GEOLOGICAL SURVEY of WESTERN AUSTRALIA

ANNUAL REPORT 1978

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ANNUAL REPORT

FOR THE YEAR

1978

EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

Minister: The Hon. A. Mensaros, M.L.A.

Under Secretary: B. M. Rogers

Director, Geological Survey: J. H. Lord

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DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1978

CONTENTS

REPORTS

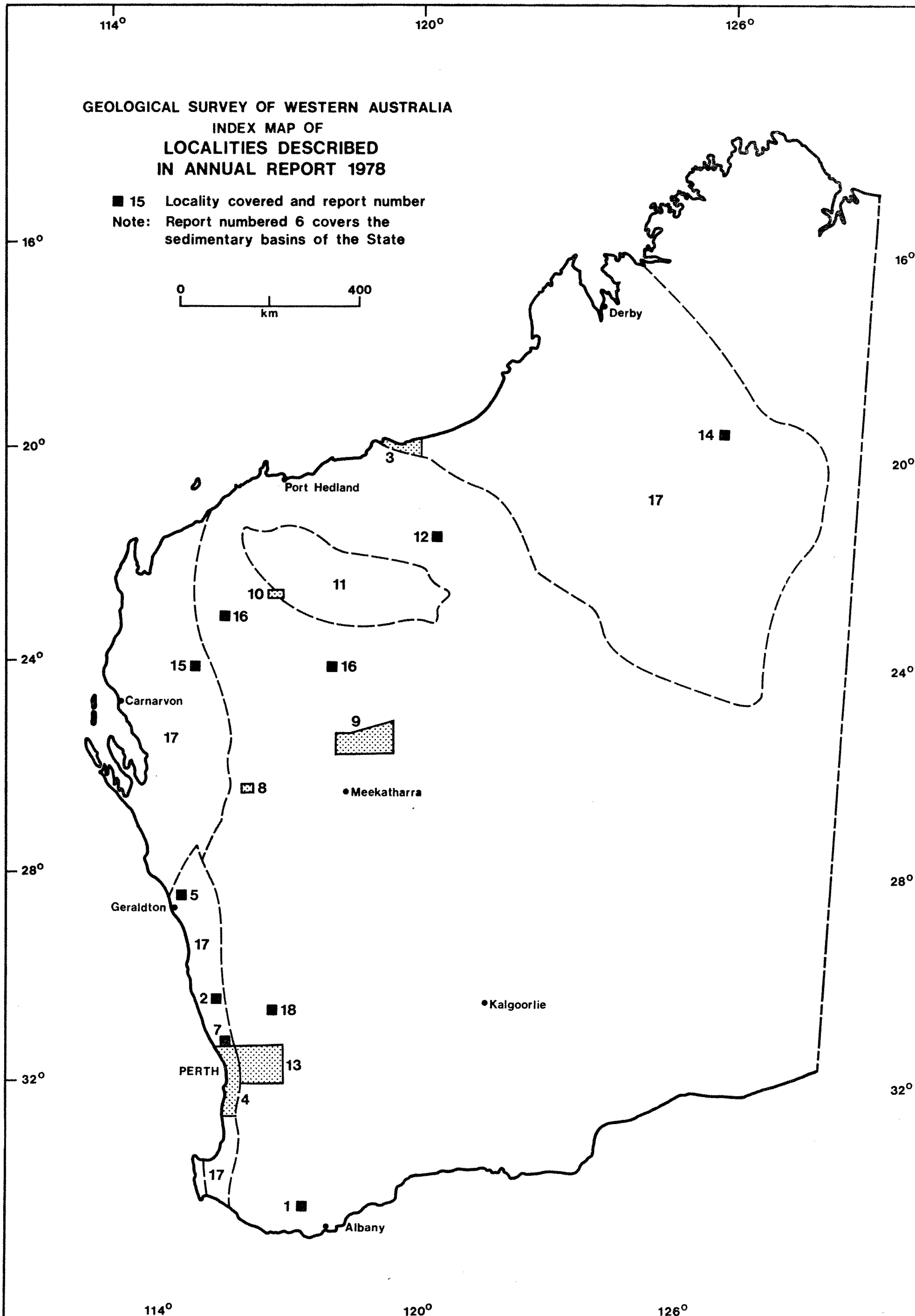


Figure 1 Index map showing areas and localities described in the Annual Report for 1978. GSWA 17746

LIST OF FIGURES

DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1978

Under Secretary for Mines:

My report for 1978 on the activities of the Geological Survey of Western Australia for the information of the Honourable Minister for Mines is forwarded herewith, together with selected reports on investigations and studies made for Departmental purposes.

INTRODUCTION

Previously it was reported that mineral exploration activity had levelled off in 1977, but in 1978 there was a rapid expansion in all exploration in this State, despite the fact that the world metal prices have not recovered to any great extent. The main search continued to be for uranium, but the diamond search, previously reported to be expanding, developed into a boom. Interest has been renewed in gold due to the increase in the world price, while the search for nickel, copper, zinc and other minerals continues on a limited scale.

This upsurge in exploration for minerals is illustrated in the statistics for temporary reserves granted.

Temporary Reserves Approved
(other than gold, iron and coal)

Year	New applications	Renewals	Total
1973	182	—	182
1974	47	28	75
1975	20	18	38
1976	117	11	128
1977	92	37	129
1978	228	53	281

Of the 228 new applications for temporary reserves 101 included diamonds in the minerals sought, but uranium remained as the most often included in the minerals listed. These applications cover an area of 36 841 square kilometres with a minimum exploration expenditure commitment of $7 368 200 if the areas are held for the full tenure of twelve months.

Many companies continued the search for uranium throughout the State, both on the Precambrian areas and in the Phanerozoic basins. No new occurrences of economic importance were reported. The development of the Yeelirrie deposit should commence in 1979. Feasibility studies are being carried out on a deposit at Lake Way near Wiluna, and it should be known shortly if it is to be developed.

While the search for diamonds has been going on for many years in the Kimberley, it was not until 1978 that it became generally known that the consortium with Conzinc Riotinto of Australia (CRA), as operator, had found diamonds associated with kimberlitic plugs. CRA has reported a cluster of kimberlitic plugs covering in total some 610 hectares and located 120 km east-southeast of Derby, on and near Ellendale Station.

A substantial sampling plant was established during the year and 2 730 m^3 of kimberlitic material from pipe A yielded 966 stones and 4 170 m^3 from pipe B yielded 2 700 stones. Until the quality of the diamonds has been determined it is difficult to assess the value of these plugs.

Many companies and prospectors have been attracted to the diamond search, which has extended from the Kimberley to many other parts of the State. While prospecting for diamonds is very expensive, the companies remain undaunted having included diamonds in some 101 temporary reserve applications throughout the State, and having applied for 5 775 mineral claims in the Kimberley area.

Exploration for iron ore in the Hamersley Basin on incompletely tested temporary reserves continued, but interest in the Nabberu Basin has waned rapidly. Some 32 new temporary reserves for iron ore were granted and there were 127 in force at the end of the year.

The search for coal in this State, particularly in the northern portion of the Perth Basin, has decreased with no new finds being reported. The two active companies in the Collie coalfield continue their drilling programmes to delineate extractable reserves.

Due to the rise in price, the search for gold, particularly by prospectors, syndicates and small companies, has increased and the State Batteries are being kept fully occupied treating parcels of ore. No new finds of note have been reported but the Telfer, Central Norseman and Mount Charlotte mines continued to operate very profitably. Although the average price of gold is at a high level, it is not considered opportune to reopen the Golden Mile until current fluctuations stabilise at such a level.

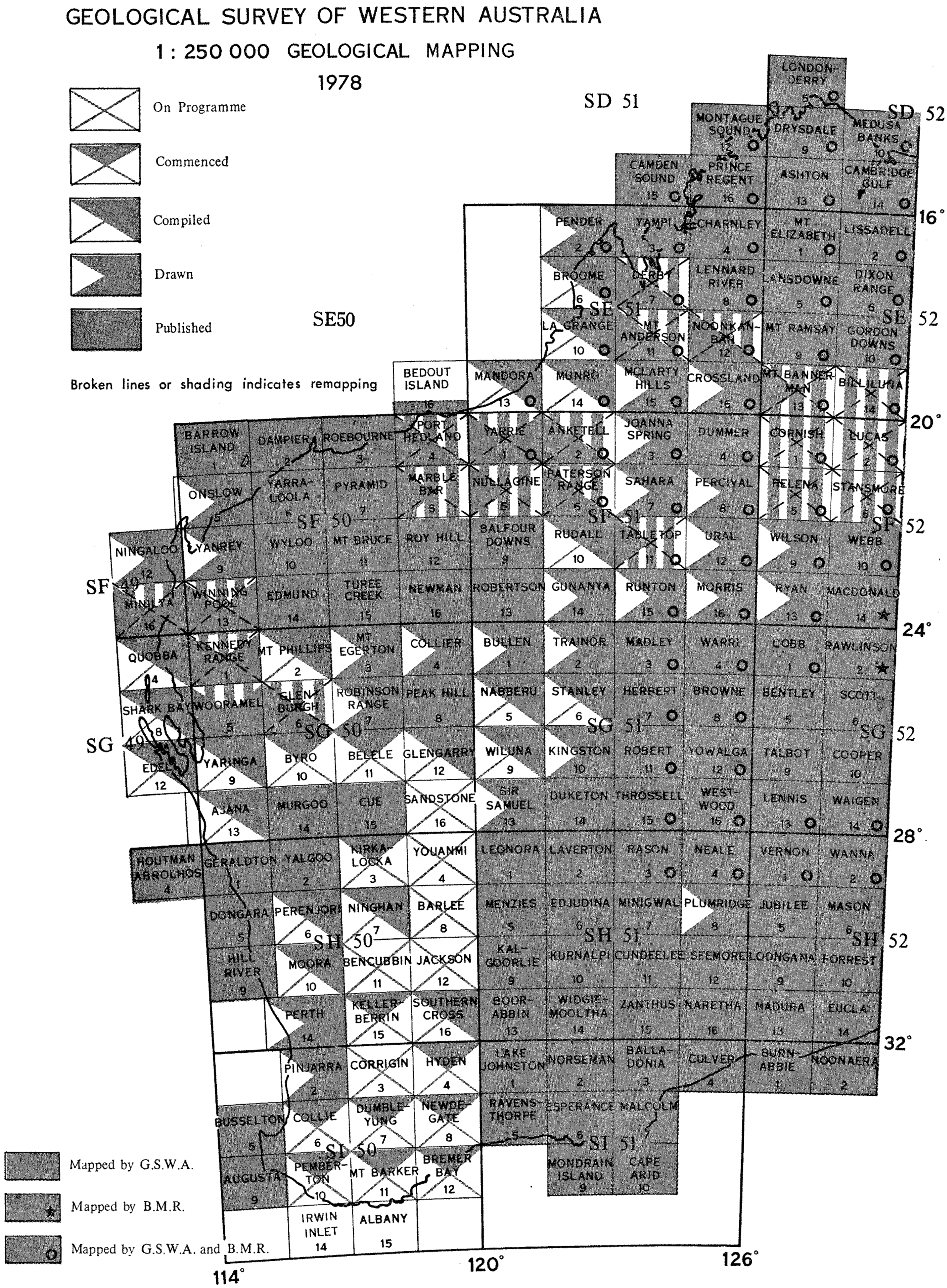
Over 4 000 enquiries from Metropolitan landholders for advice on the depth of water, strata and possible salinity were answered; in addition 224 country inspections were made by the Hydrogeological Division. Deep drilling in the Quindalup area and eastwards has disclosed major supplies of good water while further drilling in the Fortescue-Robe River area also continues to show valuable water resources for the Pilbara.

Regional geological mapping on 1:250 000 scale continues and the field work should be completed for the whole State by the end of 1979.

As anticipated, petroleum exploration was very active during 1978, particularly with marine seismic surveys on the Exmouth Plateau in preparation for drilling in 1979. There was a resurgence of onshore prospecting in the Canning Basin. The number of exploratory holes drilled in oil exploration also showed a marked increase.

Year	Total holes drilled	Total metrage drilled	Seismic (km)	
			Land	Marine
1971	29	70 620	2 744	19 933
1972	29	102 876	3 266	43 218
1973	22	63 612	1 776	14 904
1974	21	48 172	559	11 815
1975	6	17 115	484	2 733
1976	6	22 171	443	2 599
1977	8	35 339	Nil	5 994
1978	15	48 110	1 143	38 996

There was no discovery of oil or gas of commercial interest made in 1978.



GSWA 17928

Figure 2 Progress of 1:250 000 or 4 mile geological mapping at the end of 1978

Public lectures: Public lectures were presented again in 1978 and on the first day (March 30) lectures with an emphasis on topics relating to the exploration of minerals within sedimentary rock environments were given. On the second day (April 1) lectures were confined to regional geology and mineralization of Precambrian rocks.

The attendance at the sessions varied according to the topics from 75 to 95 with persons attending the sessions appropriate to their interest.

Field excursions: No field excursions were held during 1978 as the required map sheets were not ready. It is proposed to visit the Nabberu Basin in April, 1979, and probably also to visit the Collie and Pemberton sheet areas later in the year.

Microfilm library: The microfilm library was described in last year's annual report, was opened and has operated very satisfactorily during the year. There was a strong demand for open file information released on 35 mm film and it was necessary to install a third reader printer midway through the year. At the end of 1978 there were 91 rolls of film of company reports on mineral exploration and 72 rolls on oil and gas exploration available in the library. Each film has about 500 frames, some of which display two pages of a report.

All the 1978 Records, as listed later, have been produced on microfiche and are readily available to the public. They are classed as publications. A start has been made on placing earlier Records on microfiche and these will become available as the project develops.

Regional offices: A review of the need for and possibilities of opening regional offices has been made. It is considered that such offices would, by the resulting decentralization, bring geological assistance closer to prospectors and exploration geologists. Such offices have been considered for Kalgoorlie, Karratha and Kununurra, and it is hoped that the first may open at Kalgoorlie about mid-1979.

STAFF

In addition to some resignations there were three retirements of officers who have given loyal and valuable service to the Geological Survey.

Mr Eugene O'Driscoll retired on March 17 after 15 years service. With academic qualifications in both geology and engineering he was appointed as chief hydrogeologist in 1962 to supervise the Hydrology and Engineering Geology Division. Early in 1978 his position was retitled Assistant Director. Eugene O'Driscoll, on joining the branch, had already established an internationally respected reputation in the field of groundwater study and this was enhanced during his service with this branch. He made a major contribution to the knowledge and development of groundwater in this State.

Mrs Sheila Fawcett retired on February 28 after nearly 12 years service. Mrs Fawcett joined the branch as a library assistant, was promoted to senior library assistant and later to librarian in 1969. Her efficiency and unfailing courtesy was greatly appreciated by all library users.

Mr Jack Dyer, stores and transport assistant, retired on November 9, after over 12 years of efficient and cheerful service.

A Ph.D. was conferred on R. Thom as a result of his studies at the Imperial College, University of London, London.

PROFESSIONAL

Appointments

Name	Position	Effective Date
Lavaring, I. H., B.Sc. (Hons)	Geologist L1	18/1/78
Whitfield, S. J., Grad.Dip.Lib.Stud.	Librarian L1	15/5/78
Moors, H. T., B.Sc., M.Sc., Ph.D.	Geologist L3	16/10/78
Johnstone, M. H., B.Sc. (Hons)	Geologist L5	13/11/78
Daetwyler, N. A., B.Sc. (Hons)	Geologist L1	22/11/78

Promotions

Hind, P.	Librarian L4	24/2/78
Playford, P. E.	Assistant Director L6	24/5/78
Denman, P. D.	Geologist L3	13/12/78

Retirements

Fawcett, S. M.	Librarian L4	28/2/78
O'Driscoll, E. P. D.	Assistant Director L6	17/3/78

Resignations

Klenowski, G.	Geologist L1	10/2/78
Harley, A. S.	Geologist L1	1/9/78
Van de Graaff, W. J. E.	Geologist L3	8/9/78

CLERICAL AND GENERAL

Appointments

May, Y.	Typist	16/1/78
Blight, E. K.	Clerical Assistant	20/2/78
Brown, T. H.	Geological Assistant	20/2/78
Stewart, F. W.	Geophysical Assistant	8/5/78
Monaghan, R. P.	Technical Assistant	22/5/78
Collier, J. M.	Geophysical Assistant	29/5/78
Prichard, D. E.	Technical Assistant	12/6/78
Donovan, G. K.	Laboratory Assistant	5/7/78
Evans, D. G.	Technical Assistant	20/11/78
Moore, B. J.	Stores and Transport Assistant	18/12/78
Paff, J.	Geophysical Assistant	18/12/78

Retirements

Dyer, J. M.	Stores and Transport Assistant	9/11/78

Transfers Out

Emery, L. S. G.	Laboratory Assistant	27/12/78
Willis, R.	Laboratory Assistant	22/12/78

Resignations

Elms, B.	Typist	10/1/78
Lutter, M. O.	Technical Assistant	19/1/78
Baggott, S.	Geophysical Assistant	9/2/78
Whiskin, M.	Laboratory Assistant	17/2/78
Quinn, P.	Technical Assistant	27/2/78
Slater, R.	Geophysical Assistant	28/2/78
Dickie, D. F. (nee Kelly)	Technical Assistant	31/8/78
Stewart, F. W.	Geophysical Assistant	3/11/78

ACCOMMODATION

There was no increase in the space allocated to the Branch in 1978. The most pressing need is for extension to the store building at Russell Street, Morley in which are stored the bulk supply of Branch publications and many of the original copies of company reports that have been recently microfilmed. Drawings for the extension are currently being prepared and it is hoped that the work will be carried out in 1979.

