig. 6).

Mapping results

A new stratigraphic interpretation of the Whim Creek Group, and its relationships to other formations of the SHERLOCK area, is presented in a technical paper (Smithies, 1996) in this Annual Review. Important conclusions are that the internal stratigraphy of the Whim Creek Group requires revision, and that the depositional extent of the group was not limited to a restricted fault-bounded basin as previously suggested. However, despite detailed mapping, the stratigraphic relationship between the Whim Creek Group and the Mallina Formation is still unclear, and will be examined further during mapping of Mount Wohler during 1996.

A. H. Hickman

Lennard Shelf – Shark Bay Project



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

Progress summary

Mapping and section measuring in the Devonian outcrop belt of the Lennard Shelf, with associated biostratigraphic, sedimentological, and subsurface studies for the present project, has been in progress since 1992, the objective being to increase geological understanding of the Devonian reefal sequence and associated terrigenous conglomerates. Field mapping of the area was essentially completed in 1995–96, with field work by P. E. Playford and R. M. Hocking concentrating especially on little known or complicated areas, including those around Bohemia Downs, Horse Spring Range, Minnie Pool, and Mount Winifred. Several key sections in platform carbonates were also measured. The examination of company cores by I. A. Copp was also completed, with work during the year concentrating especially on the Napier Range and Fossil Downs areas. Biostratigraphic collecting for conodonts, ammonoids, and trilobites was finalized, in association with several university research workers.

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, a unit that has long been subject to small-scale mining operations, which are still continuing. The coquina research is being carried out in conjunction with Dr Patrick Berry of the W A Museum (studying modern populations of the bivalve *Fragum erugatum*, which forms the coquina) and Dr Malcolm Wallace of Melbourne University (studying the mineralogy and petrology of the coquina).

Highlights

Fieldwork in the area of Horse Spring Range and Shady Bore on Fossil Downs Station showed that a major tectonic event occurred during the late Frasnian. An isolated mass of Pillara Limestone near Shady Bore was strongly rotated (up to 60°) before being covered with strong angular unconformity by deep-water deposits of the Virgin Hills Formation. Similarly, the Pillara Limestone forming the core of the Horse Spring Range was rotated steeply prior to deposition of the Virgin Hills Formation. It seems clear that low-angle listric faulting was responsible for this rotation, and that the tectonic event coincided with the boundary between the Sadler and Virgin Hills Formations. That boundary is marked in several areas by massive megabreccia deposits and by a pulse of terrigenous conglomerate.

Masses of well developed stromatolites that grew in major cavity systems were identified at several localities. In some cases barite is associated with the stromatolites, and it is believed that they must have grown in total darkness, through chemo-synthetic microbial activity. These occurrences are expected to be important in understanding the genesis of Mississippi Valley-type mineralization in the Lennard Shelf area, and some additional fieldwork is needed to clarify the relationships.

Further work on cyclicity in platform carbonates has shown that the average thickness of such cycles in the Givetian, Frasnian, and Famennian platforms is between 3.2 m and 4.5 m, and that the duration of each cycle is between about 50 000 and 80 000 years. On the other hand, cycles in terrigenous conglomerates are 10 to 15 m thick, and are presumed to be of similar duration to those in the carbonates. The difference is believed to result from increased rates of subsidence in areas of conglomerate deposition.

An important fossil-fish locality was found in the basal part of the Fairfield Group near Red Bluffs. It is believed that this locality has the potential to provide some of the best fossil-fish display material in Western Australia.

Subsurface core studies have provided evidence that late Famennian platform and reefal-slope carbonates emerged and were eroded prior to deposition of shales of the Fairfield Group, and possible evidence that Frasnian platform carbonates emerged briefly before being covered by deep-water shales of the Gogo Formation.

Analysis of gamma-ray logs of cored holes shows that there is a reliable correlation between logs and lithofacies in marginal-slope deposits.

At Hamelin Pool and Lharidon Bight, shallow cores were obtained by driving PVC tubing into the soft sediment on the sea-floor at localities where living *Fragum erugatum* populations are being monitored. These cores showed that relatively small thicknesses of *Fragum* coquinas (less than 50 cm thick) have accumulated at such localities, and it is clear that most dead shells have been transported to adjoining beaches, probably through storm activity.

Future work

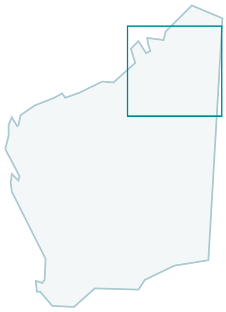
A small amount of fieldwork on the Lennard Shelf will be carried out in 1996 to clarify relationships in cavity systems containing stromatolites and barite mineralization, and to check problems encountered during map compilation. Compilation of maps to accompany the Bulletin on the project will be completed during 1996, and preparation of the Bulletin text and illustrations will begin. The Lennard Shelf project is scheduled for completion in 1997–98.

The Shark Bay project will continue, with the results of the Hamelin Coquina project due to be compiled during 1996. Further fieldwork will be required before the project is completed, as scheduled, for the end of 1998.

P. E. Playford

King Leopold and Halls Creek Orogens

Objectives: *To increase geoscientific 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 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, and diamonds.

Progress of maps and other publications

The 1995 field season saw the completion of remapping on the LISSADELL and part of the CAMBRIDGE GULF 1:250 000 map sheets, covering the northern part of the Halls Creek Orogen (Fig. 7). This was the last phase of a field mapping program that had commenced with remapping of the King Leopold Orogen, beginning in 1986. Since then, the YAMPI and LENNARD RIVER 1:250 000 map sheets have been published, and a Bulletin on the Precambrian geology of the King Leopold Orogen has been prepared and is currently at the editing stage. A 1:500 000 geological map and a structural and metamorphic interpretation map to accompany the Bulletin were published during 1995–96. Compilation and digitizing of the MOUNT RAMSAY 1:250 000 map sheet, which covers the area where the King Leopold and Halls Creek Orogens meet, has been completed and is being prepared for publication.

Remapping of the Halls Creek Orogen commenced in 1990 in conjunction with AGSO as part of the NGMA Kimberley–Arunta Project. The Geological Survey published 1:100 000 map sheets for ANGELO and DOCKRELL during 1994–95, and MOUNT REMARKABLE in 1995–96. RUBY PLAINS has been released by AGSO in preliminary format. HALLS CREEK, McINTOSH, and DIXON have been compiled and digitized. Compilations of TURKEY CREEK and BOW, along with the LISSADELL 1:250 000 map sheet are complete.

Field and laboratory studies of the stromatolite biostratigraphy of the Proterozoic rocks in the East Kimberley were carried out during 1995–96.

Promotion and dissemination of results

During 1995–96 a number of talks and poster presentations were made

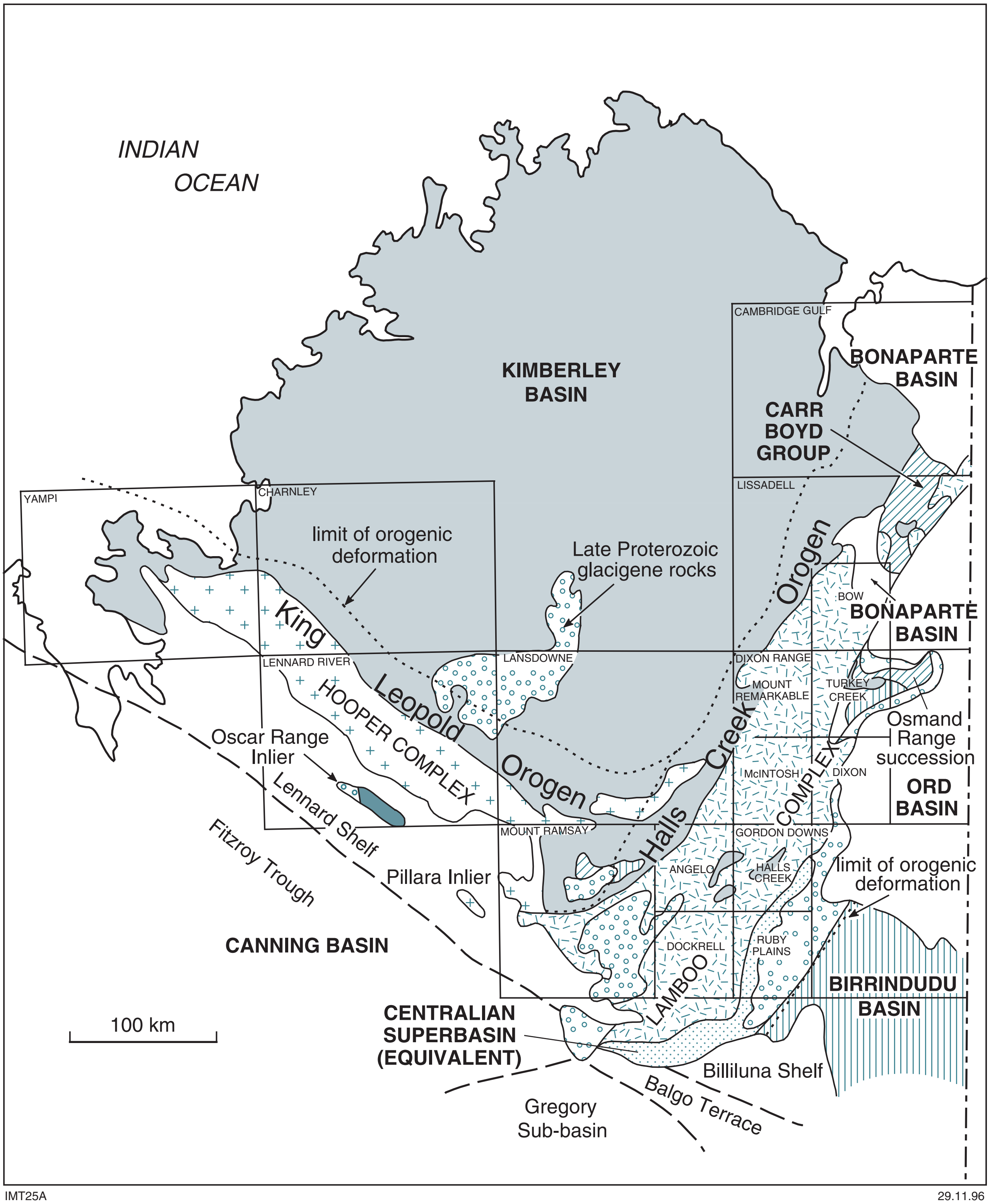


Figure 7. Geological map of the Kimberley Region showing the location of GSWA mapping projects

in collaboration with geoscientists from AGSO and the University of Western Australia. These covered a number of subjects:

- Palaeoproterozoic tectonic evolution of the Kimberley — International Conference on Tectonics and Metallogeny of Early/Mid Precambrian Orogenic Belts, held in Montreal, Canada, in August 1995;
- Geochronology of magmatism and metamorphism in the Kimberley — 3rd Australian Conference on Geochronology and Isotope Geoscience, held at Curtin University of Technology, November 1995;
- Palaeoproterozoic deformation, metamorphism, and igneous intrusion in the central zone of the Lamboo Complex, Halls Creek Orogen — 13th Australian Geological Convention held in Canberra in February 1996;
- Neoproterozoic glacial episodes in the Kimberley region — 13th Australian Geological Convention held in Canberra in February 1996;
- Magmatism and tectonic evolution of the Halls Creek Orogen — University of Western Australia seminar series, April 1996.

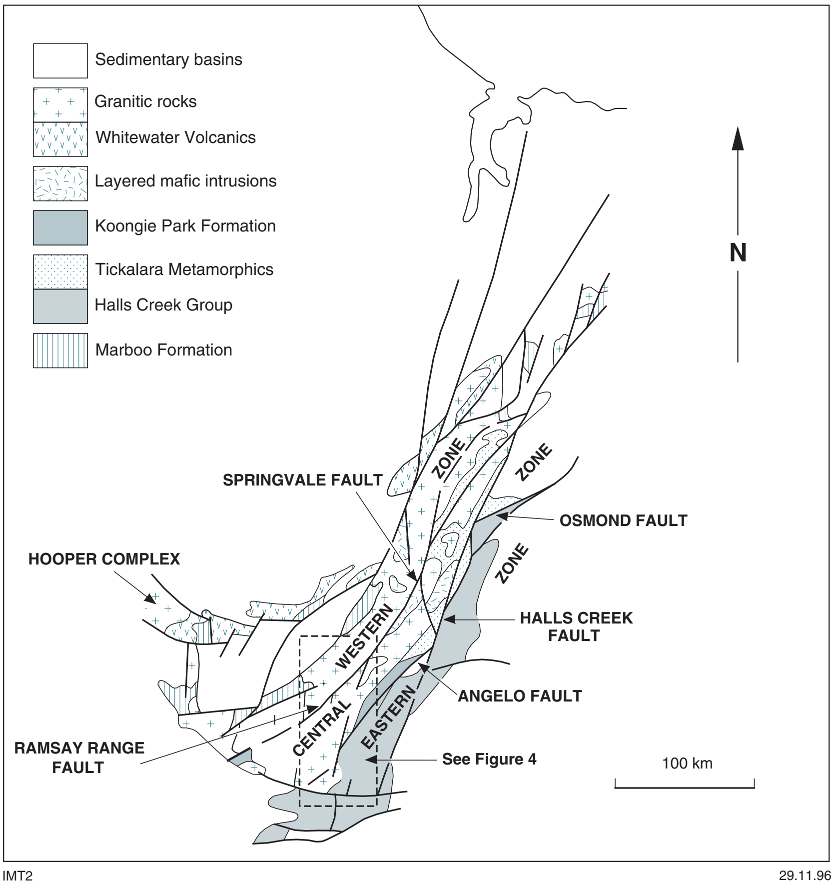


Figure 8. Map showing zones and zone boundaries within the Lamboo Complex of the Halls Creek Orogen

Summary of results

The remapping, together with the extensive SHRIMP U–Pb zircon dating carried out by R. W. Page at AGSO, has shown that the Palaeoproterozoic rocks of the Lamboo Complex in the Halls Creek Orogen can be divided into three zones (Fig. 8):

- The western zone has a geological history similar to that of the Hooper Complex in the King Leopold Orogen. It is dominated by 1865–1850 Ma felsic volcanic rocks (Whitewater Volcanics) and associated granitoids and gabbros (Paperbark supersuite), together with layered mafic–ultramafic intrusions (e.g. Springvale intrusion), that intruded deformed and metamorphosed turbiditic metasedimentary rocks deposited around 1870 Ma (Marboo Formation).
- The central zone is dominated by metamorphosed sedimentary rocks and mafic volcanic rocks of the Tickalara Metamorphics deposited around 1870 Ma. They were deformed and metamorphosed at low to high grade, and intruded by layered mafic–ultramafic intrusions (e.g. Panton intrusion) and by extensive sheet-like granitoid intrusions (including the c. 1850 Ma Dougalls suite) between 1865 and 1850 Ma. Felsic volcanic rocks of the Koongie Park Formation were erupted around 1840 Ma, and further mafic–ultramafic bodies were intruded between c. 1840 Ma (Sally Malay intrusions) and c. 1830 Ma (e.g. McIntosh intrusion).
- The eastern zone is dominated by the Halls Creek Group. The lower part of the group consists of c. 1880 Ma mafic volcanics, felsic volcanics, and metasedimentary rocks (Saunders Creek Formation, Biscay Formation). These unconformably overlie c. 1910 Ma mafic and felsic volcanic rocks intruded by related high-level granitoids (Ding Dong Downs Volcanics, Sophie Downs Granite). Alkaline volcanic rocks (Butchers Gully Member) were erupted between 1860 and 1850 Ma, and are overlain by post-1850 Ma turbiditic metasedimentary rocks that form the upper part of the Halls Creek Group (Olympio Formation).

All three zones were intruded by granitoids and gabbros of the 1835–1800 Ma Sally Downs supersuite.

The Palaeoproterozoic tectonic history of the King Leopold and Halls Creek orogens can be interpreted in terms of subduction of oceanic crust northwestwards beneath an ?Archaean Kimberley Craton, culminating in a collision around 1830 Ma with a craton made up of the rest of northern Australia. The eastern zone of the Lamboo Complex represents the northwestern margin of this northern Australian craton, and has a geological history entirely different from the central and western zones prior to collision.

The granitoids and gabbros forming the 1865–1850 Ma Paperbark supersuite in the western zone are dominated by K_2O-rich monzogranite and syenogranite, which is typical of Palaeproterozoic orogenic belts throughout Australia. However, extensive sheet-like intrusions of the c. 1850 Ma Dougalls suite in the central zone consist of tonalite and trondhjemite, and their composition is similar to intrusions found in Phanerozoic island arcs or along continental margins oceanward of large calc-alkaline batholiths. Deformation and low- to high-grade metamorphism accompanied the magmatism during what is referred to as the Hooper Orogeny.

The 1835–1800 Ma Sally Downs supersuite consists of early tonalite–trondhjemite–granodiorite sheet-like intrusions (1835–1815 Ma Mabel Downs suite) and coeval Y-depleted granites, together with younger (1810–1800 Ma) K_2O-rich monzogranite and syenogranite. Intrusion of the Mabel Downs suite accompanied further subduction, followed by collision, with deformation and metamorphism occurring during the Halls Creek Orogeny, and then by the intrusion of massive monzogranite and syenogranite.

The Speewah Group was deposited on the ?Archaean Kimberley Craton around 1835 Ma and may have been derived from uplift of the Lamboo Complex during the Halls Creek Orogeny. The overlying c. 1800 Ma Kimberley Group consists of shallow marine and fluvial deposits derived from the north.

Unlike the Palaeoproterozoic orogenic belts of central and northeastern Australia, the King Leopold and Halls Creek Orogens have not undergone major orogenic reworking during the Mesoproterozoic. During this time the Halls Creek Orogen was overlain by the Birrindudu Basin. Stromatolites sampled from the Bungle Bungle Dolomite in the Osmand Range, and from the Limbunyah Group in the Northern Territory are consistent with a probable Mesoproterozoic age, and may help to establish correlations with the McArthur Basin and Mount Isa region farther to the east.

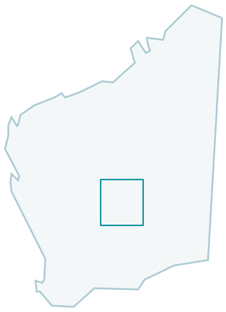
Regional-scale sinistral wrench faulting is a major feature of the Halls Creek Orogen. Remapping of the Carr Boyd Group on LISSADELL has shown that its sedimentation patterns and stratigraphy are inconsistent with the previously held view that deposition took place within a strike-slip basin (*see* Thorne and Tyler, this volume). Instead, most of the post-Palaeoproterozoic movement on the Halls Creek Fault system occurred after deposition of the Carr Boyd Group; principally during the Neoproterozoic (Yampi and King Leopold Orogenies), and during the Palaeozoic (?Alice Springs Orogeny) when faulting exerted a major influence on the development of Upper Devonian sedimentary basins.