OPERATIONS

HYDROGEOLOGY DIVISION

T. T. Bestow (Supervising Geologist), A. D. Allen, A. T. Laws (Senior Geologists), J. C. Barnett, W. A. Davidson, A. S. Harley, K-J. B. Hirschberg, E. H. Briese, D. P. Commander, L. J. Furness, R. E. J. Leech, J. S. Moncrieff, P. A. Wharton.

Despite cost inflation, exploratory drilling for water resource investigations was maintained at about the same level as last year. However, due to financial constraints, it remains at less than half of the level reached in 1974. Priority continues to be given to work in the Perth sedimentary basin. Six bores were drilled on three sites in, and east of, Bunbury on the Picton Line and two bores on Quindalup No. 7 site east of Busselton. One of the latter was drilled to a depth of 1 049 m and was the deepest hole yet to be constructed with departmental plant. The information collected further extends the substantial area known to be underlain by major groundwater resources. In the metropolitan area nine new bores have been drilled to explore the relationships between deep and shallow aquifers as part of the Artesian Monitoring program.

There has been further exploration of shallow aquifers with the drilling of 23 bores for the Yeal scheme north of Pinjar and 13 south and east of Bunbury. Work has also commenced on an evaluation of the water resources and water balance of the southwest coastal groundwater area between Bunbury and Mandurah. This area has experienced rapid development of groundwater for market garden and fodder irrigation.

Studies of the effects on stream and groundwater hydrology of the Manjimup woodchip industry and of bauxite mining in the Darling Range have continued on an interdepartmental basis. This year these have included the use of electronically recorded four-phase test pumping as an aid to the assessment of groundwater and salt discharges of catchments.

Drilling and test pumping have continued in the upper part of the Robe River catchment as part of the extended investigation of groundwater resources near the source of the west Pilbara water supply.

The continuation of water restrictions by the Metropolitan Water Board, which were necessitated by drought conditions, has encouraged landowners to seek independent sources of water for garden watering. Over four thousand enquiries for recommended bore depths and strata information were answered. The generally below average rainfall also resulted in an increase in other advisory work; 224 field investigations for bore site selection were carried out for landowners.

Liaison with other government departments regarding groundwater exploration and development, continues to be close. A number of investigations have been undertaken in reponse to applications for effluent disposal licences under the Rights in Water and Irrigation Act. Further reports have been written recording the results of hydrogeological studies of acid effluent disposal in the Leschenault dune system.

ENGINEERING GEOLOGY DIVISION

R. P. Mather (Supervising Geologist), G. W. A. Marcos, I. H. Lewis and N. A. Daetwyler.

The work of this Division was again confined mainly to investigations for other Government Departments and instrumentalities including:

Department of Public Works:

(a) Further investigations made at Nunyerry dam site in the Pilbara.

(b) Geological reconnaissances made of the following dam sites: Kumina Creek and Munni Munni Creek in the Pilbara; Marrinup Brook, Kent River, and several in the Manjimup area in the southwest.

(c) Minor investigations carried out including foundation studies for tank sites at Sawyers Valley, Beacon, South Hedland and the wharf at Wyndham.

Metropolitan Water Board:

(a) Continued mapping and provision of geological advice during construction of Wungong Dam.

(b) Continued studies on South Canning and North Dandalup dam sites.

(c) Report completed for Burns Beach sewer tunnel and studies continued for Bibra sewer and Wungong water tunnels.

Westrail:

Geological advice given on selection and development of quarry sites.

REGIONAL GEOLOGY DIVISION

R. D. Gee (Supervising Geologist), I. R. Williams (Senior Geologist), P. C. Muhling, J. A. Bunting, R. Thom, A. T. Brakel, R. J. Chin, M. Elias, S. J. Williams, I. W. Walker.

Regional mapping continued on the Precambrian portion of the State for publication at a scale of 1:250 000 (Fig. 2). Field mapping on Albany, Belele, Bremer Bay, Byro, Hyden, Kennedy Range, Mount Barker, Newdegate and Winning Pool was completed. Mapping on Dumbleyung was 85 per cent completed.

The Bulletin on the Bangemall Basin was compiled and work continued on the Nabberu Basin Bulletin, which should be completed shortly.

SEDIMENTARY DIVISION

M. H. Johnstone (Supervising Geologist), K. A. Crank, H. T. Moors, and P. D. Denman (Senior Geologists), M. N. Megallaa (Senior Geophysicist), R. M. Hocking, B. P. Butcher, I. H. Lavaring.

The processing of data submitted by petroleum companies continued. There was a considerable upsurge of seismic exploration during the year to delineate the regional structural style of the permit areas and to detail structures which would be targets for the drilling proposed for 1979. Onshore seismic surveys also increased in 1978 due to a renewal of interest in the northern Canning Basin.

Mapping continued in the Carnarvon Basin with the completion of compilation of the Phanerozoic portions of the Wooramel and Winning Pool 1:250 000 Sheets. Final editing of the compilations of the Ajana, Shark Bay-Edel, and Yaringa Sheets is in progress.

Editing of the comprehensive study of the southern and central Carnarvon Basin is in hand and a study of the economically important northern offshore portion of the basin is in progress.

MINERAL RESOURCES DIVISION

J. G. Blockley (Supervising Geologist), J. D. Carter and R. J. Marston (Senior Geologists), J. L. Baxter, A. H. Hickman, J. Morrison, S. A. Wilde, S. L. Lipple, K. H. Green.

Mapping of the Ninghan, Kirkalocka and the Precambrian portion of Pemberton 1:250 000 sheets was completed. The map compilation and explanatory notes for Perenjori and Ninghan were finished, and those for Collie continued.

A bulletin on the Pilbara Block was completed and work continued on a mineral resources bulletin on nickel.

Sundry field work included examinations of Ministerial Reserves for iron ore, an assessment of the possible effect on ore reserves at Eneabba caused by the mining of higher-than-average grade ore, and inspections of the Redross and Blue Spec mines prior to their closures.

A re-assessment of the State's iron ore resources was completed during the year and an assessment of nickel resources is nearing completion.

During 1978, 91 rolls of microfilm containing reports on some 600 exploration projects were placed on open file in the Branch library. The Division answered about 300 verbal enquiries from the pubic and other Government Departments and handled some 160 requests for access to company reports on surrendered tenements. About 725 new accessions were added to the Division's collection of mineral exploration reports, an increase of 65 on 1977.

COMMON SERVICES DIVISION

Petrology

W. G. Libby, J. D. Lewis, D. F. Blight.

One hundred petrological reports covering 1 677 thin sections and 57 other miscellaneous samples were completed during the year. Further thin sections were studied for incorporation into the computer based petrological data system.

The G.S.W.A./W.A.I.T. co-operative geochronology programme continued with the results of three projects published. Two further projects were completed during the year and are presently being prepared for publication. Sixteen projects were carried over to the 1979 programme.

During the year studies were completed on the geochronology of the Darling Range biotite, and an electron microprobe examination of amphiboles from the Wongan Hills was made.

The laboratory prepared 2 156 thin sections of which 2 130 were petrological; 77 polished sections were made; 88 rocks were crushed; and 262 rocks were cut and faced for examination. There were 76 mineral separations undertaken and 124 sieve analyses completed. Samples and thin sections stained for carbonate numbered 72, and 142 m of continuous peel was taken from core.

The Government Chemical Laboratories identified mineral samples and provided access to the X-ray diffractometer and computer.

Palaentology

A. E. Cockbain, J. Backhouse, K. Grey.

A total of 70 reports was written during the year. The reports covered three main areas of activity: (a) Mesozoic palynological studies of the Perth Basin for the Hydrogeology Division, (b) description of Precambrian stromatolites and microfossils, mainly from the Bangemall and Nabberu Basins, for the Regional Geology Division and (c) identification of Mesozoic and Tertiary fossils from the Carnarvon Basin for the Sedimentary Division.

Work on the Devonian faunas, especially the stromatoporoids, of the Canning Basin reef complexes continued. In conjunction with the Sedimentary Division a start was made on cataloguing palaeontological material from relinquished petroleum exploration permit areas.

Geophysics

D. L. Rowston, I. R. Nowak.

Well-logging activity declined from 204 logging operations in 1977 to 144 in 1978 with a corresponding decrease in aggregate total depths from 43 210 m to 25 720 m.

Seismic refraction techniques were used to investigate several engineering project sites raging from the Nunyerry dam site in the Pilbara to a prospective siding for Westrail at Moondyne. Ground water surveys, again predominantly refraction work, were continued for the Albany Town Water Supply and in the Fortescue Valley near Mount Elvire.

Dolerite dykes, thought to indicate fracture zones in the granulite country rock near Northampton, and therefore possible sources of groundwater, were delineated with a magnetometer. An airborne proton precession magnetometer was adapted for ground measurements by the Commonwealth Bureau of Mineral Resources in an attempt to locate shell debris in a wartime gunnery range at Warnbro. Although successful in detecting shells to depths of about one metre the method proved too time-consuming and costly to use over large areas.

Field salinity measurements totalled about 1 050 of which 360 related to water samples submitted by the public and the remainder to continuing bauxite and other salinity monitoring projects.

Normal laboratory servicing was maintained and about 100 public enquiries on geophysical matters satisfied.

Environmental Geology

E. R. Biggs, R. H. Archer.

Work on the 1:50 000 urban geology map series was continued with the completion of two sheets (Roebourne and Baynton) and the addition of two part sheets to the Dampier Sheet (Eaglehawk and Rosemary Islands).

Geological information has been supplied for a variety of projects, including the System 6 study, Special Rural Zone proposals, an examination of the present and future requirements for aggregate in Perth, planning within Bunbury townsite and many others. This year, the appraisal of major environmental review and management programme reports has occupied a large segment of the section's activities, and committee and liaison meetings continue an important function.

A study has been made of the limesand and limestone resources of the islands of the Dampier Archipelago and adjacent mainland. Appraisal continues on applications for mineral tenements in the Southwest Mineral Field with a view to lessening adverse impacts of mining on the environment.

Geochemistry

R. Davy.

Studies on low-grade zinc mineralization in the Bangemall Basin, and on the use of B-Ga-Rb diagrams for determining depositional conditions in Phanerozoic rocks of W.A. have been completed.

Reports on geochemical exploration of the Saddleback greenstone belt and on the geochemistry of the Mount McRae Shale are in preparation.

Sampling of the Mount Edgar and Corunna Downs batholiths has been undertaken preparatory to detailed geochemical studies of rocks of these batholiths.

Co-operation was received in carrying out chemical work for the above projects from the Government Chemical Laboratories.

Technical Information

W. B. Hill, M. E. Wenham, J. F. Cameron, P. Hind.

Budget restraints interfered with the printing of publications, and the withdrawal of the Bureau of Mineral Resources as publisher of the geological sheets mapped by the Survey has drastically curtailed the production of the 1:250 000 geological map and explanatory notes series. Only eight maps with explanatory notes were published.

This year two bulletins and three reports have been issued and three mineral resources bulletins and four reports were sent to press. Editing and proof reading of six explanatory notes has been carried out. Seventeen records have been edited. Three revised information pamphlets were edited.

Requisitions raised on the Surveys and Mapping Branch for drafting, photography and copying totalled 1 091. Photocopying for the public numbered 1 414 requisitions.

During 1978 this section answered 896 requests for information including rock identifications, 342 of which entailed some research; and 2 733 members of the public visited the library for research purposes. Book loans to the staff totalled 7 144, and loans to and from other libraries 598.

At the end of the first year of operation of the open file system for the "M" series, 548 users had visited the microfilm library.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

Geological and geophysical projects carried out by the Bureau of Mineral Resources included the following:

(i) Completion of compilation of field mapping in the Canning Basin as a joint project with this Survey.

(ii) Analysis and study of rocks from the Pilbara Block as continuation of a joint geochemical project with this Survey.

(iii) Completing results of crustal study between Meekatharra and Mount Goldsworthy using seismic and gravity methods.

PROGRAMME FOR 1979

HYDROGEOLOGY DIVISION

1. Continuation of the hydrogeological survey of the Perth Basin including deep drilling and reports on Quindalup and Boyanup lines.
2. Hydrogeological investigations and/or exploratory drilling for groundwater in the following areas:
   (a) Fortescue River area—further investigations including Weelumurra and Robe River.
   (b) Re-assessment of the groundwater resources of the Gascoyne River.
   (c) Investigation of the water resources of the Collie Coal Basin.
3. Town water supply investigations and/or drilling for the following: Bunbury, Albany, Horrocks Beach, Brookton, Bindoon, Watheroo, Esperance (mallee), Port Gregory, Kalbarri and others as required.
4. Hydrogeological investigations for the Metropolitan Water Supply Board:
   (a) Deep drilling at Jandakot, Wanneroo, Mirrabooka.
   (b) Shallow drilling at Yeal, Lake Marginiup, East Mirrabooka.
   (c) Continuation of pollution studies at Hertha Road/Jones Street, Gnangara liquid waste disposal and Alcoa red mud lake areas.
   (d) Study of water balance in coastal lakes.
5. Interdepartmental studies concerning groundwater salinity problems in the Darling Range bauxite and woodchip areas.
6. Continuation of bore census of selected areas, salinity studies and supervising consultants work.
7. Miscellaneous investigations and inspections as required by Government departments and the public.

ENGINEERING GEOLOGY

1. South-West Division—continuing investigations on Wungong, South Canning, North Dandalup, Victoria, Manjimup, Kent River, Brunswick River and commencing investigations in Marrinup, Little Dandalup and Dirk Brook dam sites.
2. Investigation of tunnel lines at Bibra Lake and Wungong.
3. Review of dam sites in Pilbara and Kimberley.
4. Miscellaneous investigations as required by Government departments including quarry sites for Westrail.

SEDIMENTARY GEOLOGY

1. Maintain an active interest in the progress and assessment of exploration and potential for fossil fuels in Western Australia including the checking and assessing of all company reports on exploration.
2. Continuation of the surface mapping and sub-surface study of the Carnarvon Basin including the Kennedy Range and Wooramel 1:250 000 sheets.
3. Continuation of the compilation of a bulletin on stratigraphic studies of Devonian reef complexes in the Canning Basin.
4. Minor geological investigations as required.

REGIONAL GEOLOGY DIVISION

1. Continuation of mapping in the Great Southern portion of the South-West Division on Dumbleyung and Corrigin 1:250 000 sheets.
2. Mapping of portions of the Murchison and Yilgarn Goldfields on Sandstone, Youanmi, Barlee and Jackson 1:250 000 sheets.

3. Mapping the eastern wheatbelt Bencubbin and Kellerberrin 1:250 000 sheets.
4. Continuation and completion of the bulletin on the Nabberu Basin.

MINERAL RESOURCES DIVISION

1. Maintain records and assess mineral potential and resources in Western Australia.
2. Complete bulletin on the regional study of nickel resources in Western Australia.
3. Commence bulletin on the geology and bauxite occurrences in the Darling Range area.
4. Detailed mapping and study of the Warriedar fold belt.
5. Continue assessment of Ministerial Reserves for iron ore.
6. Examination and study of the talc occurrences near Three Springs.
7. Miscellaneous investigations as required.

COMMON SERVICES DIVISION

Petrology

1. Carry out petrological investigations as required by other Divisions.
2. The following topics to be investigated:
   (a) Petrology of the northern margin of the Yilgarn Block.
   (b) Petrological history and geochronology of the western margin of the Yilgarn Block.
   (c) Alkaline granitoids and possible extrusive equivalents, Eastern Goldfields.
   (d) Rb-Sr isotope distribution in the vicinity of the Black Range Dolerite.
   (e) A comparative study of the Archaean and Proterozoic geothermal gradients.
3. Miscellaneous minor petrological studies.

Palaeontology

1. Carry out palaeontological investigations as required by other Divisions.
2. Completion of a study of the Devonian stromatoporoids, Lennard Shelf, Canning Basin.
3. Continuing the palynological study of Early Cretaceous of Perth Basin.
4. Completion of study of Precambrian stromatolites and microfossils.
5. Miscellaneous minor palaeontological studies.

Geophysics

1. Well-logging on groundwater drilling projects as required.
2. Seismic surveys for
   (a) Dam sites in Pilbara and Darling Range as required.
   (b) Groundwater investigations at Manjimup, mouth of Robe and Fortescue Rivers and Horrocks Beach.
3. Miscellaneous geophysical investigations as required.

Geochemistry

1. Continuation of the study of the Corunna Downs and Mount Edgar batholiths to identify further potential tin/tantalum bearing rocks.
2. Completion of statistical studies on gossans/ ironstones with reference to the Yarri sheet.
3. Completion of the study of the geochemistry of the Mount McRae Shale.
4. Investigation of possible geochemical studies applicable to the Warriedar fold belt.

Environmental Geology

1. Completion of urban geology maps in the Roebourne and Port Hedland areas.
2. Field work and compilation for the urban geology of the Bunbury area.
3. Assessment of environmental reports and studies.
4. Miscellaneous environmental geological problems as required.

Regional Office

Kalgoorlie—it is hoped to establish this office about mid-year.

1. Re-mapping of the Widgiemooltha 1:250 000 sheet.
2. Detailed mapping and mineral investigation of an area near Kalgoorlie.
3. Study of the fossil drainages and Phanerozoic sediments in the Kalgoorlie area.

PUBLICATIONS

Issued during 1978

Annual Report, 1977.

Bulletin 124: The geology of the Perth Basin.

Bulletin 125: Quaternary molluscs of the western part of the Eucla Basin.

Report 4: A comparative study of the geochemistry of Archaean bedrock in part of the northeast Yilgarn Block.

Report 5: Devonian atrypid brachiopods from the reef complexes of the Canning Basin.

Report 7: Palynological zonation of the Late Jurassic and Early Cretaceous sediments of the Yarragadee Formation, central Perth Basin, Western Australia.

Geological map of Cornish 1:250 000 sheet (SF/52-1 International Grid) with explanatory notes (second edition).

Geological map of Crossland 1:250 000 (SE/51-16 International Grid) with explanatory notes.

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23rd January, 1979.

J. H. LORD,
Director.

SALINIZATION AND THE APPROXIMATE SALT BALANCE OF LAKE POORRARECUP

by T. T. Bestow

ABSTRACT

Lake Poorrarecup is a high-level lake sustained by rainfall and groundwater inflow. Clearing of native vegetation for farming since 1958 has resulted in the release of salt stored in the soil profile, with consequent increases in groundwater salinity. This has produced the steep rise in lake salinity of some 230 mg/L per year which has been experienced since about 1964.

The suggestion is made that the salinity of the lake may be stabilized by artificially discharging about 86 000 m^3 of lake water into one of the surrounding drainages each year.

LOCATION AND TOPOGRAPHY

Lake Poorrarecup is situated 33 km west-southwest of Cranbrook and is the largest of nearly one hundred lakes and swamps in an area of about 270 km^2. This area is on the watershed between the Kent and Frankland River catchments and the Gordon River, which is a tributary of the Frankland River (Fig. 3). The lake area is generally flat or gently undulating and contains relatively few well-defined drainage courses. In contrast to this the surrounding catchments, although exhibiting quite mature landforms, display a degree of dissection with moderately well-defined drainages. The lake area occupies a similar position in the landscape to a comparable, but smaller, lake area west of Lake Matilda, and a very much larger area centred on Lake Balicup, respectively south and east of Cranbrook. They appear to lie on a relatively high-level erosion surface at much the same topographic elevation.

Lake Poorrarecup has an average surface area of about 1.94 km^2. This varies somewhat in response to seasonal changes in rainfall. The shore is mainly sandy and appears to shelve quite gently (from minimum seasonal levels) towards the lake centre. At higher (flood) levels the lake shore steepens. However, no bathymetric or hydrographic details are available, except that a Department of Agriculture file report indicates that lake levels were exhibiting a rising trend in 1973 which prompted an investigation into the possible effects of overflow.

The lake provides the habitat for a variety of bird life and is a popular venue for recreation in the Cranbrook district.

GEOLOGY

The Lake Poorrarecup area is underlain by sediments of Tertiary or Quaternary age, which rest on Precambrian granites and migmatites which are not known to crop out. The form of the bedrock surface is not known but it is probable that erosion has produced a floor of variable relief. Without data from bores or deep sections it is not possible to estimate how thick such sediments might be. The low hills or rises in the landscape are generally capped with pisolitic laterite, but sandy ridges having the form of lunettes frequently occur parallel to lake margins, for example at Lake Poorrarecup itself. These appear to be ancient dunes.

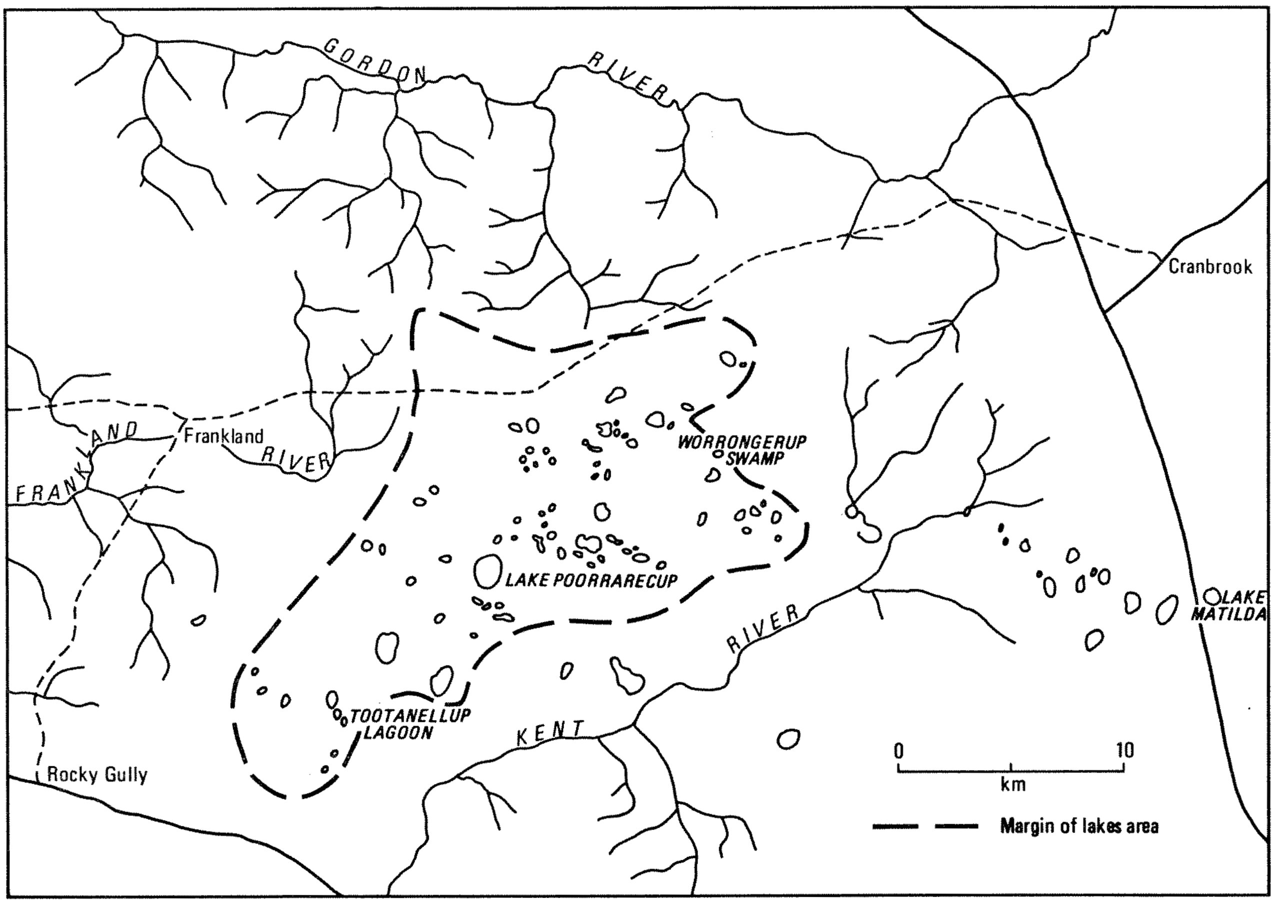
HYDROGEOLOGY

Lake Poorrarecup and other lakes and swamps within the study area exist because the hydrogeological conditions differ fundamentally from those in the surrounding catchments. The general lack of stream channels in the lake area is an obvious major difference and it points to a relatively high rate of infiltration by rainwater to replenish the groundwater system. This appears to be extensive, in that each lake or swamp is at least partially sustained by groundwater inflow as well as by direct rainfall and a limited amount of run-off. However, the pattern of groundwater movement and the extent to which each lake is connected with the groundwater cannot be defined without detailed and accurate groundwater levels. Similarly it is not possible to indicate whether the groundwater exists in an essentially closed system or whether it discharges into the surrounding catchments. As there are no obvious barriers to groundwater discharge it seems probable that the system as a whole is an open one. However, the possibility of parts of the system being closed due to the presence of hydraulic boundaries created by recharge mounds should not be excluded.

HYDROLOGY

RAINFALL

Long-term rainfall records are available for three stations in the vicinity of Lake Poorrarecup: Cranbrook, Rocky Gully and Mount Barker. Monthly averages for these stations are listed in Table 1.



GSWA 17703

Figure 3 Lake Poorrarecup and associated lakes.

TABLE 1. MONTHLY RAINFALL, EVAPORATION, AND RAINFALL EXCESS (mm)

Month	Rainfall				Evaporation		Rainfall excess or deficiency
	Observed			Estimated			
	Mount Barker	Rocky Gully	Cranbrook	*Lake Poorrarecup	Open pan	Estimated lake surface (0·8 x O.P.)	
Jan.	22	15	14	14·5	175	140	—125·5
Feb.	24	20	17	18·5	155	124	—105·5
Mar.	37	29	25	27	119·5	95·5	—68·5
Apr.	57	53	36	44·5	66	53	—8·5
May	86	89	61	75	61	49	+26·0
June	100	111	75	93	35·5	28·5	+64·0
July	108	123	78	100·5	33	26·5	+74·5
Aug.	94	87	65	76	35·5	28·5	+47·5
Sept.	82	72	53	62·5	61	49	+13·5
Oct.	74	65	45	55	89	71	—16·0
Nov.	42	38	25	31·5	117	93·5	—62·0
Dec.	30	21	17	19	165	132	—113·0
Total	756	723	510	617	1 112·5	890·5	—273·5

* The averages of the Cranbrook and Rocky Gully monthly means have been taken to approximate the rainfalls at Lake Poorrarecup, which is nearly midway between the two. The monthly figures indicate that about two-thirds of the rainfall occurs in the five months May to September which is also the period of rainfall excess over evaporation. The mean annual rainfall at the lake is estimated to be about 617 mm.

WATER AND SALT BALANCE

If lake levels are to remain within a reasonably narrow range over a period of years then the input of water from all sources must equal the losses. In the absence of overland flow and in the presence of groundwater inflow and outflow, the water-balance equation for a defined period is:

$$P + G_{in} + V_1 = E + G_{out} = V_2 \qquad (1)$$

where

P is the direct rainfall on the lake (m^3)
G_{in} is groundwater inflow (m^3)
G_{out} is groundwater outflow (m^3)
E is the open-water surface evaporation (m^3)
V_1 is the initial volume of the lake (m^3)
V_2 is the final volume of the lake (m^3).

In an average year there is an excess of evaporation over rainfall of about 273.5 mm (Table 1) which must be made up by the difference between groundwater inflow and outflow for the lake volume to remain fairly constant.

The salinity balance of the flow system associated with Lake Poorrarecup for a defined period may be determined from the equation:

$$P\,C_p + G_{in}\,C_{g1} + V_1 C_{L1} = G_{out}\,C_{g2} + V_2 C_{L2} \qquad (2)$$

where

C_p is the concentration of salt (NaCl) in rainfall
C_{g1} is the concentration of salt in groundwater input
C_{g2} is the concentration of salt in groundwater output
C_{L1} is the initial concentration of salt in the lake
C_{L2} is the final concentration of salt in the lake
All are expressed as mg/L = g/m^3.

A lake will normally exhibit a seasonal fluctuation in its salinity depending very largely on the amount of the level fluctuation and hence the lake volume. Thus a shallow lake showing a seasonal fluctuation equivalent to half its maximum depth might double its salinity in the course of a summer but would later return to its initial salinity when the lake level rose during the following winter.

Obviously during years of below-average rainfall, salinities will tend to be higher than the average and vice versa.

In an open groundwater system which resulted in the quantity of salt being discharged from the lake equating with the combined input of salt from rainfall and groundwater, the long-term average lake salinity would remain constant. This situation almost certainly existed prior to the commencement of farming in the district.

In the event of Lake Poorrarecup lying in a closed groundwater system the annual accession of salt with rainfall could be expected to result in a progressively increased salinity. An additional contribution of salt could result from the release of salt stored in the soil profile above the water table in the area surrounding the lake. This is known to have occurred in other areas where clearing of native forest has resulted in a reduced transpirative loss and an increased infiltration of rainfall to groundwater (Peck and Hurle, 1973). As the salt content of rainfall in that area is about 13 mg/L (Hingston and Gailitis, 1977) the mean annual input to the lake from this source is about:

$1.94 \times 10^6 \times 0.617 \times 13$ g or 15.5 t
where $1.94 \times 10^6 m^2$ is the area of the lake, and
0.617 is the annual precipitation.

It has already been noted that to sustain lake levels a mean net groundwater input of 273.5 mm is required additional to the mean annual rainfall. In the absence of salinity data from suitably sited boreholes less direct information may be used to estimate the salt concentration of this groundwater inflow. Thus it is reasonable to expect it to approximate to the salinities of springs which flow into swamps in the lakes area. A water sample collected from Worrongerup Swamp in December 1976 had a salinity (TDS) of 390 mg/L and another swamp 2 km east of Tootanellup Lagoon contained water having a TDS of 1 700 mg/L. Both of these samples came from areas in which clearing commenced in 1922. The average of the two values is 1 045 mg/L (TDS) or very approximately 785 mg/L NaCl (derived by applying a NaCl/TDS ratio of 0.7513) (Table 2).

The contribution of salt from groundwater inflow at this salinity would therefore be of the order of $1.94 \times 10^6 \times 0.2735 \times 785$ g. This amounts to 416.5 t, making a total annual input of 432 t.

If the lake is assumed to have a mean depth of 1.0 m then the annual salinity increase which would result from a lack of salt discharge becomes—

$$\frac{432 \times 10^6}{194 \times 10^4 \times 1.0} = 223 \text{ mg/L}$$

This may be compared with the approximate quantity of salt stored in the lake waters at the salinity (NaCl) measured in November 1978 of 3 381 mg/L (Table 2). If the lake is one metre deep then this is $1.94 \times 10^6 \times 1.0 \times 3381$ g or 6 559 t. This is equivalent to only 15 times the estimated annual input, which implies that much of the salt has accumulated in the lake over a relatively short period.

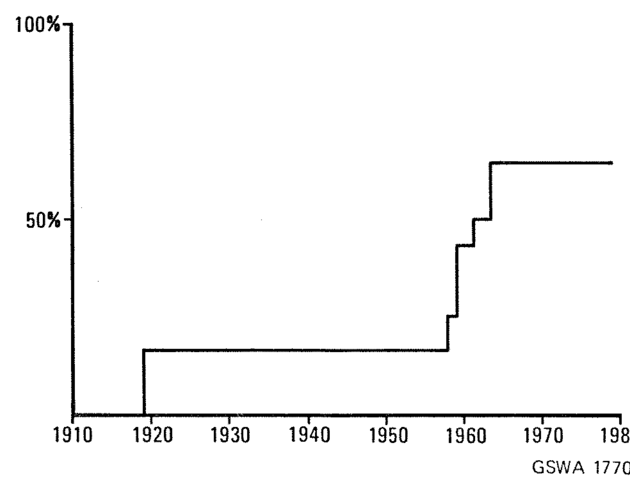


Figure 4 Percentage of land released for farming within 2 km of Lake Poorrarecup.

Clearing of native vegetation for farming is known to have started in the Lake Poorrarecup area in 1919 but it was not until 1958 that large-scale clearing occurred. The pattern of land release for farming within 2 km of

TABLE 2. LAKE POORRARECUP SALINITY

Sample No.	Date	pH	TDS	NaCl	Ratio NaCl TDS
1636	3/4/67	7·8	1 970	1 390	·7056
	28/4/69		1 659	1 246*	·7513
	29/12/72		2 715	2 040*	·7513
	31/1/75		3 174	2 385*	·7513
	2/4/75		3 890	2 923*	·7513
	7/5/75		4 290	3 223*	·7513
	13/6/75		3 805	2 859*	·7513
	9/7/75		3 737	2 808*	·7513
	11/8/75		3 098	2 328*	·7513
	8/9/75		2 764	2 077*	·7513
	12/10/75		3 045	2 288*	·7513
	17/11/75		3 251	2 442*	·7513
	5/1/76		3 184	2 392*	·7513
	29/2/76		4 075	3 062*	·7513
	18/3/76		3 892	2 924*	·7513
	19/5/76		4 097	3 078*	·7513
	27/7/76		4 290	3 223*	·7513
	3/9/76		4 001	3 006*	·7513
	1/11/76		4 000	3 005*	·7513
18765	14/12/76	8·5	4 300	3 427	·7970
	24/1/77		5 170	3 884*	·7513
	15/4/77		5 459	4 101*	·7513
	10/7/77		5 250	3 944*	·7513
	31/8/77		4 729	3 553*	·7513
	14/11/77		4 515	3 392*	·7513
	11/1/78		6 020	4 523*	·7513
	3/2/78		5 720	4 297*	·7513
	3/3/78		6 101	4 564*	·7513
	5/4/78		5 370	4 034*	·7513
	5/5/78		5 870	4 410*	·7513
	27/6/78		6 522	4 900*	·7513
	4/8/78		5 123	3 849*	·7513
	11/9/78		4 642	3 488*	·7513
	13/11/78		4 500	3 381*	·7513

* Calculated from given NaCl/TDS ratio derived by averaging the analyses of sample numbers 1636 and 18765.

the lake shore is indicated in Figure 4. The maximum occupancy of 64.7 per cent of the area was reached in 1963 but not all of this would have been fully cleared until later. A Department of Agriculture study in 1973 records that 63 per cent of a 3 950 ha area adjoining the northern side of the lake had been cleared at that time.