A sequence of sandstone and dolomite units overlying the Lamboo Complex to the east of Halls Creek on GORDON DOWNS (Fig. 7) has been correlated previously with the Mesoproterozoic Osmand Range succession. However, the stromatolites present in a prominent dolomite unit are unlike those in the Bungle Bungle Dolomite in the Osmand Range, and have been identified as *Linella avis*, a form characteristic of Supersequence 1 of the c. 830 Ma Neoproterozoic Centralian Superbasin, not recognized previously in this area. The possible extent of these rocks in the Kimberley region is being assessed.

In the Louisa Downs area on MOUNT RAMSAY, correlation of the Neoproterozoic glacigene rocks of the Kuniandi Group and the overlying Louisa Downs Group with the Sturtian and Marinoan glaciations in central and southern Australia has been controversial. The identification of the stromatolite *Tungussia julia* in the Egan Formation of the Louisa Downs Group indicates a biostratigraphic correlation with the Julie Formation of the Amadeus Basin and the upper Wonoka Formation of the Adelaide Geosyncline, implying an episode of glaciation younger than the Marinoan. The Landrigan Tillite in the Kuniandi Group probably correlates with tillites in the Duerdin and Mount House Groups and is probably equivalent to the Marinoan glaciation. The Sturtian glaciation is apparently absent.

I.M.Tyler

Geochemical mapping project



Objective: *Map the distribution of regolith over selected 1:250 000 map sheets and sample regolith at a regular interval. Carry out chemical analysis of these regolith samples and use these data to identify areas of anomalous element concentrations, relate regolith to bedrock, and understand the chemical changes during regolith formation.*

Summary of progress

In 1995–96, Explanatory Notes were published for Leonora, Peak Hill, Glengarry, and Sir Samuel 1:250 000-scale map sheets. Work in progress includes preparation of Explanatory Notes for Robinson Range, Mount Phillips, and Nabberu (Fig. 9).

Nature of program

The regional regolith and geochemical mapping program, which commenced in 1993–94, aims to provide information on the distribution of regolith and its chemistry in order to assist the mineral-exploration companies, pastoralists, and environmental agencies. The main components of the program are the production of regolith materials maps from a combination of remotely sensed data and ground observations, and analysis of regularly spaced regolith samples for a variety of major and trace elements. In particular, the program:

- attempts to identify metallogenic provinces which may have potential for mineralization.
- complements regional geological mapping
- identifies areas that have existing or potential environmental problems.

The program is assisted by a Regolith and Geochemical Mapping Technical Advisory Sub-Committee whose members are drawn from industry and other government agencies. The program has concentrated on the northeastern part of the Yilgarn Craton, and adjacent marginal basin sequences, that represent areas of known and potential mineral prospectivity respectively.

The sampling procedures have been described in the 1993–94 and 1994–95 Annual Reviews. Sampling is carried out at a nominal density of 1 sample per $16km^2$. The preferred sample medium is stream sediment, but colluvium is collected in areas lacking well-defined drainage channels. A sample of the -2mm to +450mm fraction is analysed, and a 5 kg sample of the -2mm fraction is collected and archived for future use by GSWA or companies. At each site, a standard set of information is recorded (e.g. characteristics of the sample, surrounding regolith, bedrock) and used to interpret the sample chemistry and help in construction of the regolith materials map.

Compilation of the regolith materials map relies on interpretation of remotely sensed data (Landsat TM, radiometrics, magnetics), aerial photography, and regolith characteristics recorded during regolith sampling.

Project status

In 1995–96, field work was completed on Mount Phillips and Nabberu, and chemical analysis of regolith samples was completed for Robinson Range, Mount Phillips, and Nabberu. Explanatory Notes were published for Leonora, Peak Hill, Glengarry, and Sir Samuel. Robinson Range is planned for publication in August 1996, Mount Phillips in October, and Nabberu in December. Sample collection was contracted out, under the supervision of a GSWA geologist, and chemical analysis of regolith samples was carried out by commercial laboratories.

Owing to funding restrictions, the budget allocation for the Regional Geochemical Mapping section was severely reduced for 1996–97 to the extent that the planned sheets (Glenburgh, Mount Egerton and Turee Creek) will not be mapped or sampled until additional funding becomes available. The program will then recommence with sampling of the first two of the planned sheets.

In addition to the production of a regolith-materials map and a set of element-concentration maps, contour maps of pH and total dissolved solids (TDS) have been produced for all maps that post-date Glengarry. Measurements of both parameters, which are of great interest to the pastoral industry, are recorded in the field during regolith sampling.

In order to better identify areas of prospective economic mineralization and to understand the relationship between bedrock and regolith, there has been increasing emphasis placed on statistical treatment of regolith chemical data. This has taken the form of element indices that are indicative of certain types of mineralization, as discussed by Kojan et al. (this volume) for regolith samples from greenstones spanning the Menzies, Leonora and Sir Samuel sheets. This study has also integrated geochemical data from two company reports available on the WAMEX open-file database in the Department of Minerals and Energy. The results of the study show that company data and the results of the GSWA regolith geochemistry program can be successfully integrated, and that indices are capable of identifying areas of known gold mineralization, even when regolith gold concentrations are near or indeed less than detection level.

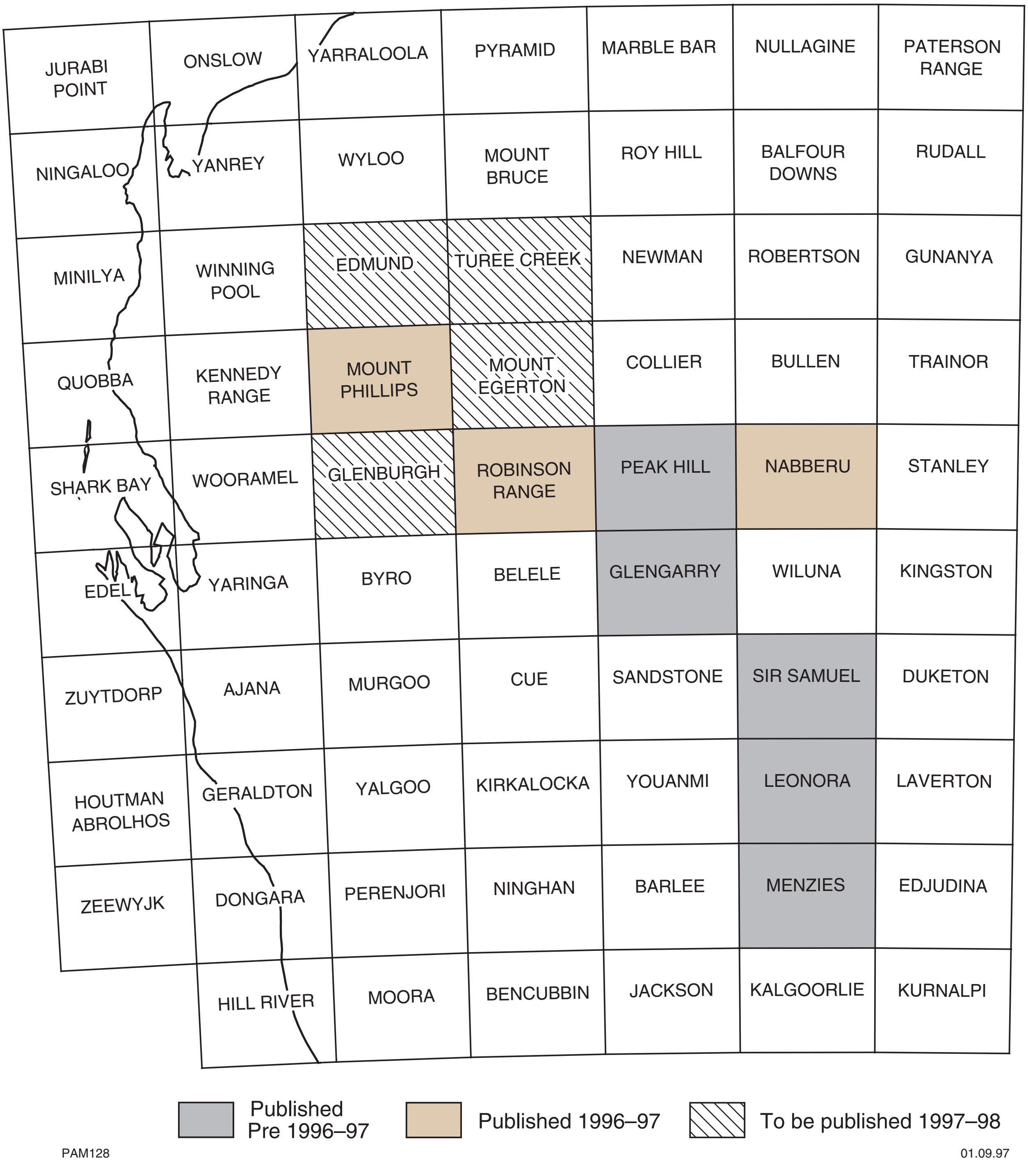


Figure 9. Summary of projects for the regional regolith and geochemical mapping program

Subramanya and Sanders (this volume) have investigated the downslope changes in regolith chemistry by examining regolith samples sourced solely from the Narracoota Volcanics on Peak Hill. They showed that the early stages of regolith formation are characterized by rapid breakdown of rock-forming minerals, whereas more advanced stages are characterized by the enhancement of resistate phases.

Program methodology

The sampling rationale has been explained in the 1993–94 and 1994–95 Annual Reviews, and is summarized in each of the Explanatory Notes. The sampling methodology remains essentially unchanged, although the results of recent programs have indicated that some attention should be paid to variations in chemistry according to grain size, within-site variations, and the difference in chemistry of regolith samples sourced from the same unit but comprising different media (e.g. stream sediment, sheetwash, soil). To this end, a limited resampling program will be carried out to examine, in particular, grain-size and within-site effects.

On recent map sheets (e.g. Nabberu) there has been more emphasis placed on the use of remotely sensed imagery (particularly LANDSAT TM) in construction of the regolith materials map. Following consultation with industry, future maps will contain fewer regolith subdivisions and therefore will be more suited to remotely sensed interpretation.

There has been some interest shown by exploration companies in gaining access to the approximately 5 kg of -2 mm archive materials that is collected at each regolith sampling site. Currently, there are in excess of 7000 samples stored by the GSWA. For a nominal charge, companies can obtain a sub-sample of the archive material, with all analytical work to be reported to the GSWA within a three-month time period. It is anticipated that these data will then be made available to the public.

In addition to sales of hardcopy, there has been increasing interest in obtaining data from the regolith geochemistry program in digital form.

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*

Publications

The year 1995–96 was a period of geophysical data acquisition, interpretation, and publication on a major scale. As part of a project associated with the National Geoscience Mapping Accord (NGMA), GSWA and AGSO jointly flew an aeromagnetic program over the West Pilbara, comprising parts of the Dampier, Roebourne, Yarraloola, and Pyramid 1:250 000 sheets, and also released data and images for Wiluna, Sir Samuel, and Duketon 1:250 000 sheets.

For the West Pilbara, colour pixel maps at scales of 1:250 000 and 1:500 000 were produced for the entire area flown. These consisted of total magnetic intensity maps, and two versions of radiometric ternary images of potassium, thorium and uranium. In addition, preliminary contour maps were produced for a number of 1:100 000 map sheets: Preston, Dampier, Roebourne, Sherlock, Fortescue, Pinderi Hills, Cooya Pooya, and Mount Wohler.

For the northern part of the Eastern Goldfields, twelve total magnetic intensity pseudocolour maps at scales of 1:100 000 were published. This project comprised each of the six 1:100 000 sheets that make up each of the Sir Samuel, and Duketon 1:250 000 map sheets.

Aeromagnetic contour maps of parts of the Yilgarn and Eastern Goldfields were prepared and published from multi-client data supplied by Western Geoscience Corporation. The following sheets were published at the 1:100 000 scale: Melita, Menzies, Bardoc, Gindalbie, Mulgabbie, Pinjin, Kanowna, Kurnalpi, and Roe.

Interpretation

Aeromagnetic interpretation at the 1:50 000 scale has been commenced on a number of 1:100 000 map sheets in the West Pilbara and Glengarry Basin including: Mount Bartle, Glengarry, Mereweather, Yanganoo, Mooloogool, Thaduna, Gabininthа, Marymia, Milgun, Padbury, Sherlock, Roebourne, Dampier, and Mount Wohler.

Data and image processing of magnetic, radiometric, elevation and Landsat data were undertaken and maps produced at various scales as an aid to field geologists mapping in various parts of the State. Additional processing of AGSO data was undertaken for the interior basins projects.

Assistance to WAMEX

Digital data submitted to the Department are now verified using INTREPID and ER Mapper software. It is intended to archive submitted data, together with any internal processing, onto CD ROM. Twenty-three data tapes have been verified to date.

Digital data previously submitted on nine-track tape have been transferred onto CD ROM. These data are still being verified.

Some companies have voluntarily submitted data to the Department. These data are processed and complimentary images forwarded to the companies in return.

Assistance to industry

The geophysics section has provided assistance to local geophysical contractors to locate suitable calibration ranges for airborne electromagnetic and airborne radiometric surveys.

The aerial magnetic surveys index, MAGCAT was updated to the 22 March 1996 and contains reference to reported airborne magnetic surveys up to item 7971.

Work has commenced in establishing a GIS layer (MAGIX) outlining regional airborne geophysical digital datasets for WA. This will eventually replace MAGCAT and will be available to the public.

J. H. Watt

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, for the Albany–Fraser Orogen and 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 Leeuwin, Rudall and Narryer Complexes, the Albany–Fraser Orogen, the Eastern Goldfields and Pilbara granite–greenstone terranes was undertaken during 1995–96. Results for the calendar year 1995 were published in GSWA Record 1996/05.

D. R. Nelson

Laboratory and field support

Objectives: *To provide quality field and laboratory services including preparation of samples for petrology, geochronology, palynology and geochemistry.*

The Geological Survey Laboratory has a long established reputation for high-quality geological sample preparation. The year 1995–96 has been no exception, with a variety of laboratory work having been carried out at the Carlisle Laboratory with a continued emphasis on separation of zircons for SHRIMP analysis.

Fifty-six zircon samples were processed for analysis. Techniques are continually being developed and the process refined to produce higher quality results at an increasing rate. Geological Survey technicians have recently taken over the final task of the process, that of gold coating, which they carry out at Curtin University.

Routine laboratory support for the mapping program has been maintained with the preparation of 2830 thin sections including 430 polished thin sections. Other work carried out in the laboratory includes heavy-mineral separations, samples crushed and pulverized for geochemistry, specific gravity determinations, polishing rock faces, staining rock chips and many other minor procedures. There were also 180 palynology samples prepared for examination.

Field assistants again provided valuable support to geologists in the field. Several additional assistants were employed on a casual basis to meet the demands of the busy field season.

G. T. Williams

Subprogram 3105 GEOSCIENTIFIC EDITING AND PUBLISHING

At the start of 1995–96 Component 3105 comprised three sections: Publications and Information; Cartography; and Geographical Information Systems. In December 1995 the Cartography Section was further subdivided into two discrete groups — Computer Assisted Map Production (CAMP) and Computer Assisted Drafting and Design (CADD). This reorganization provided the new sections with automonous budgetary control and and a more direct line to internal clients, thereby improving production efficiency. This review is based on the resultant four-section structure under Component 3105.

- Publications and Information;
- Computer Assisted Map Production;
- Computer Assisted Drafting and Design and
- Geographical Information Systems.

Publications and information

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 Sub-program 3.1 during 1995–96, twelve 1:100 000 scale geological maps and seven maps at other scales were released. Four regolith geochemistry packages, as well as five aeromagnetic datasets and two gravity datasets, including various processed images and contour maps, were released. Geoscientific manuscripts published for the year totalled 21. At year end, two 1:100 000 and two 1:250 000 maps, as well as four manuscripts were at the printer in preparation for release in July 1996.

At the time of the departure of the Geological Survey's Hydrogeology Section to the newly established

Water and Rivers Commission in December 1995, several hydrogeological maps and manuscripts were in preparation for publication. Of these, two hydrogeological maps and five manuscripts were also released during 1995–96.

Promotional activities

The inaugural GSWA Annual Review (covering 1993–94) was published in 1995, and the 1994–95 edition in January 1996. Both were well received and have served their dual purpose of providing to industry status reports on ongoing program work, as well as a vehicle for publication of short technical papers discussing matters of interest or importance that arise in the course of program work.

The first and second issues of Fieldnotes, a new GSWA newsletter informing industry of current activities in the field and the office, were published in January and April. They too have been well received by industry and the growing mailing list has now exceeded 430.

GSWA publications released were advertised monthly in the 'Western Australian Geologist', organ of the Geological Society of Australia (WA Branch), and quarterly in Fieldnotes. Fourteen advertisements for selected products were also placed in ten industry-specific journals and magazines during the year. New editions of the GSWA Catalogue of Maps and Catalogue of Publications were released in November 1995 and January 1996 respectively.

A presentation on the promotion of GSWA products was made to the annual Mining Registrars' Conference in Perth in November 1995 to raise awareness of GSWA products. Arrangements were made for the advertising of GSWA publications in Mining Registrars' offices.

A first edition GSWA home page was put onto the World Wide Web in July 1995. A searchable copy of the GSWA publications catalogue is accessible from the home page. Further development is planned for 1996–97.

In March 1996, service to customers buying GSWA publications was improved by isolating publication sales from tenement enquiries. This was achieved by reserving one window of the public counter for publication sales only. Further improvements in customer service are expected in 1996–97 as a result of the training of counter staff by officers of the GSWA Publications Section. The area used for display of new products near the sales counter was enlarged and improved.

Displays were mounted to exhibit the work of the GSWA and to promote the mineral and petroleum prospectivity of Western Australia at the following conferences:

- Australian Society of Exploration Geophysicists 11th Geophysical Conference and Exhibition (Adelaide, September 1995)
- New Generation Gold Mines: Case Histories of Discovery — Conference and Exhibition (AMF, Perth, November 1995)
- Eastern Goldfields Projects Exposition — Joint GSWA/ AGSO display of recent NGMA work (Kalgoorlie, November 1995)
- Recent Developments in Base Metal Geology and Exploration (Australian Institute of Geoscientists, Perth, November 1995)
- 13th Australian Geological Convention and AGSO Jubilee Symposium (Canberra, February 1996)
- WALIS Forum 1996 (Perth, April 1996)
- Australian Petroleum Exploration and Production Association (APPEA) Conference and Exhibition (Darwin, June 1996)

In early 1996 a GSWA Strategy Team was formed to develop a promotional strategy to be adopted by GSWA. The team formalized the existing strategy and expanded it to better address the objective of promoting not just the products of GSWA, but the prospectivity of Western Australia for both minerals and petroleum. A 'Promotion and Publicity Strategy' paper was compiled to guide future promotional activities.

Museum

Although the resignation of the GSWA Museum Curator in early 1995 left the Museum in care and maintenance mode throughout the year, educational use of the Museum facilities continued. A total of 12 groups (265 students) from primary and secondary schools, TAFE and Universities were 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 1995–96 was approximately 50 per month. This was considerably lower than in recent years (130 per month average) as a result of the diversion of simple, non-geological enquiries to either 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. Relevance to the Geological Survey is best described by the following quotation from R. Logan Jack, ex Government Geologist, Queensland 1904:

The chief end of a Geological Survey is the construction of geological maps. Whatever else, in the way of reports, bulletins, memoirs, monographs or statistical information that may be produced, the geological map is, and must always be, its staple product, and the ultimate measure of its usefulness.