There is no precise historical information available regarding the level of Lake Poorrarecup, although a Department of Agriculture report indicates that the lake level has tended to rise in recent years. However, some salinity data have been obtained (Table 2, Figure 5). It is clear from these data that the lake is increasing in salinity at a rate of 231 mg/L per year (NaCl), which is close to the figure calculated above on theoretical grounds.

When this trend is extrapolated back in time to 1965 it falls below the presently estimated mean groundwater salinity of 785 mg/L (NaCl) and it is probable that the salt storage of the lake would have been close to stability in 1964. It may therefore be inferred, by comparison with the clearing pattern broadly indicated by Figure 4, that less than 6 years elapsed between the clearing of vegetation and the resultant onset of salinity increases.

Clearing between 1919 and 1958 would appear either to have had negligible effect on the recent salinity record or that its influence was confined to the period before 1967 when salinity records began.

An approximation of the recharge area required to sustain the estimated average groundwater inflow to Lake Poorrarecup of 530 590 m^3 (273.5 mm over the lake area), may be calculated from the rainfall/groundwater salinity ratio. The salinity of the rainfall is 13 mg/L NaCl and the lower of the two observed groundwater salinities (390 mg/L TDS) may be assumed to represent the resultant salinity after infiltrating rainfall has been subjected solely to evapotranspirative losses, i.e. it is unaffected by any solution of stored salt in the soil. The proportion of the annual rainfall which reaches groundwater is then $\frac{13}{390 \times 0.7513}$ or 4.44 per cent. As the mean annual rainfall is 617 mm, the area required to provide the groundwater inflow into Lake Poorrarecup is 1 940 ha ($= \frac{530\,590}{0.617 \times 0.0444}$ ha) which is rather less than the area of about 2 300 ha encompassed by a 2 km radius from the lake shore. It therefore seems probable that unless the lake is receiving runoff from areas at greater distances, the bulk of the salt contributing to the salinity increase of the lake is coming from stored salt in soil in the immediate vicinity of the lake itself and may be directly attributed to clearing in the peripheral area.

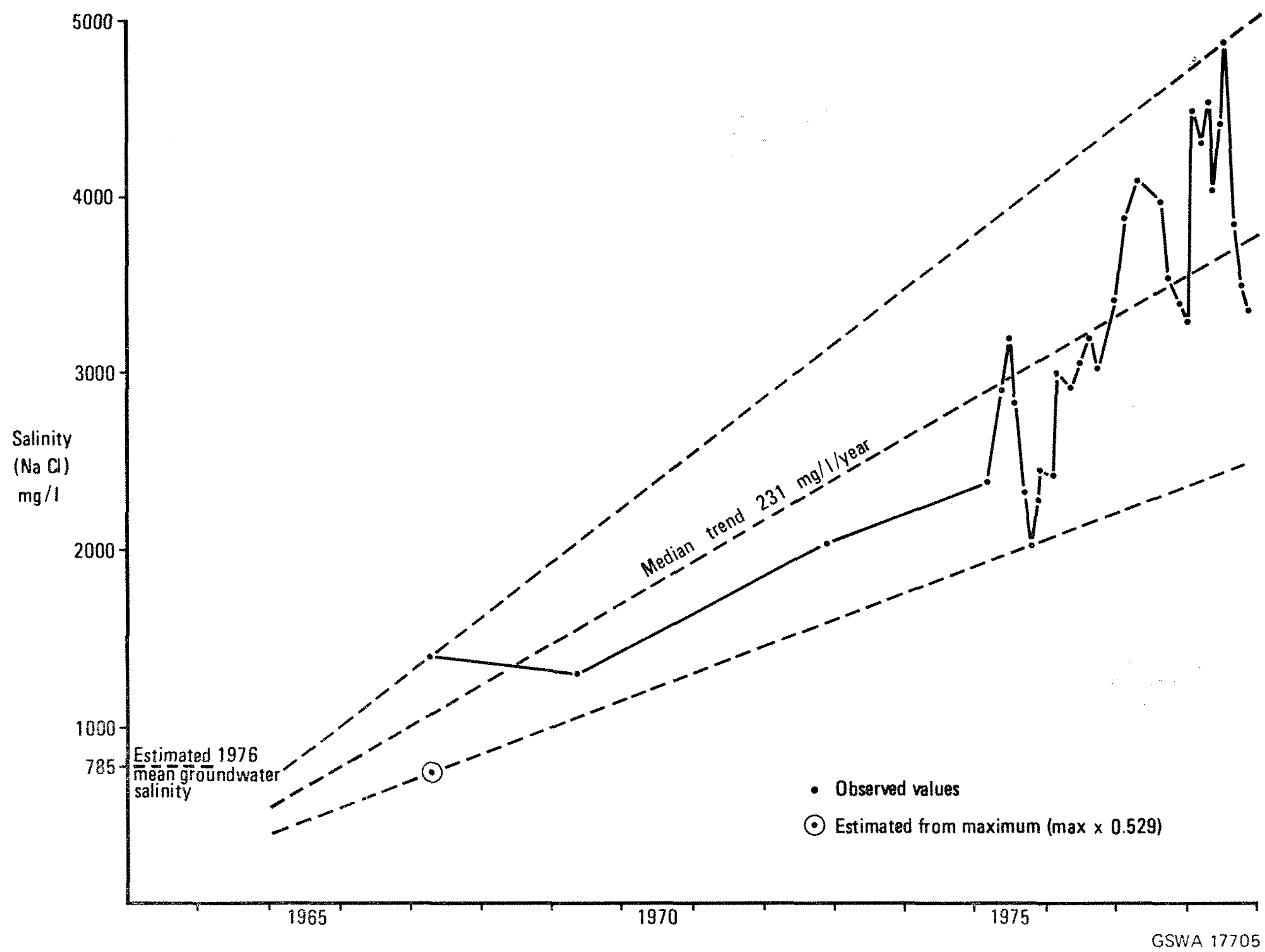


Figure 5 Variations in the NaCl salinity of Lake Poorrarecup.

CONCLUSION

It is most probable that the present salinity trend involving an annual average increase of 231 mg/L per year (NaCl) will continue until the surrounding catchment ceases to yield salt from the soil store. Unless remedial measures are taken, this increase in salinity will reduce the utility of the lake as a sanctuary for a wide range of wildlife and as a public amenity.

To stabilize the salinity at its present level, it would be necessary to effect the discharge of about 430 t of salt per annum from the lake into one of the surrounding drainages. This would best be achieved at minimum lake levels during the summer, when the salinity could now be expected to be at about 5 000 mg/L. At this concentration the volume of water required to be removed annually would be about 86 000 m³ ($= \frac{432 \times 10^6}{5000}$) which would represent only about 5 per cent of the mean annual inflow to the lake from all sources. The resultant reduction in level, of 40 to 60 mm, may be regarded as negligible, especially as the lake has shown a tendency to rise in level in recent years.

ACKNOWLEDGEMENTS

The writer is indebted to Mr A. L. Prout of the Department of Agriculture for most of the Lake Poorrarecup salinity record quoted in Table 2, and the Department of Lands for the data on which Figure 4 is based.

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THE GEOLOGY AND HYDROGEOLOGY OF THE MOORA BOREHOLE LINE

by E. H. Briese

ABSTRACT

The Moora Line consists of 19 bores located at 9 sites and ranging in depth from 25 m to 801 m. These have an aggregate depth of 8 767 m and were drilled to explore the geology and hydrogeology of an east-west section of the Perth Basin approximately 150 km north of Perth.

Drilling encountered continental and marine sediments of Late Triassic to Holocene age and confirmed that the structure consists of a deep basin (Dandaragan Trough) bounded to the east by the Darling Fault and to the west by the Beagle Ridge.

The Otorowiri Siltstone Member of the Yarragadee Formation was intersected in bores to the east of the Dandaragan Scarp. In this area it is a thick siltstone-claystone unit, and is unconformably overlain by the Leederville Formation.

Large groundwater resources occur in the Leederville Formation (444 m thick) and in the Yarragadee Formation. Groundwater of less than 1 000 mg/L T.D.S. was encountered almost throughout the Leederville Formation, and extends at least to the maximum depth of 800 m drilled in the Yarragadee Formation. The Otorowiri Siltstone Member acts as an aquiclude between the two aquifers and maintains a head difference of 70 m.

West of the Warradarge Fault, the Cockleshell Gully Formation and Lesueur Sandstone contain reserves of brackish water. The Tamala Limestone is an important source of potable groundwater along the coast.

Recharge to the aquifers is by infiltration of rainfall in their outcrop areas, and by leakage from overlying formations. The barrier boundaries of the Darling Fault in the east and impermeable Triassic sediments in the west constrain groundwater movement into a southward-flow direction.

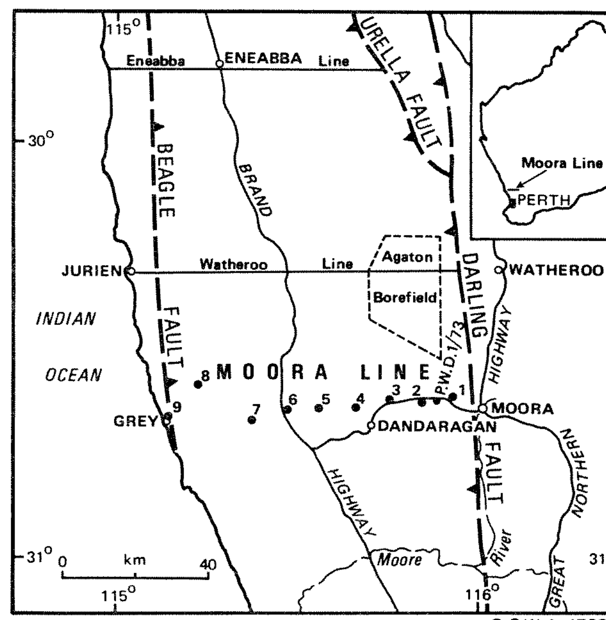

Figure 6 Location map, Moora Line.

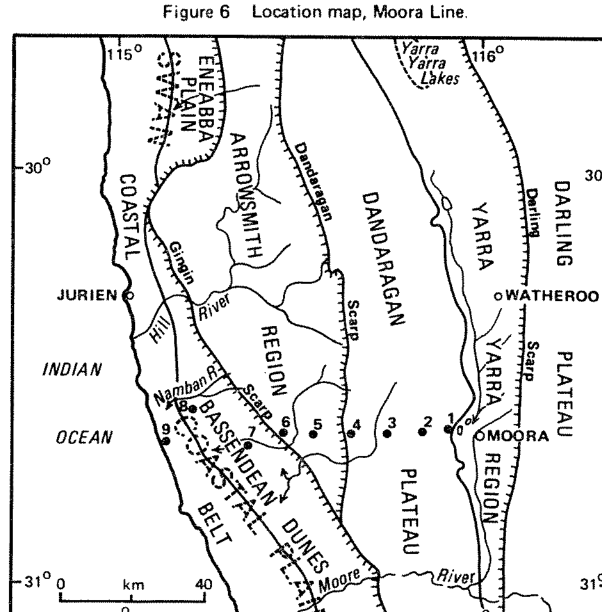

Figure 7 Physiographic regions.

INTRODUCTION

LOCATION AND TOPOGRAPHY

The Moora Line of bores is situated about 150 km north of Perth (Fig. 6). They are sited about 6 km apart across the width of the Perth Basin, from 8 km west of Moora to Grey townsite on the coast.

The area through which the line passes has been divided into four physiographic regions by Playford and others (1976) (Fig. 7). The Swan Coastal Plain extends from the coast to the Gingin Scarp and is a Cainozoic marine erosion and construction feature. It has been divided into the Coastal Belt consisting of calcarenite dunes and beach ridges, and the Bassendean Dunes, consisting of leached Pleistocene quartz sands. The Arrowsmith Region to the east of the Gingin Scarp is a dissected area with hills of Mesozoic strata commonly capped by laterite. East of the Arrowsmith Region, and separated from it by the topographic feature of the Dandaragan Scarp, is the Dandaragan Plateau, a sand- and laterite-covered plateau overlying Cretaceous sediments. The Yarra Yarra Region, between the Dandaragan and Darling Plateaus, is a flat low-lying region characterized by essentially internal drainage with intermittent streams feeding into numerous swamps and salt lakes.

PURPOSE AND SCOPE

The Moora Line of bores is part of a long-term programme, commenced by the Geological Survey in 1961, of drilling a series of east-west lines of bores across the Perth Basin to obtain information on its stratigraphy, structure and hydrogeology to a depth of about 800 m. The information obtained from the Moora Line has been correlated with that from other projects to derive a broader stratigraphic and structural picture than would otherwise be possible. All bores are completed for long-term monitoring of water levels and salinity changes.

Exploratory drilling in the northern Perth Basin has been carried out at Arrowsmith River (Barnett, 1969), Agaton Borefield (Balleau and Passmore, 1972), the Watheroo Line (Harley, 1975) and the Eneabba Line (Commander, 1978).

DRILLING AND TESTING

Drilling of the Moora Line commenced in December 1974 and was completed in December 1977 after several interruptions totalling 15 months during which time the drill rig was employed elsewhere. All bores were drilled by the mud-flush rotary technique. Sludge samples were taken every 3 m, and on reaching total depth, gamma-ray, long- and short-normal resistivity and caliper wire-line logs were run. These were used to select sidewall-coring targets for palynological samples, and aquifer intervals for sampling and observation.

Generally three aquifer intervals were sampled at each site. At sites 1-4 a separate bore was drilled for each interval, but on the remaining sites two intervals were tested in each deep bore. This was achieved by installing large-diameter (155 mm) casing to total depth and explosively perforating it at the deepest interval to be tested. The interval was then airlifted until the true static water level and a representative water sample had been obtained. A shallow interval was then explosively perforated and developed. It was then separated from the lower interval by inserting a string of 76 mm pipe and a compressible packer which was designed to seat between the two intervals. The shallow interval was then airlifted from the annulus of the pipe and casing. Slots in the 76 mm pipe below the compressible packer allow the water level of the deep interval to be monitored from inside the pipe. The water level of the shallow interval is monitored from the annulus.

A summary of the data from the exploratory bores is given in Table 3, together with information from the Moora town water supply bore 1/73 which was drilled between Moora Line sites 1 and 2. All potentiometric levels are related to Australian Height Datum (A.H.D.).

TABLE 3. SUMMARY OF MOORA LINE BORE DATA

Name	Latitude S	Longitude E	Drilling		Elevation (m) A.H.D.		Depth (m)	Completed depth (m)	Tested interval (m)	Head (m) A.H.D.1	Salinity T.D.S. by evap. (mg/L)	Status
			Commenced	Completed	Surface	Casing						
ML 1A	30°37′04″	115°55′21″	11/11/74	27/11/74	213·250	213·810	756	648	622–629 (P)	198·090	1 300	obs—Lower Leederville Fm
ML 1B	....	....	4/12/74	10/12/74	213·460	213·810	399	391	312–320 (P)	....	460	abd—blocked with sand
ML 1C	....	....	13/12/74	18/12/74	213·035	213·425	222	207	187–195 (P)	....	....	abd—blocked with sand
ML 1D	....	....	17/2/77	3/3/77	214·108	214·548	356	326	316–322 (S)	195·288	410	obs—Leederville Fm
ML 1E	....	....	16/3/77	21/3/77	213·881	214·181	205	201	189–195 (S)	194·031	6 800	obs—Leederville Fm
PWD 1/73	30°36′51″	115°52′28″	7/9/73	22/9/73	243·032	243·451	434	350	333–350 (S)	190·937	450	Moora town water —Leederville Fm
ML 2A	30°36′19″	115°49′22″	14/1/75	30/1/75	205·950	206·650	464	292	273–281 (P)	148·900	430	obs—Leederville Fm
ML 2B	....	....	30/1/75	24/2/75	205·950	206·490	762	733	713–721 (P)	124·110	3 650	obs—siltstone, mudstone unit
ML 2C	....	....	26/2/75	27/2/75	205·855	206·395	100	95	66–72 (P)	146·785	....	obs—Leederville Fm
ML 3A	30°37′22″	115°44′15″	7/3/75	26/3/76	192·948	193·383	762	750	730–740 (P)	122·773	2 340	obs—siltstone, mudstone unit
ML 3B	....	....	14/4/75	23/4/75	192·820	193·405[2]	280	252	228–235 (P)	198·025[3]	820	obs—Lower Leederville Fm
ML 3C	....	....	24/4/75	28/4/75	193·190	193·550	117	112	88–95 (P)	149·590	490	obs—Leederville Fm
ML 4A	30°37′55″	115°38′18″	1/4/76	21/5/76	284·628	285·153	731	664	644–652 (P)	80·228	820	obs—Yarragadee Fm
ML 5A	30°37′55″	115°32′22″	15/6/77	5/7/77	204·261	204·801	772	760	741–749 (P)	88·941	390	obs—Yarragadee Fm
ML 5A (annulus)	....	....	15/6/77	5/7/77	204·261	204·761	772	760	458–466 (P)	....	450	obs—Yarragadee Fm
ML 5B	....	....	26/7/77	27/7/77	204·216	204·766	146	146	134·146 (S)	89·806	770	obs—Yarragadee Fm
ML 6A	30°38′48″	115°27′43″	28/5/76	16/8/76	114·759	116·004[2]	772	761	723–733 (P)	117·214[3]	350	obs—Yarragadee Fm
ML 6A (annulus)	....	....	28/5/76	16/8/76	114·759	115·349[2]	772	761	493–503 (P)	117·359[3]	330	obs—Yarragadee Fm
ML 6B	....	....	18/8/76	27/8/76	114·164	114·699	170	168	147–157 (P)	111·699	450	obs—Yarragadee Fm
ML 7A	30°39′36″	115°22′24″	30/3/77	13/5/77	69·479	70·059	801	759	695–703 (P)	55·199	610	obs—Yarragadee Fm
ML 7A (annulus)	....	....	30/3/77	13/5/77	69·479	69·929	801	759	318–326 (P)	55·189	630	obs—Yarragadee Fm
ML 7B	....	....	2/6/77	3/6/77	69·429	69·929	86	81	75–81 (S)	68·321	480	obs—Yarragadee Fm
ML 8A	30°45′05″	115°13′25″	3/10/77	10/11/77	38·546	39·186	770	674	642–651 (P)	34·626	5 770	obs—Lesueur Sandstone
ML 8A (annulus)	....	....	3/10/77	10/11/77	38·546	39·096	770	674	446–456 (P)	35·306	4 790	obs—Lesueur Sandstone
ML 8B	....	....	8/12/77	12/12/77	38·446	38·746	103	103	91–103 (S)	35·926	4 570	obs—Cockleshell Gully Fm
ML 9A	30°39′28″	115°08′08″	2/8/77	31/9/77	8·702	8·702	25	22	open hole	0·530	930	abd—Tamala Limestone

[1] Readings in April 1978
[2] Elevation to top of valve
[3] Artesian flow

A.H.D.—Aust. Height Datum
P—Perforated
S—Screened

obs—observation bore
abd—abandoned bore

GEOLOGY

STRATIGRAPHY

The area lies within the Perth Basin, a sedimentary trough over 950 km long, on the western side of the Precambrian Yilgarn Block. In this area the basin has been divided into two structural subdivisions: the Dandaragan Trough and the Beagle Ridge.