After 90 years that statement is still relevant, but with computer-assisted techniques the quality and quantity of maps produced has increased immeasurably. The output of series maps from CAMP in 1995–96 is equivalent to the area of the State of Victoria.

Maps completed by CAMP for multi-colour lithographic printing in 1995–96 included:

- fourteen 1:100 000 series geological maps,
- three 1:250 000 series geological maps,
- two 1:250 000 series hydrogeological maps,
- one 1:1 000 000 series geological map,
- two plates to accompany Bulletin 143 — King Leopold Orogen,
- four plates to accompany Record 1996/02 — Groundwater Contamination, Perth Basin,
- one plate to accompany Report 47 — Greenstone Terranes in the Kurnalpi–Edjudina Region and
- one Atlas of Western Australian Mineral Deposits and Petroleum Fields.

Products completed by CAMP for short run (plotter or plan printer) output included:

- State Petroleum Wells Drilled map in four sheets,
- twelve 1:100 000 Aeromagnetic Interpretation maps,
- one map of Basic Raw Materials of Shark Bay World Heritage Area,
- two 1:250 000 Aeromagnetic Interpretation maps, and
- nine 1:100 000 Magnetic Intensity Contour maps.

Spatial data digitally captured by CAMP to be published by other agencies were:

- two draft maps of the Kimberley Prospectivity Study for the Department of Resources Development,
- simplified State geology for the Western Australian Land Information System,
- four 1: 250 000 regolith maps for the Regolith Geochemistry program and
- four 1:250 000 sheets of M series open-file data

The highlight of 1995–96 for the CAMP Section was undoubtedly the production of the Atlas of Western Australian Mineral Deposits and Petroleum Fields. This publication displayed data from the MINEDEX database in an attractive, colourful and useful format and since its release demand has been high for both the digital and hardcopy versions.

The CAMP Section continued to respond to a high demand for base maps to support field activities of Geological Survey geoscientists undertaking field mapping.

B. Dawson

Computer assisted drafting and design (CADD)

Objectives:
- *To provide quality graphic support to the geoscientific manuscripts and publications of the Geological Survey*
- *To ensure that these products are provided in a timely manner*
- *To provide graphic support to public presentations of geoscientific information*

Products completed by CADD included 850 diagrams, small format maps and 35mm slides to support Geological Survey publications and reports.

The section also continued to contribute to the development of the software package CADscript through its role as a 'beta' site. CADscript, an add-on software package to MicroStation, is now used extensively in Perth and is fast gaining international recognition.

A major achievement for the year was the placement of digital illustrations, prepared using CADscript, directly into manuscripts formatted using PageMaker software. As a result, manuscripts were produced that could be provided to commercial printers wholly in digital form.

P. Carroll

Geographic information systems (GIS)

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 hardcopy maps and digital products*

GIS continued to be used as an analysis and map-production tool during 1995–96. Despite the distractions of Divisional restructuring, milestones and productivity goals for 1995–96 were achieved.

Geophysical image maps

ER Mapper dynamically linked to ARC/INFO has provided an opportunity to produce high-quality geophysical image maps using the imaging processing of ER Mapper and the cartographic processing of ARC/INFO. A total of twenty-two image maps have been produced covering the Merlinleigh and Savory Basins, and the SIR SAMUEL and WILUNA 1:250 000 sheets.

Geochemical and regolith mapping

The geochemical and regolith mapping continued. Four regolith geochemistry packages consisting of maps and digital data were released.

Other digital and map products

Other digital data and short run map products completed by GIS included:

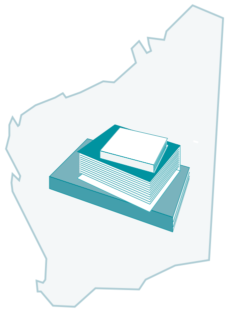
- simplified State geology and mineral prospectivity dataset,
- revision of the Pilbara Iron Ore Assessment map and dataset,
- prototype of the WAMEX Open-File Activity Area Index (EXACT) dataset for Sir Samuel,
- aerial photography index dataset,
- translation of 25 geological series digital data in Microstation format into a format suitable for use in GIS environment.

S. Bandy

The Publication, CAMP, CADD and GIS sections have continued to develop processes to improve quality, quantity and delivery times within allocated resources. These improvements are illustrated by the timely delivery of published products in both analogue and digital formats, and the high regard held by industry for the quality of presentation of the geoscientific output of the Geological Survey.

Subprogram 3106
GEOSCIENTIFIC AND EXPLORATION INFORMATION

Geoscience Information Library



Objective: *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 9095 clients visited the library, including 1241 users of the microfiche facilities to access openfile exploration data. In January 1996, compilation of statistics commenced on the number of research enquiries handled by library staff. There were 3456 enquiries for the six months to June 1996.

Automated library system

The implementation strategy continues to be focused on entering all new material as received and completing data-uptake projects to enable the library to operate using a single automated system. Accordingly, the transfer of book catalogue records from the interim RMS database to the Oracle Libraries database has continued during the year and is almost complete.

Development of the system to allow for the provision of direct access to staff and public users in the library has been delayed due to the need to transfer the software from the Chemistry Centre (WA) library server to the GSWA SUN server. Delays have also been associated with a change of Australian service providers.

Library collections

Organizational changes within the department resulted in large amounts of material being returned to the library for storage and/or re-cataloguing. This included collections from the former Environmental and Engineering Geology Sections, and the Petroleum and Mining Operations Divisions. Much remains to be done to complete the integration of these materials and to amend library records. A large effort was made by library staff to audit and despatch material relevant to the transfer of the Hydrogeology Section to the Water and Rivers Commission.

Some 250 mineral processing publications from the Chemistry Centre library were transferred to the GSWA library. These were re-catalogued and issued to the Department's Mineral Processing Laboratory in Bentley.

All aerial photography up to 1959 has been stocktaken and relocated to Carlisle store to allow space for continued growth of this collection.

Library services

Library staff completed a review of journal circulation requirements to ensure effective distribution to Departmental staff was maintained. All journal issues received are now displayed in the library for two weeks prior to circulation to permit all staff to peruse the latest information.

A printer was acquired to enable users to print reports from the MAGCAT II Airborne Geophysical Survey database.

The Library has developed a ‘Library News Bulletin’ which records all the latest materials received and other information on Internet sites and conferences. This bulletin is issued to staff via e-mail and has been well received.

The library has continued to maintain its level of services during the year despite difficulties in filling a vacant Library Technician position. However, 1995–96 has been an exceptionally busy year and much work remains to deal with backlogs and collection maintenance.

B. J. Knyn

Mineral exploration data (WAMEX)

Objective: *To ensure that annual mineral-exploration reports for all current tenements are submitted to the Department in compliance with the relevant legislation, and to provide the mining industry with ready access to historical mineral-exploration data from statutory reports that have been released to open file.*

This sub-program covers all aspects of the submission, curation, and release of mineral exploration reports through WAMEX, the Western Australian Mineral Exploration Index.

Highlights for 1995–96

Highlights for 1995–96 included the gazetting of the 'Guidelines for Mineral Exploration Reports on Mining Tenements', and establishing dial-in access into the WAMEX database

Report submission

During the year, 3193 mineral exploration reports on 10 562 tenements were received, down by 4% from last year. This brings the total number of volumes held to 52 078. Gold is still the most commonly sought commodity with 75% of reports covering exploration programs for gold. It is also noted that about 10% of reports submitted contain some digital data. Digital data submission is expected to rise steadily.

Reporting standards

Recent changes to the Mining Act 1978 and Regulations in regard to reporting requirements came into force with the gazettal of the 'Guidelines for Mineral Exploration Reports on Mining Tenements' on 3 November 1995. 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.

Compliance figures for exploration licences show that during 1995–96, 38% of required reports had been submitted on or before the due date. By the end of June 1996 about 28% of required reports were still outstanding.

Of the reports submitted, about 17% at present require some rectification in regard to format and/or content. It is envisaged that this figure will improve as industry adjusts to the reporting guidelines.

The Department is currently involved with two projects relevant to reporting. One is an interdepartmental working group which 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.

Combined reporting

One of the changes to the Mining Act that came into effect this year was the legal recognition of '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, 414 reporting groups covering 4056 tenements were formalized. This is a decrease of 8% from last year. The total number of current combined reporting groups is 1232 covering 13 051 tenements.

WAMEX database

It is envisaged that WAMEX will be taken off the mainframe and redeveloped as a PC-based system in the medium term. It is therefore not planned to significantly enhance or develop the existing mainframe system.

However, some work was done to prepare WAMEX for remote access. It is now possible to search the database through a dial-in facility or via the Internet. Both access modes do require 3270 emulation software to permit communication with the Department's mainframe. The WAMEX index information may be printed or downloaded. There is no charge for this service.

Open-file releases

During the year, 626 Items (1156 volumes) were released to open file, which brings the total number of volumes on open file to 21 819

The number of releases was down by about 35% compared with last year, and there is currently a backlog of 459 volumes.

Carlisle store

During the year, an extension to the Norton Building (GSWA Carlisle Complex) was built to house the combined Minerals/Petroleum collection of hard-copy reports. This replaced previous fragmented storage arrangements. Most reports are now stored at Carlisle with only those most recently submitted being kept in the Department.

Workload and productivity index

Most routinely undertaken tasks are recorded to give an indication of the overall workload of the section. During 1995–96, the measured workload decreased by 9% compared with that of the previous year. This is due mainly to decreases in the number of reports submitted and number of applications received for combined reporting. Some new activities related to the monitoring of reporting standards may not have been fully represented in the figures.

Table 2 shows some key areas of activity.

The productivity index is derived from weighted activities (i.e. tasks have been weighted to reflect time needed to carry them out). These 'Data Transaction Units' are then divided by the number of staff (or FTEs =full-time equivalents) to show productivity per FTE. The workload measured in this way accounts for 75% of available time.

Figure 10 shows the productivity index for the last four years.

The figures demonstrate that individual productivity rose by about 3.5%. A slight reduction in measured workload was balanced by the loss of one FTE during the second half of the year.

J. Pagel

Table 2. Key areas of activity in the handling of mineral exploration reports

	1993–94 Reports (volumes)		*1994–95 Reports (volumes)*		*1995–96 Reports (volumes)*	
Report accessioning	2 849	(3 955)	3 322	(4 346)	3 193	(4 290)
Open-file release	984	(1 041)	1 801	(1 882)	1 099	(1 156)
Loans	4 892	(5 658)	7 824	(8 644)	4 950	(5 996)

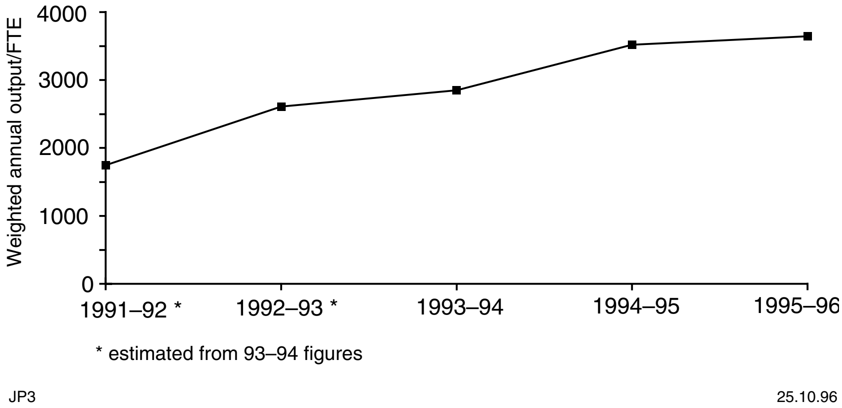


Figure 10. Productivity index 1992–93 to 1995–96

Petroleum exploration data (WAPEX)

Objectives: *To provide access to a computerized petroleum exploration data indexing system to assist in the management, administration, storage and retrieval of the large volumes of exploration data submitted to Government by the petroleum exploration and development industry. To ensure a timely release of the data when available as open-file information.*

WAPEX, the Western Australian Petroleum Exploration Index, is a computer-based information system containing data on permits, wells, surveys, and specialist studies conducted in Western Australia for petroleum exploration. It also registers petroleum exploration data submitted to the Department in compliance with reporting requirements of the Petroleum Acts. WAPEX is maintained to encourage petroleum exploration and to ensure that previous activities are not wastefully duplicated. In addition, WAPEX provides essential information for use in basin studies. This service is provided through the following processes:

- Monitoring of company compliance with reporting requirements under the State and Commonwealth Petroleum Acts for the Department.
- Accessioning, capture into the WAPEX database, and archiving of all petroleum exploration data submitted to the Department.
- Release of information as either basic or interpretative data.
- Performance of data searches for outstanding data when permits are renewed, surrendered or expire. Performance of searches for available data for release of acreage by the Petroleum Operations Division.
- Microfilming unedited reports for wells, surveys and specialist studies for release by contractors.
- Provision of advice and access to the petroleum industry and the public requiring open-file information on permits, surveys, wells and other geoscientific data.

The section provides the following services and products:

- Provision of access to open-file cores, cuttings and palaeontological and digital data requested by industry under the Department's jurisdiction.
- Photocopies and microfiche copies of company reports on surveys, wells, and selected geoscientific reports, either as edited or unedited versions, for release by private organizations (Exploration Data Services, Advanced Reprographic Services and Wiltshire Geological Services) contracted to release this information to industry and the general public.
- Monthly and quarterly lists of data declared open file.
- Quarterly production of comfiche showing all surveys, wells, and specialist studies conducted in Western Australian acreage, including, if open file, their microform number, or S-file number if released as full-scale hardcopy.
- Production of the semi-annual 'Wells drilled for petroleum in Western Australia' map in both hardcopy and digital format.
- Provision of digital database snapshots for data requested by the public.
- Provision of advice to industry and the public on the WAPEX database.

During 1995–96, there were 176 active petroleum tenements of which 158 are currently active, 18 expired during the year, and 16 were awarded or renewed during the year. Thirty-nine surveys, 57 wells and 75 general studies were conducted in the State providing 43 669 sets of data which were submitted to the WAPEX section. These datasets include reports, seismic sections, well logs, digital data, maps, cores and cuttings, and palaeontological data, bringing the total data registered in WAPEX to 476 740 items. Data released to third-party agencies included 228 edited reports, 291 unedited reports, 45 sets of well logs, 136 sets of seismic sections, and 16 020 digital tapes. The year 1995–96 saw the introduction of sales of digital datasets downloaded from the petroleum databases. Twenty sets of data were sold during the year.

Highlights for 1995–96

- The continued use of Total Quality Management techniques to improve the quality and efficiency of the petroleum data management processes has provided a 13.7% increase in productivity by the section.
- The continued production, using digital methods, of a set of three maps entitled 'Wells Drilled for Petroleum in W.A.'
- The prototype of the WAPEX MkII databases continues to be tested and used for petroleum data in the production of maps, reports and the development of the 'Schedule of Wells' product which has now been completed for the Perth, Bremer, Eucla, Officer, Southern Bonaparte Basins. Datasets from this system were made available to the public in 1995–96.
- Completion of the extensions to the Norton building at Carlisle

for the consolidation of the WAPEX/WAMEX archives.

- Proposals for funding the building of a new core-storage facility, restructuring the WAPEX database and repair of the States ageing digital data were submitted to Cabinet in 1995–96.

J. Haworth

Subprogram 3201 HYDROGEOLOGY AND GROUNDWATER RESOURCES

Hydrogeological mapping resource base

Objectives: *To collect, store, maintain, and further develop, a fully computerized, GIS-linked database of the State's groundwater resources, in order to provide the digital and graphical data for the preparation of hydrogeological maps for areas of the State, and the background data upon which groundwater resources exploration and assessment, investigation for town water supplies, the delineation of groundwater contamination plumes, and other groundwater investigations, can be planned and implemented.*

Work proceeded on the initiatives, partially funded by the National Landcare Program (NLP), to produce digital databases and hydrogeological maps for the South Coast region (Farm Water Plan) and for the whole Blackwood River Catchment (Hydrogeological Resource Base for Management). The Mount Barker–Albany 1:250 000-scale hydrogeological map was published, the Esperance map was in the final stages of editing by the end of December, Bremer Bay was at an advanced stage of drafting and compilation of Ravensthorpe had been mostly completed.

In another NLP-funded initiative, the capture of all recorded waterbore records of the State into a computer database system (AQWABase) was two-thirds completed. The remaining data points are mostly within the metropolitan area. Digital information is now available to external clients.

In response to widespread water deficiencies for the second successive year, exploratory and production bore drilling was undertaken in the South Coast region on behalf of the Farm Water Coordinating Committee, shires and landcare catchment groups. Exploration undertaken in areas in which stock water is very difficult to locate resulted in the establishment of one production bore and the identification of several other suitable sites.

Presentations were made to the Jerramungup, Cridland, and Devil Swamp Catchment Groups, the Blackwood Catchment Coordinating Group and the Gnowangerup Shire, and manned displays of hydrogeological maps were presented at the Ravensthorpe Wool and Show Day and at the Landcare '95 Conference held in Perth.

A high level of activity was associated with the separation of the Hydrogeology and Groundwater Resources Branch from the Geological Survey of Western Australia and its subsequent merging into the Water and Rivers Commission, which began operations on 1 January 1996.

R. A. Smith

Groundwater exploration and assessment

Objectives: *To provide basic hydrogeological data for water resource assessment by carrying out exploratory drilling and other studies in areas where there is potential for groundwater resources to occur, and to provide and update groundwater resource assessments to assist water resources planning, development and management, especially in previously unexplored areas.*

The 1995–96 program was curtailed with the relocation of the group into the Water and Rivers Commission in December 1995, and the attendant need to finalize plant sales and terminate the drilling advances account. Three drilling projects (two of which were continued from the previous year) were carried out under the Groundwater Exploration Initiative Program between June and December 1995. Planned exploratory drilling in the Ord River Irrigation Area extension could not proceed because of land access issues.

Table 3 summarizes the purposes and outcomes of each of the projects.

The Dongara Line project marks the virtual completion of the planned strategic groundwater assessment of the Perth Basin at a reconnaissance level, which has been continuing since 1962. In contrast to the Irwin View bores to the north of the Irwin River, the Dongara Line has shown that there is up to 400m of fresh water in the Yarragadee Formation. These results can reasonably confidently be extrapolated to the Eneabba Line, 50 km to the south. Parts of the basin are still relatively poorly known, and continuing investigation will still be necessary to provide information for groundwater resource development.

The drilling project on the South Coast adds substantially to the information being compiled for the RAVENSTHORPE hydrogeological map. In conjunction with water-deficiency drilling for the Farm Water Coordinating Committee, this project has led to the better delineation of areas of comparatively low-salinity groundwater in confined aquifers not previously used.