The Dandaragan Trough is bounded in the east by the Darling Fault and in the west by the Beagle Fault. The deepest part of the trough is west of Moora where it contains about 15 000 m of Phanerozoic (predominantly Mesozoic) sediments resting on Precambrian basement.

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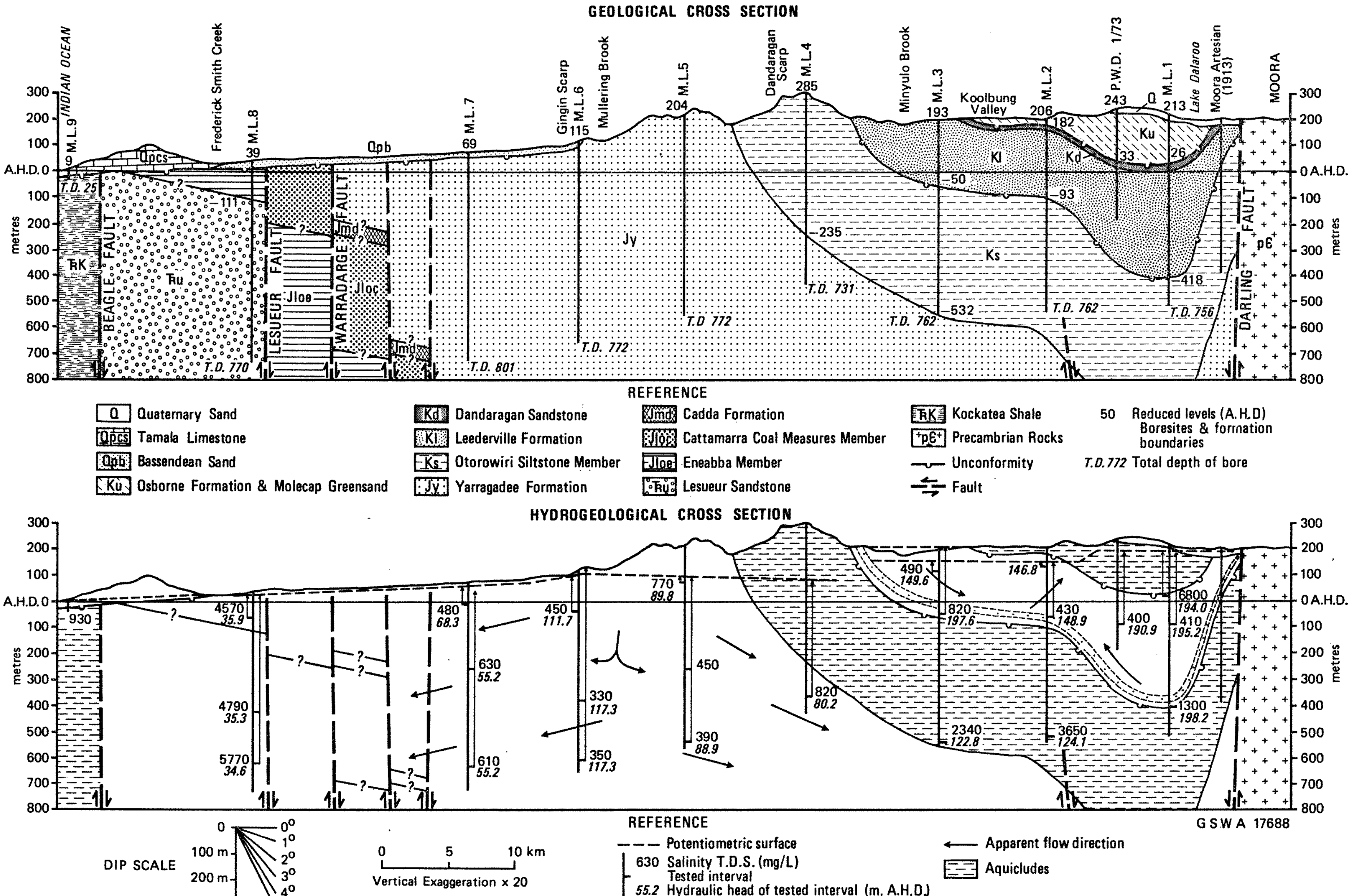

Figure 8 Geological and hydrogeological cross sections of the Moora Line.

The Beagle Ridge is a mid-basin ridge of relatively shallow basement covered by Permian and Triassic sediments and separated from the Dandaragan Trough by the Beagle Fault.

Cainozoic sediments mantle much of the surface in the area, obscuring the underlying geology. Table 4 summarizes the Mesozoic and Cainozoic stratigraphy intersected by drilling, and a cross-section of the borehole line is shown in Figure 8.

Palynology indicates that the section intersected at site 8 is of Late Triassic or Early Jurassic age, which is consistent with the basal section of the formation. It was deposited under non-marine conditions.

Yarragadee Formation: An aggregate thickness of 2 524 m of Yarragadee Formation was intersected at sites 4, 5, 6 and 7.

TABLE 4. STRATIGRAPHIC SEQUENCE—MOORA LINE

Formal age	Group	Formation	Maximum thickness (m)	Summary lithology	Remarks
CAINOZOIC Quaternary		"Superficial formations"*	36	Sand, limestone, silt, clay	Major and minor aquifers
		UNCONFORMITY			
MESOZOIC Early Cretaceous	Coolyena Group	Poison Hill Greensand .... Gingin Chalk .... Molecap Greensand .... Osborne Formation	34 } 168	Sand, clay .... Chalk .... Siltstone, minor sand	Not definitely intersected Not intersected Aquiclude
		UNCONFORMITY			
Middle to Early Cretaceous	Warnbro Group	Dandaragan Sandstone .... Leederville Formation	33 411	Sandstone, siltstone .... Sandstone, siltstone	Major aquifer Major aquifer
		UNCONFORMITY			
		Otorowiri Siltstone Member	507+	Siltstone, claystone	Aquiclude
Late Jurassic		Yarragadee Formation....	2 524+	Sandstone, minor siltstone	Major aquifer
Middle Jurassic		Cadda Formation		Sandstone, siltstone	Not intersected
Early Jurassic		Cockleshell Gully Formation .... Cattamarra Coal Measures Member Eneabba Member	 134+	Siltstone, sandstone, shale Coal measures	 Not intersected Aquifer
Late Triassic		Lesueur Sandstone	620+	Sandstone, minor siltstone	Major aquifer
Middle Triassic		Woodada Formation		Sandstone, siltstone	Not intersected
Early Triassic		Kockatea Shale	5+	Shale, siltstone	Aquiclude

* Informal name for various recognized Quaternary formations.

Triassic

Kockatea Shale: Five metres of Kockatea Shale was intersected below the Tamala Limestone at site 9 on the Beagle Ridge. It consists of finely laminated siltstone and very fine-grained sandstone.

The formation occurs in fault blocks in juxtaposition with the Lesueur Sandstone to the east. Palynological examination of the bottom hole core from site 9 indicated an Early Triassic age and a marine depositional environment. The fossel assemblage suggest a correlation with the upper part of the formation.

Lesueur Sandstone: The uppermost 620 m of the Lesueur Sandstone was intersected at site 8. It consists of thick beds of sandstone composed of fine- to very coarse-grained angular and sub-rounded quartz sand. It includes some feldspar and intergranular clay (which appears to be kaolinized feldspar), and accessory heavy minerals and pyrite. Interbeds of grey, micaceous, laminated claystone up to 6 m thick, occur infrequently.

The Lesueur Sandstone occurs in fault blocks which bring it into juxtaposition with the Cockleshell Gully Formation to the east. This sandstone disconformably overlies the Woodada Formation which was not intersected in the Moora Line bores, and is conformably overlain by the Cockleshell Gully Formation.

Palynology indicates the Lesueur Sandstone to be of non-marine origin and Late Triassic age.

Jurassic

Cockleshell Gully Formation: The bottom 134 m of the Eneabba Member of the Cockleshell Gully Formation was intersected below the Bassendean Sand at site 8. This formation is an interbedded siltstone-sandstone sequence. The siltstones are multicoloured, laminated and moderately lithified. The sandstones are composed of fine to very coarse angular to sub-rounded quartz with rare feldspar, accessory pyrite, heavy minerals and mica.

The formation occurs in fault blocks faulted against the Yarragadee Formation to the east. A complete section of the formation is believed to occur in a fault block to the east of site 8. The Cockleshell Gully Formation is conformably overlain by the Cadda Formation, which was not encountered in the Moora Line bores.

It is composed predominantly of thick-bedded sandstone with subordinate conglomerate and siltstone interbeds. The sandstones vary from pink (in weathered sections) to grey; they are generally poorly sorted and consist of fine to very coarse, sub-angular to sub-rounded quartz. Varying proportions of intergranular clay and feldspar are present, together with accessory heavy minerals, garnet and pyrite. Sandy conglomerates intersected in the upper part of the formation at site 5 consist of quartz and grey to pink feldspar ranging in size from fine sand to pebbles up to 10 mm in diameter. The siltstone interbeds which constitute about 25 per cent of the formation are light to dark grey, micaceous, and vary from laminated to fissile. The formation is argillaceous in its upper section which subcrops between site 5 and the Dandaragan Scarp. It also becomes argillaceous and contains minor lenses of coal at site 7, where the bore probably penetrated almost to the base of the formation.

The Yarragadee Formation outcrops or subcrops between the Warradarge Fault and Dandaragan Scarp and conformably overlies the Cadda Formation. In Wapet's Walyering No. 1 well 9 km south of site 6, the Yarragadee Formation is 2 686 m thick (Bird and Moyes, 1971).

The sediments are fluviatile deposits of Late Jurassic age ranging from Tithonian at site 5 to Callovian at site 7.

Cretaceous

Otorowiri Siltstone Member: A siltstone-claystone unit which outcrops in the Dandaragan Scarp was intersected in all bores to the east of the scarp. The unit has a maximum thickness of 507 m and can be correlated on palynological evidence with the Otorowiri Siltstone Member of the Yarragadee Formation of the northern Perth basin. The unit can also be traced in outcrop south to the Moore River and then in the subsurface in deep bores, to the Gingin Brook Line, where it is possibly represented in Gingin Brook bores 1 and 5 (J. Backhouse, pers. comm., 1978).

In the Moora Line bores the unit is a thick interbedded siltstone and claystone with minor thin clayey sandstone interbeds. The siltstone is olive brown, fissile, moderately lithified and micaceous; it also contains rare lignite and pyrite. The claystones are more massive; they are grey and contain rare lignite and mica. The rare clayey sandstone interbeds are light grey and consist of fine- to medium-grained quartz with accessory heavy minerals, garnet, mica and lignite.

The unit is the top member of the Yarragadee Formation. It is unconformably overlain by the Leederville Formation.

Palynological examination of side-wall cores indicate the unit is of Early Neocomian age and was deposited under non-marine (lagoonal) conditions.

Leederville Formation and Dandaragan Sandstone: The Dandaragan Sandstone has been grouped with the Leederville Formation for the purpose of this paper as they have similar lithologies, are conformable, and the Dandaragan Sandstone has a maximum thickness of only 33 m.

The formations were intersected at sites 1, 2 and 3. The Leederville Formation consists of an interbedded sandstone-siltstone sequence.

The sandstones are grey, and consist of fine to very coarse angular to sub-rounded quartz and rare feldspar, commonly in a clayey matrix. The siltstones are grey, micaceous, and moderately lithified. Individual beds of both the argillaceous sediments and sandstones are up to 20 m thick; however, they are lenticular and correlation of these beds between distant bores is not possible. Correlation is therefore based on broad gamma-ray log characteristics and stratigraphic relationships with adjoining formations.

A maximum thickness of 444 m was intersected at site 1, the centre of the Dandaragan Trough at the time of deposition. The formations thin to the west and have a combined thickness of 237 m at site 3, but part of the Dandaragan Sandstone has been eroded away.

Palynology indicates that the Leederville Formation is of Early Cretaceous (Neocomian to Aptian) age and was deposited in a non-marine environment.

Osborne Formation and Molecap Greensand: The Molecap Greensand has been grouped with the Osborne Formation for the purposes of this paper, as they are neither lithologically nor geophysically distinguishable in the Moora Line bores. The Osborne Formation was intersected at site 1, PWD 1/73 and possibly site 2. It consists of black to grey-green glauconitic shales and siltstones with thin sandier interbeds, and contains rare pyrite and phosphate, the latter occurring as a coating on the glauconite grains.

The Osborne Formation disconformably overlies the Dandaragan Sandstone and is conformably overlain by the Molecap Greensand. A maximum thickness of 168 m was intersected at site 1. Marked thinning occurs towards the margin of the trough so that near Dandaragan townsite, the formation is only 6 m thick (Low, 1965).

The glauconitic sequence was deposited in a marine environment and as palynological determinatons also indicate a Middle Cretaceous (Albian-Cenomanian) age, most of the section intersected by drilling is apparently Osborne Formation rather than Molecap Greensand, which is considered to be Coniacian to possibly Late Cenomanian in age (Playford and others, 1976).

Gingin Chalk and Poison Hill Greensand: The Gingin Chalk crops out along the sides of Koolbung Valley, but was not intersected in the Moora Line bores as sites 2 and 3 are at a lower elevation than the formation. As the formation lenses out east of site 2 it was not intersected in the more easterly bores. The Gingin Chalk conformably overlies the Molecap Greensand and is itself conformably overlain by the Poison Hill Greensand, which was only tentatively recognised from gamma-ray logs as occurring in PWD 1/73. These three formations are marine deposits of Late Cretaceous age.

Quaternary

'Superficial formations': The 'superficial formations' comprise the following: laterite and associated sand, which are widely developed over the Mesozoic sediments east of the Gingin Scarp; Bassendean Sand, consisting of low irregular quartz sand dunes; Tamala Limestone, which is a lithified dune system parallel to the coast, and consisting of calcarenite and quartz sand; and Safety Bay Sand, consisting of coastal dune and shallow-marine to littoral sand overlying the Tamala Limestone.

STRUCTURE

Faulting and Folding

The geological section illustrated in Figure 8 suggests that the Mesozoic structure is characterised by faulting rather than folding. The Darling Fault forming the eastern boundary has a displacement of up to 15 000 m west of Moora. This has imposed a predominantly easterly dip on the sediments.

An asymetric syncline has developed near the axis of the Dandaragan Trough and there is marked thinning of the Warnbro Group and Osborne Formation from east to west (Fig. 8). This may be interpreted as being caused by differential compaction across, and in association with, growth faults (Cope, 1972), and suggests that movement on the underlying faults continued to Late Cretaceous times.

On the western side of the Dandaragan Trough there are a series of faults, the most important being the Beagle Fault which has a throw of about 2 000 m.

HYDROGEOLOGY

INTER-RELATIONSHIP OF AQUIFERS

Perched aquifers and unconfined aquifers in weathered sediments and Quaternary sand occur on the Dandaragan Plateau. They are separated over most of the area from the underlying Dandaragan Sandstone and Leederville Formation aquifers by the impermeable Osborne Formation, but are in direct contact where the Osborne Formation has been eroded away and where the Dandaragan Sandstone and Leederville Formation subcrop at the margins of the basin.