Exploratory drilling in the Savory Basin was carried out in conjunction with the Petroleum Initiative drilling program. The need to establish access routes, and drill for rig water supply, provided the opportunity, at no mobilization cost, for groundwater exploration of the palaeodrainages crossed by the new tracks. The information has added substantially to knowledge in an area of no data. Fresh groundwater was found in Proterozoic bedrock and in Tertiary palaeodrainages in the BULLEN sheet area, but the groundwater in the palaeodrainages of the TRAINOR sheet area is saline.

D. P. Commander

Table 3. Summary of Groundwater Exploration Initiative projects July–December 1995

Project	*Outline*	*Results*
Dongara Line	Completion of deep exploratory drilling for strategic evaluation of Perth Basin aquifers	Groundwater in Yarragadee Formation contains fresh water to 400 m
Savory Basin	Exploration of palaeochannel aquifers	Groundwater in Tertiary palaeochannels fresh in the BULLEN area, but saline in the TRAINOR area
South Coast	Exploration of Bremer Basin aquifers for hydrogeological map	Groundwater in Werillup Formation shown to be brackish

Groundwater supply investigations

Objective: *To provide expert advice and assistance to the Water Authority of Western Australia, in its role as manager of the State's water resources, and to other Government departments, agencies, and authorities, and the general public, on the availability, distribution, and quality of groundwater resources for domestic, urban, community, rural, and industrial development.*

This component has two Subcomponents: Scheme Water Supply Investigations and Special Supply Investigations. The strategic nature of these necessitates operation from two offices, one at the GSWA and the other at the Water Authority.

During the period July through to and including December 1995, the projects carried out by the Section were disrupted by processes involved in establishing the newly formed Water and Rivers Commission. At least the equivalent of two FTEs were fully employed in this activity. Nevertheless, the primary objectives of the Component have been accomplished Statewide, with expert advice being provided in the form of verbal communications, written reports, field inspections, and supervision of projects.

Activities and outcomes

The work carried out can be grouped into three broad categories of advice: Metropolitan and Town Water Supply, Aboriginal Community Water Supply, and Special Projects.

Metropolitan water-supply investigations were carried out at Lexia, Pinjar, Lake Nowergup, Barragoon, Jandakot, and Leederville. These involved assessments for water supply and the effects of groundwater abstraction on the environment. Advice relating to management of the groundwater schemes was provided to the Water Authority.

About 90 towns rely entirely on groundwater for water supply. During the six-month period, five town scheme reviews were assessed for sustainability of groundwater abstraction. Groundwater investigations, including field studies, were carried out adjacent to the Cane River for the town of Onslow; adjacent to the Gascoyne River for the irrigation district of Carnarvon, and in the fractured rock terrain within a 10 km radius of Meekatharra.

Technical assistance in the location of water supplies for Aboriginal Communities continues to be provided, funded by the Aboriginal and Torres Strait Islanders Commission (ATSIC). During the six-month period, eighteen communities were investigated in the West Kimberley, seven in the East Kimberley, and six in the Goldfields. Exploratory drilling was also carried out at the communities in the West and East Kimberley.

Several Special Projects have contributed to the knowledge of the hydrogeology and groundwater resources of the State. The most significant of these is the groundwater resources assessment of the Pilbara region, a project which was funded by the Water Authority and which will be used to initiate additional very important hydrogeological projects in the region. Other projects include drilling and hydrogeological investigations of the Spectacles and Yalgorup Lakes, both of which are Landcare funded projects, and finalization of the groundwater assessment of four areas in the Carnarvon area for the Gascoyne Development Commission.

During the review period, hydrogeological advice was also given to the public, and three site inspections were carried out. Student projects from Curtin University were supervised. These included hydrogeological investigations at Lake Nowergup, pump-test analysis of bore P105, and development of an isochrone map of the groundwater in the metropolitan area.

W. A. Davidson

Groundwater contamination

Objective: *To identify sources of, and to develop and disseminate knowledge of, groundwater contamination within the State. To provide high quality and timely technical advice on contamination issues, in order to assist with landuse planning, with particular emphasis on urban areas and mine sites, and to minimize the potential impacts of contamination on human health and the environment.*

The Section has continued to provide technical advice and assistance to Mining Operations Division, other government agencies and the general public on groundwater contamination issues. However, the volume of work carried out was greatly reduced by restructuring undertaken by the Hydrogeology and Groundwater Resources Branch during the first half of 1995–96. The Section now forms part of the Groundwater Investigations Branch of the newly created Water and Rivers Commission.

Activities and outcomes

A major groundwater investigation was completed during the review period of PCB contamination at an incinerator site in Welshpool. Drilling indicated that there was extensive contamination at shallow depth in the aquifer and that PCBs were accumulating on top of a clay layer. As these chemicals have a low solubility and are denser than water, they tend to sink in an aquifer. Drilling has indicated that there has been leakage of the chemicals through the shallow clay layer, and that some PCBs are accumulating at the base of the superficial aquifer.

Groundwater investigations near five pest-control depots indicated that groundwater near these commercial sites is contaminated with a wide variety of pesticides. The most commonly detected pesticide was diazinon, which was detected in about 80% of the water samples collected. Results from these investigations, which are being published in an international journal, will help develop government policy on how this commercial activity is managed.

S. J. Appleyard

Appendices

Planned achievements and publications released

Major planned achievements for 1995–96

The GSWA had an ambitious project-based program of work designed to promote Western Australia's exploration potential. Planned achievements for 1995–96 included:

- release of fourteen 1:100 000 geological maps, seven 1:250 000 hydrogeological maps, and eight geological maps at other scales
- release of images, interpretative maps, and data packages for three major aeromagnetic and two major gravity surveys
- publication of four GIS-based 1:250 000 regolith and geochemical maps and data packages, and accompanying notes
- publication of 21 Reports, Bulletins, and other papers, and completion of 20 hydrogeological drilling reports
- continued provision of geoscientific data and exploration-information services to industry

The hydrogeological component of the above planned achievements were not completed owing to the transfer of the Hydrogeological Section to the Water and Rivers Commission in December 1995.

Maps and volumes published 1995–96

Geological maps

1:100 000 Geological Series

GINDALBIE
ROCKLEA
DARLOT
RIVERINA
DUKETON
SIR SAMUEL
ISABELLA
BRAESIDE
PEARANA
THROSSELL
MOUNT REMARKABLE
RUDALL

1:250 000 Hydrogeological Series

MOUNT BARKER–ALBANY

Geological maps at other scales

ESPERANCE 1:1 000 000
EDJUDINA 1:250 000 (reprint)
Geology of the King Leopold Orogen (2 Plates at 1:500 000 for Bulletin 143 (in prep.))

Geological maps at other scales (continued)

Geology of the Kurnalpi–Edjudina Greenstone Terranes (1:250 000 Plate for Report 47)
Atlas of Mineral Deposits and Petroleum Fields (various scales)
Wells Drilled for Petroleum Exploration (4 sheets at 1:2 500 000)
Pilbara Iron Ore Assessment (1:500 000)

Regolith Geochemistry GIS packages

LEONORA 1:250 000 sheet
PEAK HILL 1:250 000 sheet
GLENGARRY 1:250 000 sheet
SIR SAMUEL 1:250 000 sheet

Aeromagnetic data packages (digital, images, contour maps)

West Pilbara
Merlinleigh Sub-basin
DUKETON 1:250 000 sheet
SIR SAMUEL 1:250 000 sheet
WILUNA 1:250 000 sheet
Eastern Goldfields

Gravity data packages

Merlinleigh Sub-basin
Savory Sub-basin

Reports

42. The Woongarra Rhyolite — a giant lavalike felsic sheet in the Hamersley Basin of Western Australia
by A. F. Trendall

45. Structural evolution and hydrocarbon potential of the Merlinleigh and Byro Sub-basins, Carnarvon Basin, Western Australia
by A. Crostella

47. Geology of the greenstone terranes in the Kurnalpi–Edjudina region, southeast Yilgarn Craton
by C. P. Swager

48. Geology of the Archaean Kalgoorlie Terrane — an explanatory note
by C. P. Swager, T. J. Griffin, W. K. Witt, S. Wyche, A. L. Ahmat, W. M. Hunter, and P. J. McGoldrick

Records

1995/02 **Geochemical analyses of Archaean acid to intermediate igneous rocks, including granitoids, minor intrusions, and volcanic rocks, southwest Eastern Goldfields Province, Western Australia**
by W. K. Witt, R. Davy, W. M. Hunter, and L. Pescud

1995/03 **Compilation of SHRIMP U–Pb zircon geochronology data, 1994**
by D. R. Nelson

1995/04 **Geochemistry of felsic igneous rocks from the southern Halls Creek Orogen**
by S. Sheppard, T. J. Griffin, and I. M. Tyler

1995/05 **Petroleum source rocks, Merlinleigh and Byro Sub-basins, Carnarvon Basin, Western Australia**
by K. A. R. Ghori

1995/07 **Geology and hydrogeology of the Scott Coastal Plain, Perth Basin**
by L. J. Baddock

1996/04 **Hydrogeology of the northeastern Goldfields, Western Australia**
by A. D. Allen

1996/05 **Compilation of SHRIMP U–Pb zircon geochronology data, 1995**
by D. R. Nelson

1996/08 **Depositional history of the Lower Permian Carolyn Formation and Poole Sandstone in the northern Canning Basin: implications for hydrocarbon potential**
by S. N. Apak

Explanatory Notes

1:100 000 Geological Series

Mingenew–Dongara
Rocklea
Wedge Island

1:1 000 000 Geological Series

Esperance

1:250 000 Geological Series

Trainor

1:250 000 Hydrogeological Series

Boorabbin
Kurnalpi
Widgiemooltha

1:250 000 Geochemical Mapping

Glengarry
Leonora
Peak Hill
Sir Samuel

Miscellaneous publications

GSWA Annual Review for 1993–94
GSWA Annual Review for 1994–95
Catalogue of Geological Maps, November 1995
Catalogue of Geological Publications, January 1996
GSWA Fieldnotes, v.1, January 1996
GSWA Fieldnotes, v.2, April 1996

Major planned achievements 1996–97

The GSWA will continue to pursue a project-based program of work and maintain a vigorous level of output. Planned achievements for 1996–97 include:

- release of 22 geological maps at various scales covering areas throughout Western Australia
- publication of three GIS-based 1:250 000 regolith geochemical maps, related data packages and accompanying notes
- release of images, interpretative maps and data packages for two aeromagnetic/radiometric and two gravity surveys
- publication of 25 geoscientific Reports, Bulletins, and other papers including data packages on the petroleum resources of various on-shore sedimentary basins and on the fluorite, barite, and limestone mineral resources of WA
- 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

BLIGHT, D. F., and *FERGUSON, K. M.*, 1995, Oil and water can mix: the relevance of the GSWA's petroleum exploration initiative program to base metal exploration: Australian Institute of Geoscientists, Bulletin 16, p. 33–39.