The main groundwater flow system is divided into two parts by the thick Otorowiri Siltstone Member which maintains a head difference of up to 70 m between the systems. The upper part comprises the Leederville Formation and Dandaragan Sandstone, together with Quaternary sand where it is in hydraulic connection with these formations. The lower part comprises the superficial formations of the Bassendean Sand and Tamala Limestone and the Mesozoic aquifers of the Yarragadee Formation, Cockleshell Gully Formation, and Lesueur Sandstone. These Mesozoic aquifers are considered to be in hydraulic continuity both vertically and across fault planes.

The barrier boundaries of the Darling Fault in the east and impermeable Triassic sediments of the Beagle Ridge in the west impart an overall southward flow in the aquifers.

AQUIFERS

'Superficial formations'

Small supplies of groundwater occur in perched and unconfined aquifers in the Quaternary sand and associated weathered sediments of the Dandaragan Plateau. Recharge is by infiltration of rainfall and movement is downward and laterally to discharge via springs along the sides of the valleys or in topographic depressions. However, where the impermeable Osborne Formation is absent the perched aquifers may discharge by downward infiltration into the underlying Mesozoic aquifers.

The groundwater salinity is generally less than 1 000 mg/L T.D.S., but where springs have given rise to large areas of swampy ground, concentration by evapotranspiration has increased salinities up to 7 000 mg/L T.D.S.

On the Swan Coastal Plain, the Bassendean Sand and Tamala Limestone constitute unconfined aquifers. The former is up to 21 m thick and is recharged by direct infiltration of rainfall and streamflow. A number of westward-flowing water courses dissipate into the Bassendean Sand. Groundwater movement is to the west, under the influence of a gentle hydraulic gradient between the Gingin Scarp and the Coastal Belt. Discharge is by evapotranspiration from numerous interdunal swamps, by flow into the Tamala Limestone, and by leakage into the underlying Mesozoic aquifers. Groundwater salinity is generally less than 1 000 mg/L T.D.S.

The Tamala Limestone covers an elongate area along the coastline and extends as far as 10 km inland. It is up to 36 m thick in the vicinity of the Moora Line. Recharge is directly from rainfall through solution tubes, cavities, and intergranular porosity within the linestone; outflow from the Bassendean Sand; and the infiltration of stream flow from the east. The Namban River discharges into a cave system within the limestone. Groundwater movement is predominantly westwards with discharge into the ocean and lakes. There is also potential for vertical leakage into the underlying Mesozoic aquifers.

Groundwater with a salinity of less than 1 000 mg/L T.D.S. can generally be obtained at distances greater than 1 km from the coast. Closer to the sea the near-surface water is potable, but the salinity increases rapidly with depth as the zone of mixing of fresh and salt water is penetrated.

The Tamala Limestone is generally a high-yielding aquifer and has considerable importance as a source of freshwater to the fishing communities along the coast.

Leederville Formation

The Dandaragan Sandstone is in hydraulic connection with the Leederville Formation and the two units are lithologically similar. It also has a common area of recharge and extends over essentially the same area. They are therefore regarded as being a single multi-layered aquifer system consisting of about equal proportions of sandstone and siltstone.

This aquifer underlies an area from the Dandaragan Scarp to the Darling Fault (Fig. 8). Recharge is by infiltration of rainfall via the overlying 'superficial formations' where the Osborne Formation is absent. The Leederville Formation ranges from about 200 m to 444 m thick and contains a large volume of water in storage.

Isopotential contours drawn from water levels measured on the Agaton Borefield (Balleau and Passmore, 1972) and the Moora Line indicate the regional flow to be towards the south or southwest. However, the elevation of the potentiometric surface declines from east to west along the Moora Line, from 190.9 m in PWD 1/73 to 147.9 m at site 2 (Fig. 8). This is possibly caused by the marked thinning of sediments from east to west resulting in changes in vertical hydraulic conductivity. Where the Osborne Formation is thickest it effectively confines the Leederville aquifer, but conditions become unconfined to the west where the Osborne Formation has a much thinner section (Fig. 8).

Most discharge presumably occurs south of Moore River in the low-lying areas west of the Gingin Scarp and offshore; however, there is minor evaporative discharge from permanent pools in the Moore River and possibly some contribution to river base-flow.

The salinity of groundwater from the Leederville Formation along the Moora Line is generally less than 1 000 mg/L T.D.S. A local area of 6 800 mg/L T.D.S. in the Dandaragan Sandstone at site 1 is probably due to local intake from the saline drainage of the Yarra Yarra Region.

The Leederville Formation contains major resources of low-salinity groundwater. Present development is very limited and there is scope for considerably increased production for town and agricultural water supplies.

A 30 m thick sandstone bed at the base of the Leederville Formation, confined by a siltstone of similar thickness, has a hydrostatic head of about 198 m, which is higher at site 3 than the hydrostatic heads in either the upper part of the Leederville Formation or in the Yarragadee Formation. This sandstone is considered to be of local significance only, but gives rise to small artesian flows in some areas. An increase in salinity from west to east suggests recharge is along the topographic high of the Dandaragan Scarp where it is thought this sandstone outcrops.

Yarragadee Formation

The Yarragadee Formation extends westwards to the Warradarge Fault, eastwards to the Yilgarn Block beneath the cover of younger sediments, and to the north and south throughout the Dandaragan Trough (Fig. 8). The formation consists predominantly of sandstone; the aquifer is unconfined west of the Dandaragan Scarp and is confined beneath the thick Otorowiri Siltstone Member at the top of the formation to the east.

Recharge to the formation is by infiltration of rainfall into the weathered sediments and by leakage from the overlying Bassendean Sand. A groundwater mound has developed beneath the Arrowsmith Region.

Although the Moora Line bores were drilled to a maximum depth of 800 m they did not intersect the base of the groundwater body having a salinity of less than 1 000 mg/L T.D.S. However, the Wapet well, Walyering No. 1, has shown that groundwater of less than 1 000 mg/L T.D.S. extends to a depth of 1 500 m (Nowak, 1978). An extremely large volume of low-salinity groundwater is therefore contained in storage.

Groundwater movement is radial from the apex of the mound. To the east it becomes confined beneath the Otorowiri Siltstone Member and to the west it discharges laterally across the Warradarge Fault into the Cockleshell Gully Formation. Data from surrounding bores indicate the regional flow direction to be to the south where offshore discharge may be expected.

The groundwater salinity from the intervals tested in the Moora Line bores ranged from 330 to 770 mg/L T.D.S. An unusual feature at sites 5 and 6 is that the water quality improves with depth. This may result from variation in hydraulic conductivity, or source and time of recharge.

The large volume of low-salinity groundwater, very thick sandstone beds and the large recharge area indicate that the Yarragadee Formation is a major potential source of groundwater. It exists within the central part of the coastal plain and extends well beyond the vicinity of the Moora Line. This source is virtually undeveloped.

Cockleshell Gully Formation

The base of the Eneabba Member, the lower member of the Cockleshell Gully Formation, was intersected at site 8. The formation consists of alternating sandstones and siltstones and occurs in a series of north-south fault blocks which have been faulted against the Yarragadee Formation.

Recharge is presumably by direct infiltration of rainfall where the sandier sections of the formation crop out, by leakage from the overlying Bassendean Sand and Tamala Limestone, and by westward outflow from the Yarragadee Formation. Flow is south to southwest following the same general direction as the Yarragadee Formation. Discharge presumably is by outflow across fault boundaries into the Lesueur Sandstone and offshore.

A salinity of 4 570 mg/L T.D.S. was recorded from 103 m at site 8, and high salinities were also recorded from the Watheroo Line (Harley, 1975).

Test results, geophysical logs and the generally silty nature of the formation, all indicate that the Cockleshell Gully Formation is unlikely to be a major source of low-salinity groundwater in this area; it is mainly prospective for stock water.

Lesueur Sandstone

The Lesueur Sandstone occurs in a fault block faulted against the Cockleshell Gully Formation. The aquifer is confined beneath the Eneabba Member of the Cockleshell Gully Formation at site 8, but is unconfined further north where it crops out in the Gairdner Range. At site 8 it is a thick coarse sandstone.

Recharge is by infiltration of rainfall where the formation outcrops, by underflow from the Cockleshell Gully Formation and by leakage from the overlying Eneabba Member. Groundwater flow probably does not occur into the impermeable Kockatea Shale on the west and is therefore most likely to be southwards, eventually discharging offshore as for the other Mesozoic aquifers.

Groundwater salinity at site 8 is over 4 500 mg/L T.D.S. throughout the thickness penetrated and is probably due to lack of surface recharge close to the site sampled. However, in the outcrop area to the north the salinity is generally less than 500 mg/L T.D.S. (Harley, 1975).

In the vicinity of the Moora Line the Lesueur Sandstone contains large volumes of brackish groundwater prospective foi stock supplies only.

HYDROCHEMISTRY

All groundwater in the area is classified as being of sodium-chloride type, and there is no significant difference in chemical composition between water from different aquifers.

Iron concentrations are known to be high in the Leederville Formation (8.9 mg/L in Dandaragan town water supply bore) and appear to be variable in the Yarragadee Formation. Treatment of the groundwater will therefore be necessary if used for domestic or town water supply.

GROUNDWATER TEMPERATURE

Temperature logs were run on the Moora Line bores 12 months after completion of the last bore. They indicate a range at site 2 of from 25°C at the water table to 42°C at a depth of 600 m. The corresponding range at site 5 in the west was 21°C to 27.5°C. These ranges indicate the existence of a low temperature gradient in the west, and a high gradient in the east across the thick Otorowiri Siltstone Member, which may act as a thermal insulator. Actual gradiants are about 2.3°C per 100 m in the Lesueur Sandstone, 1.5°C per 100 m in the Yarragadee Formation, 3.5°C per 100 m across the Otorowiri Siltstone Member, and 2.5°C per 100 m in the Leederville Formation.

CONCLUSIONS

The Moora Line of bores has provided valuable new geological and hydrogeological data in the northern Perth Basin. Drilling has confirmed the basic structure of the basin; the sediments are block faulted on the western side of the Dandaragan Trough and have a gentle east dip towards the Darling Fault which forms the eastern edge.

Fault-controlled subsidence during the Middle to Late Cretaceous and associated differential compaction of the sediments, resulted in a thick sequence of Osborne Formation and Warnbro Group being deposited in the axis of the Dandaragan Trough.

The groundwater flow system is separated into two parts by a thick siltstone-claystone unit, which has been correlated with the Otorowiri Siltstone Member of the northern Perth Basin. Very large volumes of low-salinity groundwater are available from the Leederville and Yarragadee Formations. The Cockleshell Gully Formation and Lesueur Sandstone both contain brackish groundwater; however, the Lesueur Sandstone is a major aquifer and contains potable water to the north of the area of investigation. The Tamala Limestone is an important source of low-salinity shallow groundwater for coastal communities.

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GEOLOGY AND GROUNDWATER RESOURCES OF THE SOUTHWESTERN CANNING BASIN, WESTERN AUSTRALIA

by R. E. J. Leech

ABSTRACT

A hydrogeological study was conducted to assess the stratigraphy and groundwater potential of 3 500 km² of the southwestern part of the Canning Basin. Forty-seven bores were constructed with an aggregate depth of 6 790 m. Two major aquifers have been defined, the shallowest being the Broome Sandstone, which supports an unconfined groundwater system, and the other is the Wallal Sandstone, which contains a largely confined system separated from the Broome Sandstone by the almost impermeable Jarlemai Siltstone.

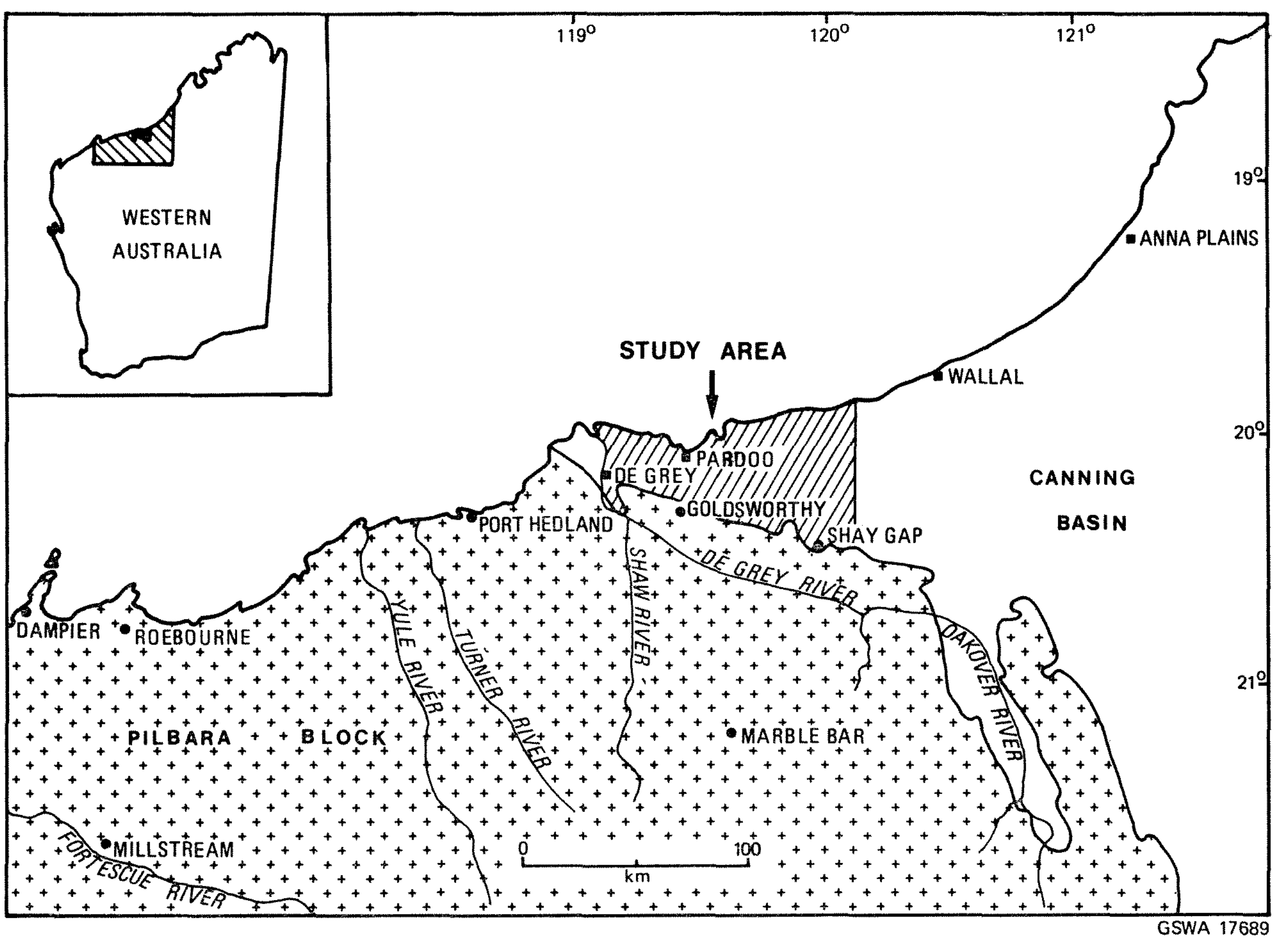

Figure 9 Location plan, southwestern Canning Basin.

The Broome Sandstone has an areal extent of about 1 575 km² and a saturated thickness of from 0 to 61 m. This aquifer is estimated to contain about 3.2 × $10^9 m^3$ of groundwater in storage. Yields of up to 1 000 m^3/day of potable water have been obtained from suitably constructed bores. The groundwater salinity (TDS) in this formation ranges from 380 mg/L in the east to more than 3 000 mg/L in the west. Nitrate concentrations are locally higher than the accepted limit for human consumption. Recharge to the Broome Sandstone is by direct percolation from rainfall. Groundwater movement is towards the north where it is discharged into the Indian Ocean.

The Wallal Sandstone extends over about 2 100 km² and has a saturated thickness of from 14 to 218 m. The estimated groundwater storage in this aquifer is 54.9 × $10^9 m^3$. Close to the coast hydraulic heads may exceed 30 m above ground level, and artesian flows from individual bores range up to 3 000 m^3/day. The salinity of groundwater in the Wallal Sandstone ranges from 240 to 13 000 mg/L. Recharge to this aquifer takes place outside the area investigated, towards the east and southeast, and is by direct percolation from rainfall in areas where the Jarlemai Siltstone is absent. Groundwater movement is towards the northwest where it discharges into the Indian Ocean.

INTRODUCTION

LOCATION

The investigation area is located in the southwestern Canning Basin, about 100 km east of Port Hedland (Fig. 9). The area is approximately 3 500 km² in extent and

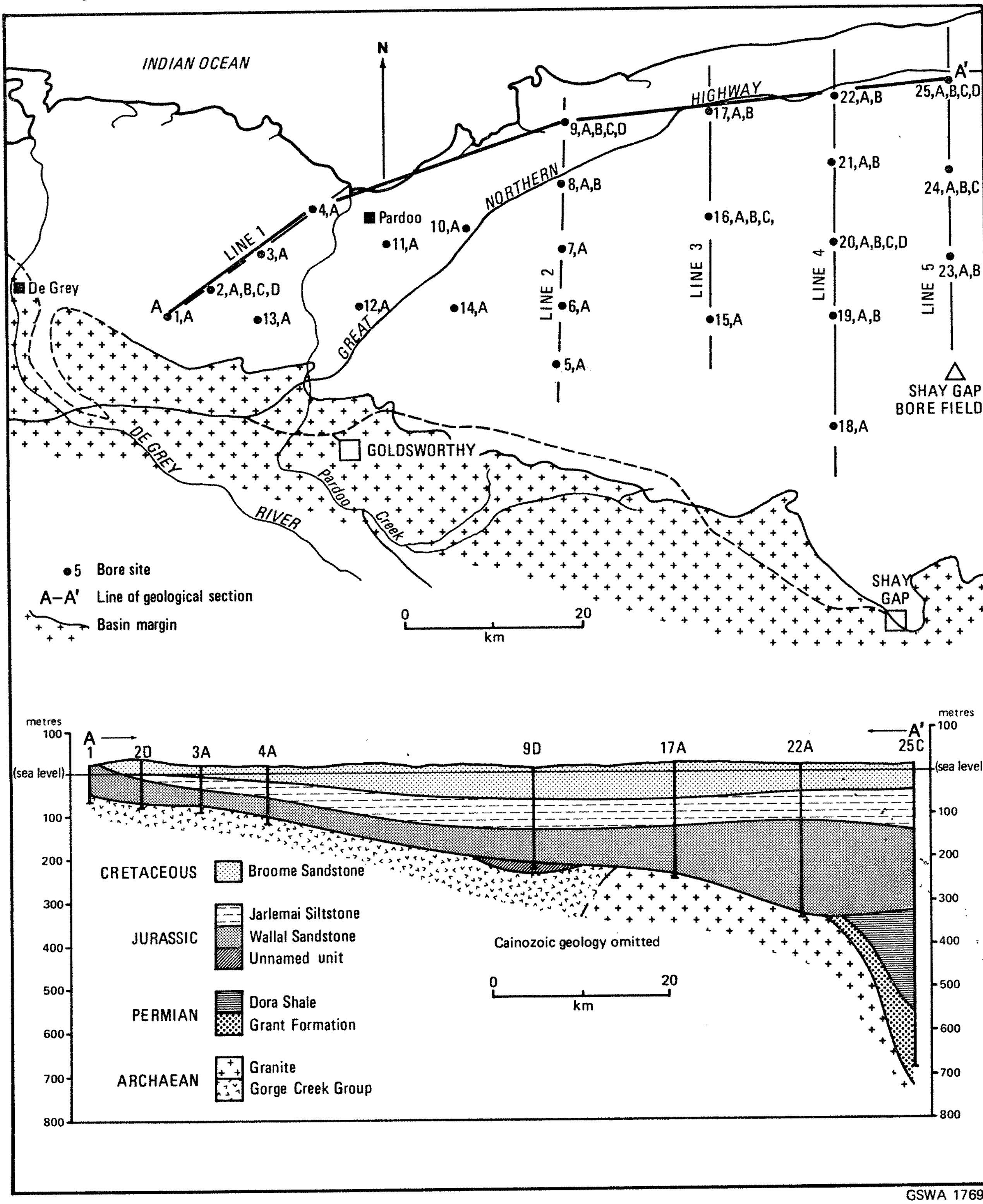

Figure 10 Bore locations and geological cross section.

is bounded by the Pilbara Block to the south, the Indian Ocean to the north and by lines of investigation bores to the west and east.

DRILLING AND BORE CONSTRUCTION

All drilling was completed by the Mines Department Drilling Section using Jacro 1500 and Mayhew 2000 rotary drilling rigs. Forty-seven bores with an aggregate depth of 6 790 m were drilled. Their locations are shown on Figure 10. Drilling difficulties were encountered when aquifers with large positive heads were intersected at sites 4, 9, 17, 22 and 25. These were overcome by the addition of barytes or a salt/sugar mixture to the drilling mud. This increased its density sufficiently to raise the pressure exerted by the mud column to that of the formation water.

Details of bore construction and test data are given in Table 5.

GEOLOGY

GENERAL

The Canning Basin is the largest sedimentary basin in Western Australia and extends over 630 000 km², of which two-thirds is onshore. The sediments that it contains

TABLE 5. SUMMARY OF PROJECT BORE DATA

Bore	Reduced level natural surface AHD* (m)	Total depth (m)	Casing		Screens†		Reduced water level AHD (m)	Discharge and drawdown at eight hours		Transmissivity (m²/day)	Salinity TDS (mg/L)	Aquifer
			Length (m)	Diameter ID (mm)	Interval (m)	Diameter ID (mm)		Discharge (m³/day)	Drawdown (m)			
1	19·666	83·2	60·0	206	Open hole		9·96	....	....	....	790	Wallal
2A	31·030	65·0	52·0	206	52·0–58·0	200	9·90	....	....	....	1 590	Wallal
2B						bore abandoned						
2C						bore abandoned						
2D	31·062	104·0	84·0	143	84·0–102·0	100	9·87	....	....	....	....	Wallal
3A	19·170	103·4	5·0 64·5	206 143	64·5– 82·5	76	11·18	614	4·3	145	1 860	Wallal
4A	12·675	133·5	5·4 67·4	206 143	67·4– 109·4	76	19·22‡	199	4·7	69	1 680	Wallal
5A	64·712	43·5	6·0 26·3	206 143	37·1– 43·1	76	30·81	....	....	....	....	Wallal
6A	48·269	78·5	6·2 50·0	206 143	50·7– 74·7	76	30·17	650	4·4	129	490	Wallal
7A	34·229	125·0	6·0 91·0	206 143	91·7– 115·7	76	29·76	641	2·7	204	360	Wallal
8A	15·115	183·0	6·0 137·5	206 143	138·1– 150·1	76	31·24‡	1 464	4·8	40	1 010	Wallal
8B	14·982	103·0	6·0 82·0	206 143	82·7– 100·7	76	31·26‡	939	3·3	104	960	Wallal
9A						bore abandoned						
9B	5·875	120·0	65·0 74·4	206 143	74·4– 95·4	143	32·85‡	....	....	....	860	Jarlemai
9C						bore abandoned						
9D	7·075	224·0	43·9 130·0 168·0	259 189 143	193·0– 211·0	50	27·70‡	508	15·5	10	1 190	Wallal
10A	20·975	116·4	41·0 71·0	206 143	71·1– 113·1	76	25·74‡	769	1·7	272	1 120	Wallal
11A	19·732	129·7	35·0 55·0	206 143	61·0– 85·0	76	22·20‡	....	....	....	1 160	Wallal
12A	32·168	45·7	26·0 31·0	206 143	31·0– 43·0	76	18·26	....	....	....	1 180	Broome
13A	46·100	69·7	41·0 71·0	206 143	42·0– 54·0	76	11·05	....	....	....	820	Broome
14A	53·704	77·1	35·0 55·0	206 143	57·7– 70·1	100	25·78	....	....	....	770	Wallal
15A	84·314	120·5	26·0 31·0	206 143	101·0– 113·0	100	38·01	....	....	....	240	Wallal
16A	41·976	184·0	29·0 42·0	206 143	138·0– 153·0	100	38·22	672	6·1	145	310	Wallal
16B	41·792	45·0	6·0 57·7	189 143	37·0– 43·0	100	30·43	393	5·6	222	440	Broome
16C	41·772	155·0	30·0 101·0	206 143	135·2– 153·4	76	38·24	....	....	....	....	Wallal
17A	18·750	259·0	29·0 220·0	206 143	220·0– 244·0	100	37·17‡	2 100	6·9	142	420	Wallal
17B	18·558	70·0	29·0 64·0	206 143	64·0– 70·0	100	2·95	632	5·0	854	720	Broome
18A	157·641	126·5	106·0	143	108·7– 120·7	100	45·60	....	....	....	310	Wallal
19A	105·918	176·0	21·0 158·0	189 143	158·0– 176·0	100	43·86	532	2·8	54	330	Wallal
19B	105·878	54·0	45·0	143	45·0– 51·0	100	Dry	....	....	....	....	Broome
20A						bore abandoned						
20B	77·000	56·0	50·0	143	50·0– 54·5	100	Dry	....	....	....	....	Broome
20C	78·164	190·0	169·0	143	169·5– 187·5	76	43·50	....	....	2 490	....	Wallal
20D	76·949	185·0	167·0	143	167·0– 183·8	100	43·39	626	2·7	720	300	Wallal
21A	37·877	235·0	29·0 200·0	189 143	200·0– 224·0	104	43·64‡	247	0·7	409	320	Wallal
21B	37·552	42·0	30·0	143	30·0– 39·0	104	14·35	29	0·03	159	380	Broome
22A	11·081	344·0	36·7 278·0	237 143	278·0– 296·0	100	38·74‡	3 030	10·0	279	320	Wallal
22B	11·078	55·0	49·0	143	49·0– 55·0	100	7·82	626	5·6	138	430	Broome
23A	70·912	210·0	96·9	143	96·9–114·9	100	46·60	645	1·3	569	290	Wallal
23B	70·481	122·0	97·0	143	97·0–114·5	100	46·60	....	....	....	....	Wallal
24A	43·768	267·0	32·0 170·7	259 143	170·7– 179·0	100	45·99‡	69	0·5	200	240	Wallal
24B	43·807	45·0	34·0	143	34·0– 40·0	100	10·70	....	....	....	480	Broome
24C	43·822	47·0	34·0	143	34·0– 40·0	100	10·70	....	....	....	....	Broome
25A						bore abandoned						
25B						bore abandoned						
25C	16·212	696·0	34·0 231·0 286·0	259 143 105	286·0– 310·0	100	41·99‡	1 394	14·7	130	300	Wallal
25D	16·158	102·0	30·9	143	30·9– 36·9	100	3·62	735	3·0	250	830	Broome

* AHD—Australian Height Datum.
† The interval between the top of the screen and the base of the casing is occupied by either a packer or blank casing.
‡ Flowing bore.

range from Ordovician to Recent in age, and reach a maximum thickness of over 8 km. The area included in the current investigation, 3 500 km², covers but a small portion of the basin and is confined to the western part of the Anketell Shelf which includes the Wallal Platform to the west of the Willara Sub-basin. The maximum thickness of sediments penetrated by boring was 696 m at site 25. trough to the northeast named the Willara Sub-basin. The Wallal Platform is a basement-high in this area, and all project bore sites with the exception of site 25 are drilled on this platform. The gradient of the bedrock floor steepens between sites 24 and 25 which suggests that this structure may be an ancient fault scarp, or a hinge line with greater subsidence to the northeast (Fig. 10).

TABLE 6. STRATIGRAPHIC UNITS IN THE SOUTHWESTERN CANNING BASIN

Age		Rock unit	Lithology
CAINOZOIC	Quaternary	Bossut Formation	Alluvium—clay, sand and gravel Sand—wind-blown, red residual soil Tidal Flat Deposits—clay, silt and sand Calcarenite—sandy, cross-bedded
	Tertiary		Calcrete—white, calcareous rock Laterite—pisolitic, ironstone, unconsolidated
		UNCONFORMITY	
MESOZOIC	Cretaceous	Broome Sandstone	Sandstone—with rare siltstone interbeds
	Jurassic	Jarlemai Siltstone Wallal Sandstone Unnamed unit	Siltstone—claystone and rare sandstone interbeds Sandstone—with rare siltstone and conglomerate interbeds Claystone—with rare lignite
		UNCONFORMITY	
PALAEOZOIC	Permian	Dora Shale Grant Formation	Shale—with siltstone interbeds Glacigene deposits—interbeds of siltstone, sandstone and claystone
		UNCONFORMITY	
ARCHAEAN		(Muccan Batholith) Gorge Creek Group	Granite—weathered; quartz, biotite and kaolinized feldspar Metasediments and volcanic rocks—shale, amphibolite, schist and quartzite

The geological succession and a brief lithological description of each geological unit encountered during this investigation either in bores or during mapping is given in Table 6. The main stratigraphic problem was to establish the correct Mesozoic succession. Several authors (Elliott, 1957; Australia Bureau of Mineral Resources, 1958; McWhae and others, 1958; Veevers and Wells, 1961; and the Geological Survey of Western Australia, 1975) had all produced conflicting geological successions; their stratigraphy together with the sequence adopted in this report are shown in Table 7.

STRUCTURE

The drilling programme has defined the geology and also allows accurate construction of structure contour and isopach maps. These indicate that the Mesozoic sediments are essentially flat lying with presumed depositional dips of less than 1° to the north. There is no evidence of folding and faulting.

Two structurally controlled subdivisions which affect the Canning Basin sediments in this part of the basin are the northwesterly trending Wallal Platform and an adjacent

GEOLOGICAL HISTORY

There are no indications of Palaezoic sedimentation in the investigation area prior to the Early Permian. It is therefore likely that either this part of the basin was a land mass before this time or, if sediments had been deposited, they had already been removed by erosion. During Permian times the glacigene Grant Formation, of Sakmarian age, was deposited unconformably on the Archaean basement rocks, and this was followed in the Late Sakmarian or Early Artinskian by deposition of the Dora Shale, a continental sequence of claystone, siltstone and sandstone. At the end of the Permian an interval of uplift occurred and sedimentation ceased.

During Middle Jurassic times renewed subsidence resulted in a marine transgression, which by the Bajocian had reached the study area. An unnamed claystone unit (Backhouse, 1978) was then deposited locally on Archaean basement. Further subsidence occurred in the Callovian, and the Wallal Sandstone was deposited. Over most of the Canning Basin this sandstone is the basal unit of the Jurassic marine transgression, and was deposited unconformably on Archaean or Permian rocks. By Oxfordian

TABLE 7. MESOZOIC STRATIGRAPHIC NOMENCLATURE IN THE SOUTHWESTERN CANNING BASIN

Age	Elliott Wallal core hole No. 1 (1957)	BMR 4 and 4A Wallal (1958)	McWhae and others (1958)	Veevers and Wells (1961)	GSWA Memoir 2 (1975)	This Report
Neocomian	Broome Sandstone	Broome Sandstone	Anketell Sandstone Callawa Formation	Broome Sandstone	Broome Sandtsone	Broome Sandstone
			Broome Sandstone	Jarlemai Silstsone		
Tithonian	Jarlemai Siltstone	Jarlemai Siltstone	Jarlemai Silststone	Anketell Formation	Jarlemai Siltstone	Jarlemai Siltstone
Kimmeridgian	Alexander Formation and Jururra Sandstone Equivalent	Alexander Formation		Callawa Formation		
Oxfordian		Wallal Sandstone	Alexander Formation		Alexander Formation	
Callovian					? Wallal Sandstone	Wallal Sandstone
Bathonian						
Bajocian						Unnamed unit
Toarcian						

times the sea had moved further inland and the marine Jarlemai Siltstone was deposited disconformably on the Wallal Sandstone in a relatively low-energy environment. During Upper Jurassic and Early Cretaceous times the regressive Broome Sandstone was deposited in a non-marine high-energy environment.

From the Early Cretaceous to the present, uplift and erosion has taken place with only very minor deposition.

HYDROGEOLOGY

AQUIFER RELATIONSHIPS

The Broome and Wallal Sandstones which comprise the main aquifers, support two flow systems that are separated by the Jarlemai Siltstone. The flow system in the Broome Sandstone is essentially unconfined, and recharge is either by direct percolation from rainfall or indirectly through the thin Tertiary or Quaternary sediments. This may take place over quite large areas. In contrast, groundwater flow in the Wallal Sandstone takes place under confined conditions and recharge from rainfall is only possible over the limited area where the Jarlemai Siltstone is absent. A limited interconnection between the two aquifer systems may occur in this area; however, elsewhere, groundwater movement in each aquifer is separate and differs markedly in direction. Thus, groundwater in the Broome Sandstone moves towards the north and is discharged into the Indian Ocean at beach seepage faces; whereas groundwater in the Wallal Sandstone moves almost westwards and probably discharges mainly as sub-ocean springs, but some minor discharges take place at springs along the coastal strip.

The Tertiary and Quaternary deposits, including the Bossut Formation, contain small groundwater storages that are probably in hydraulic continuity with the Broome Sandstone. The hydrogeology of these superficial deposits will not be discussed further as they are only of local importance for stock supplies.

BROOME SANDSTONE

Introduction

The Broome Sandstone, which reaches a thickness of up to 71 m, is the largest unconfined aquifer in this part of the Canning Basin. Recharge is by direct percolation from rainfall, and groundwater movement is generally towards the north. The water-table contour map, Figure 11, is drawn from measurements taken from private bores and wells, together with project bores which were constructed in the Broome Sandstone.

Hydraulic testing and results

Test pumping was undertaken on five single bores completed in the Broome Sandstone. As observation bores were not provided, drawdown and recovery records were only available from the pumping bores. The raw drawdown data were corrected for bore inefficiency and partial penetration effects. No dewatering correction was needed as the dewatered depth of aquifer was small when compared to the aquifer thickness.

The analytical results for the unconfined Broome Sandstone are given in Table 8. Transmissivity values varied from 138 to 854 m²/day, and averaged 325 m²/day. Hydraulic conductivity values ranged from 2.6 to 15 m/day, and averaged 7.5 m/day. The aquifer consists of a fine-to coarse-grained, moderately sorted sandstone for which the published results for similar rocks (Krumbein and Monk, 1943; Turneaure and Russell, 1947; Johnson, 1963; and Lovelock, 1970) suggest a hydraulic conductivity of between 5 and 15 m/day. The average values for transmissivity and hydraulic conductivity therefore appear to be of the correct order.