BLIGHT, D. F., and MUIR, I. G., 1996, The Syerston polymetallic project: Alta Metallurgical Services; Nickel/Cobalt Pressure Leaching and Hydrometallurgy Forum, May 1966, Proceedings.

BROWNLAW, R. L. S., *HOCKING, R. M.*, and JELL, J. S., 1996, High frequency sea-level fluctuations in the Pillara Limestone, Guppy Hills, Lennard Shelf, northwestern Australia: Historical Biology, v. 11, p. 187–212.

CARLSEN, G. M., 1996, Interior Basins Studies in Western Australia: PESA NEWS, Dec/Jan; 1995–1996.

CHADWICK, B., GARDE, A. A., and *SWAGER, C.*, 1995, Plate tectonic setting and HT/LP thermotectonic events in the Palaeoproterozoic Ketilidian Orogen, South Greenland: Precambrian 95 International Conference on Tectonics and Metallogeny of Early–Mid Precambrian orogenic belts, Program and Abstracts, p. 219.

CORKERON, M., *GREY, K.*, LI, Z.-X., POWELL, C. McA., 1996, Neoproterozoic glacial episodes in the Kimberley region, northwestern Australia: Geological Society of Australia,Abstracts no. 41, 13th Australian Geological Convention, p. 97.

FREEMAN, M. J., RICHARDS, G., MILLS, K., and RIPPON, G., 1996, Heavy mineral sands in the southern Perth Basin, Western Australia — geology, mining urbanisation and planning: Geological Society of Australia, Abstracts no. 41, p. 151.

GHORI, K. A. R., 1995, Measuring thermal conductivity improves maturation modelling in the northern Carnarvon basin, Western Australia: PESA Journal, no. 23, p. 3–12.

GREY, K., 1995, Neoproterozoic stromatolites from the Skates Hill Formation, Savory Basin, Western Australia, and a review of the distribution of *Acaciella australica*: Australian Journal of Earth Sciences, v. 42, p. 123–132.

HOCKING, R. M., and *PRESTON, W. A.*, in press, Western Australia — Phanerozoic geology and resources: AGSO Journal of Australian Geology and Geophysics, v. 17, no. 3, pt 2.

LANGFORD, R. L., and JAMES, J. W. C., 1995, Shek Pik, Sheet 13, solid and superficial geology, 1:20 000, Series HGM20: Hong Kong Geological Survey, Geotechnical Engineering Office.

LANGFORD, R. L., JAMES, J. W. C., SHAW, R., CAMPBELL, S. D. G., KIRK., P. A., and SEWELL, R. J., 1995, Geology of Lantau District: Hong Kong Geological Survey Memoir No. 6, Geotechnical Engineering Office, Hong Kong, 173p.

LANGFORD, R. L., STRANGE, P. J., FYFE, J. A., and SHAW, R., 1995, Cheung Chau, Sheet 14, solid and superficial geology, 1:20 000, Series HGM20: Hong Kong Geological Survey, Geotechnical Engineering Office.

MYERS, J. S., 1995, The generation and assembly of an Archaean supercontinent: evidence from the Yilgarn Craton, Western Australia, *in* Early Precambrian Processes *edited by* M. P. COWARD and A. C. RIES: Geological Society Special Publication 95, p. 143–154.

NELSON, D. R., *MYERS, J. S.*, and NUTMAN, A. P., 1995, Chronology and evolution of the middle Proterozoic Albany–Fraser Orogen, Western Australia: Australian Journal of Earth Sciences, v. 42, p. 481–495.

OCCHIPINTI, S., *SWAGER, C.*, and *PIRAJNO, F.*, 1996, Structural and stratigraphic relationships of the Padbury Group, Glengarry Basin, Western Australia — implications for tectonic history: Geological Society of Australia, 13th AGC, Abstracts Volume, February 1996.

PERINCEK, D. P., 1996, The age of Neoproterozoic–Paleozoic sediments within the Officer Basin of the Centralian Super-basin can be constrained by major sequence-bounding unconformities: APPEA Journal, v. 36, p. 61–79.

PERINCEK, D., SIMONS, B., PETTIFER, G. R., and GUNATILLAKE, K., 1995, Seismic interpretation of the onshore western Otway Basin, Victoria: Department of Agriculture, Energy and Minerals, Victoria Initiative for Minerals and Petroleum, VIMP Report 17.

PIRAJNO, F., *BAGAS, L.*, *HICKMAN, A.*, and GOLD EXPLORATION TEAM, 1996, Geotectonic evolution and gold metallogeny in Zhejiang Province, SE China: 30th International Geological Congress, Beijing, Abstract Volume, August 1996.

PIRAJNO, F., and *DAVY, R.*, 1996, Mafic volcanism in the Palaeoproterozoic Glengarry Basin and implications for its tectonic evolution. Geological Society of Australia: 13th AGC, Abstracts Volume, February 1996.

PIRAJNO, F., and *OCCHIPINTI, S.*, 1996, Base metal mineral potential of the Palaeoproterozoic Glengarry and Bryah basins, Western Australia: Australian Institute of Geoscientists, Bulletin 16, p. 51–56.

PIRAJNO, F., *OCCHIPINTI, S.*, *SWAGER, C.*, *ADAMIDES, N.*, and *BAGAS, L.*, 1996, The tectonic evolution and mineral deposits of the Palaeoproterozoic Glengarry basin, Western Australia: 30th International Geological Congress, Beijing, Abstract Volume, August 1996.

RUGLESS, C. S., and *PIRAJNO, F.*, (in press), Geology and geochemistry of the Copperhead albitite–carbonatite complex, East Kimberley, Western Australia. Australian Journal of Earth Sciences, vol. 43 (3).

STENDAL, H., and *SWAGER, C.*, 1995, Gold in the Early Proterozoic Ketilidian Orogen, South Greenland: setting of mineralization and geotectonic models, *in* Gold mineralization in the Nordic countries and Greenland *edited by* P.M. IHLEN, M. PEDERSEN and H. STENDAL: Geological Survey of Greenland, Open File Series 95/10, p. 110–113.

SWAGER, C., CHADWICK, B., FRISCH, T., GARDE, A., SCHONWANDT, H. K., STANDAL, H., and THOMASSEN, B., 1995, Geology of the Lindenow Fjord — Kangerluluk area, South-East Greenland: preliminary results of Suprasyd 1994: Geological Survey of Greenland, Open File Series 95/6, 78p.

WALTER, M. R., VEEVERS, J. J., CALGER, C. R., and *GREY, K.*, 1995, Neoproterozoic stratigraphy of the Centralian Superbasin, Australia: Precambrian Research, v. 73, p. 173–195.

WITT, W. K., 1995, Contrasting styles of mineralizing, synmetamorphics, hydrothermal fluid systems in the Archaean Kalgoorlie and Ravensthorpe Terranes, Western Australia, *in* Precambrian '95 — International Conference on Tectonics and Metallogeny of Early/Mid Precambrian Orogenic Belts: Ecole Polytechnique, Montreal, Canada, p. 124.

WITT, W. K., 1995, Tholeiitic and high-Mg mafic/ultramafic sills in the Eastern Goldfields Province, Western Australia: implications for tectonic settings: Australian Journal of Earth Sciences, v. 42, p. 407–422.

WYCHE, S., *FARRELL, T. R.*, *GRIFFIN, T. J.*, *LANGFORD, R. L.*, *LIU, S. F.*, STEWART, A. J., *WESTAWAY, J. M.*, and WHITAKER, A. J., 1996, Archaean geology of the northern part of the Eastern Goldfields, Yilgarn Craton, Western Australia (abstract): 13th Australian Geological Convention, Canberra.

List of acronyms and abbreviations

ABS	Australian Bureau of Statistics
AGSO	Australian Geological Survey Organisation
AMSS	Airborne multispectral scanner
APEA	Australian Petroleum Exploration Association Limited
APPEA	Australian Petroleum Producers and Explorers Association Limited
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
Landsat TM	Landsat Thematic Mapper
LCD	Land Conservation District
LIS	Land Information System
MERIWA	Minerals and Energy Research Institute of Western Australia
MINEDEX	Mines and mineral deposits information database
NGMA	National Geoscience Mapping Accord
PC	Personal Computer
RMS	Record Management System
SHRIMP	Sensitive High-Resolution Ion Microprobe
SPOT	Système Probatoire de l'Observation de la Terre
TENGRAPH	DME's electronic tenement-graphics system
WAMEX*	Western Australian Mineral Exploration Index
WAPEX*	Western Australian Petroleum Exploration Index

* WAMEX and WAPEX are registered Trade Marks

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