TABLE 8. GENERAL BORE INFORMATION AND TEST PUMPING RESULTS

Bore	Saturated aquifer thickness (m)	Pumping test discharge (m³/day)	Corrected drawdown at 1 hour (m)	Transmissivity (m²/day)	Hydraulic conductivity (m/day)
16B	34·2	393	1·91	222	6·5
17B	56·9	632	0·85	854	15
21B	19·9	29·4	0·05	159	8·0
22B	53·1	626	3·10	138	2·6
25D	48·1	735	1·27	250	5·2
Average	....	....	....	325	7·5

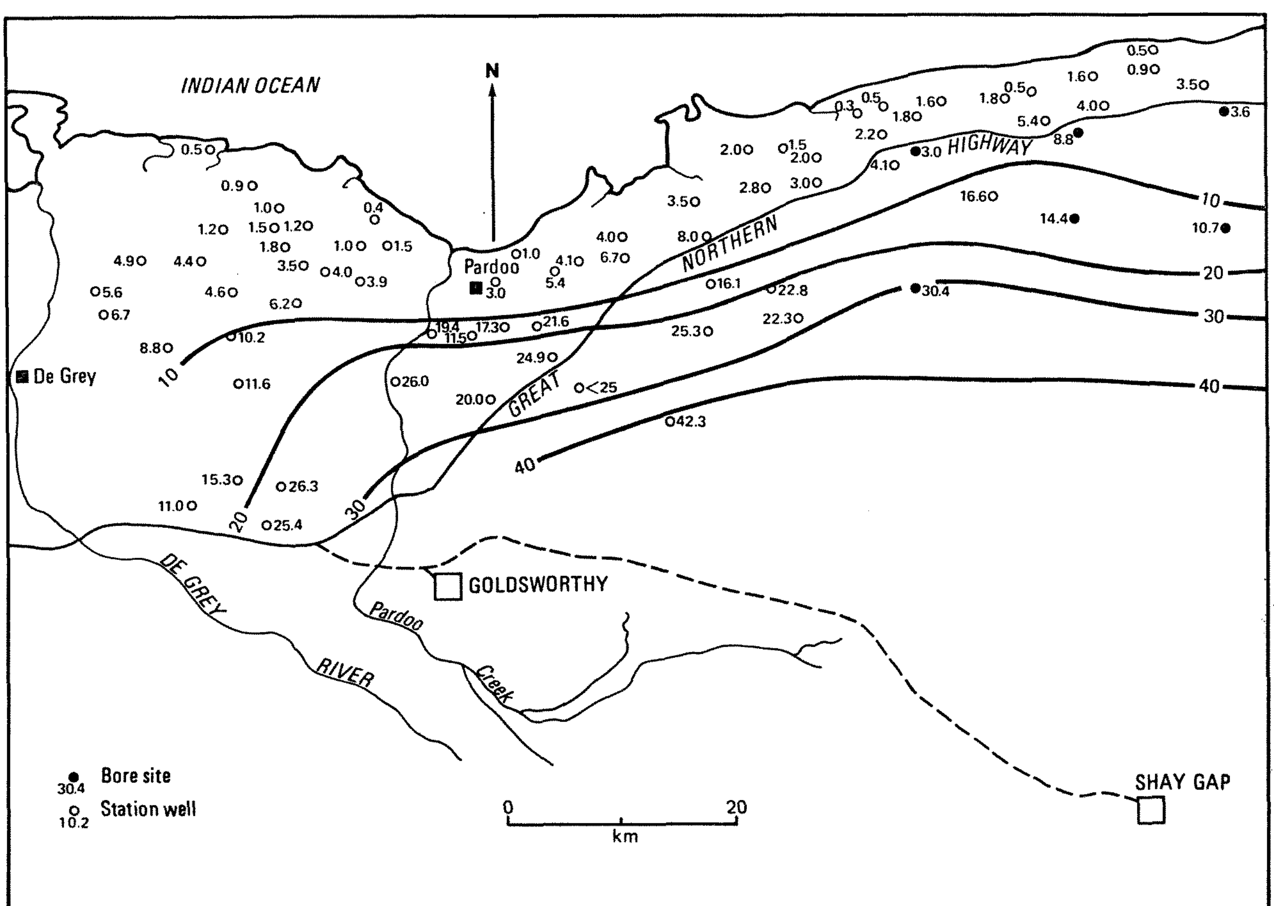

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Figure 11 Water-table contours, measured on 24th August 1977 – mAHD (Contour interval 10m).

The specific yield of the Broome Sandstone aquifer could not be determined as observation bores were not installed in the cones of depression of the pumping bores.

Storage

The groundwater stored in the Broome Sandstone (Q_s) can be estimated as the product of the saturated volume (V) and the specific yield (S_y). The volume is the product of the aquifer's areal extent and the average saturated thickness. These parameters have been estimated from known geological and hydrological data to be 1 575 km² and 20 m respectively. As a specific yield could not be calculated from test pumping a value of 0.1 has been adopted for this calculation. Thus:

$$Q_s = VS_y$$
$$Q_s = 1575 \times 10^6 \times 20 \times 0.1$$
$$= 3.2 \times 10^9 m^3$$

Throughflow

The rate of throughflow in the Broome Sandstone aquifer at the 10 m water-table contour (Fig. 11) may be calculated from the following version of the Darcy equation:

$$Q = Kbil$$

where Q is the throughflow (m³/year)
K is the hydraulic conductivity (m/day)
b is the saturated aquifer thickness (m)
i is the hydraulic gradient (dimensionless)
and l is the length of section (m)

The average hydraulic conductivity of 7.5 m/day has been derived from pumping-test results and by considerations of the aquifer lithology. The hydraulic gradient has been estimated from Figure 11 as the average of the shallowest and steepest gradients and is 2.5×10^{-3}; and the aquifer width is taken as the length of the 10 m contour (Fig. 3), which is 100 km. The mean saturated thickness along the 10 m contour was derived from this contour and the contours on the base of the Broome Sandstone, and is 29.3 m. Therefore:

$$Q = 7.5 \times 29.3 \times (2.5 \times 10^{-3}) \times 100 \times 10^3 \times 365$$
$$= 20 \times 10^6 \ m^3/year$$

This annual throughflow volume represents about 0.6 per cent of the aquifer storage calculated above.

Hydrochemistry

The isohalines for the unconfined aquifers including the Broome Sandstone, the Bossut Formation and superficial deposits are shown in Figure 12. Salinities in the Broome Sandstone east of drill line 2 are less than 1 000 mg/L, but to the west rise to more than 3 000 mg/L. Salinities from wells constructed in the coastal dunes are generally less than 2 000 mg/L. Further inland, on the coastal plain, salinities from the alluvium rise appreciably and may reach 15 000 mg/L. This may be due to a high soil salt content caused by a Holocene high sea level.

In general the concentrations of total soluble salts and the common ions in water from the Broome Sandstone make it acceptable for domestic use.

However, the nitrate ion is commonly present in greater concentrations than the recommended limit of acceptance in Australia (Hart, 1974) of 23 mg/L, and that set by the World Health Organization (1971) of 45 mg/L.

WALLAL SANDSTONE

Introduction

The Wallal Sandstone occurs in the subsurface over most of the area, and consists of a fine- to very coarse-grained, poorly to well sorted, unconsolidated sandstone. This aquifer provides large artesian flows from bores drilled into it along the coastal plain, where positive heads in excess of 30 m have been measured. The potentiometric contours for this aquifer (Fig. 13) indicate that recharge takes place in the southeast and that groundwater movement is to the west and northwest. Recharge is by infiltration of rainfall south of the Jarlemai Siltstone subcrop where the aquifer becomes unconfined, and to the southeast outside the investigation area. Groundwater discharge is mainly offshore towards the northwest except for a few small springs in the Pardoo area (Fig. 13).

Hydraulic testing and results

Pump or flow tests were conducted on 18 bores screened in the Wallal Sandstone. Only one test was successfully completed with an observation bore. Drawdown data from each test were corrected for bore inefficiency and in some cases for barometric pressure changes.

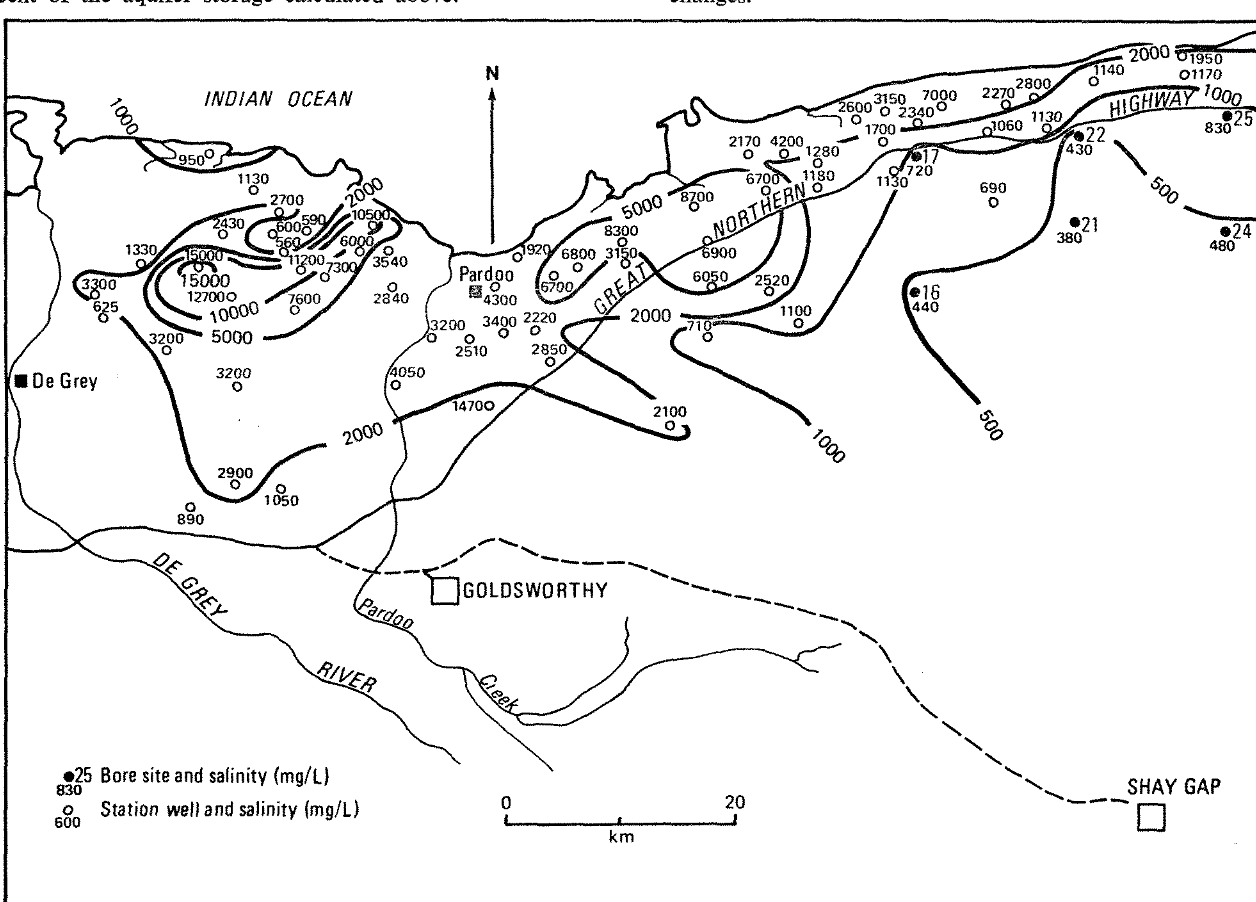

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Figure 12 Isohalines in the unconfined aquifers (mg/L T.D.S.).

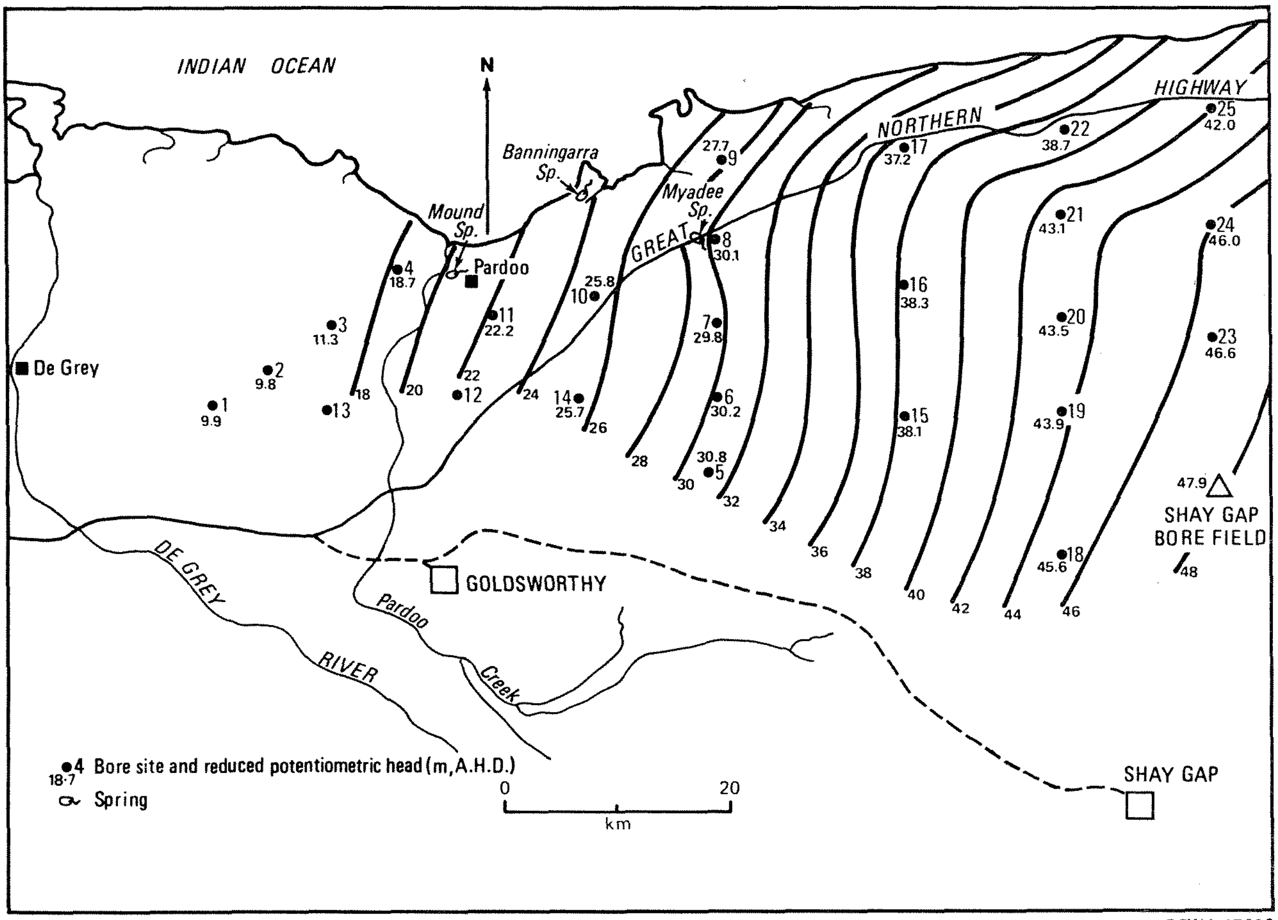

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Figure 13 Wallal Sandstone potentiometric contours 13th May 1977 (contour interval 2m).

Analytical results for the confined Wallal Sandstone aquifer are given in Table 9. Transmissivity values range from 10 to 2 490 m²/day and average 340 m²/day. The corresponding range of hydraulic conductivity values is 0.6 to 138.3 m/day, and the average is 18.5 m/day (Table 9).

confining bed would be too small to allow steady-state conditions to be reached in such a short time after the start of pumping. Further, the potentiometric head of the Wallal Sandstone, where it is confined, was above the water table throughout the flow and pumping tests. This means that during the test there was a potential for up-

TABLE 9. PUMP AND FLOW TEST RESULTS FROM THE WALLAL SANDSTONE AQUIFER

Bore	Bore status	Aquifer thickness (m)	Screen length (m)	Discharge* (m³/day)	Transmissivity† (m²/day)	Hydraulic conductivity (m/day)	Storage coefficient
3A	Pump	35	18	614	145	8·1	
4A	Flow	42	42	199	69	1·6	
6A	Pump	28	24	650	129	5·4	
7A	Pump	62	24	641	204	8·5	
8A	Flow	14	12	1 464	40	3·3	
8B	Flow	24	18	939	104	5·8	
9D	Flow	99	18	508	10	0·6	
10A	Flow	72	42	769	272	6·5	
16A	Pump	89	15	672	145	9·7	
17A	Flow	116	24	2 100	142	5·9	
19A	Pump	96	18	532	54	3·0	
20C	Obs. bore	107	18	626	2 490	138·3	2·0 x 10⁻⁴
20D	Pump	107	16·8	626	720	42·9	
21A	Flow	115	24	247	409	17·0	
22A	Flow	218	18	3 030	279	15·5	
23A	Pump	104	18	645	569	31·6	
24A	Flow	151	8·3	69	200‡	24·1	
25C	Flow	189	24	1 394	130	5·4	
Average	....	100	....	....	340	18·5	2·0 x 10⁻⁴

* Discharges shown are those for the constant discharge test.
† Transmissivity values are for the screened interval only.
‡ Estimated from specific capacity calculation.

The analysis from the observation bore gave a storage coefficient of 2.0 x 10^{-4}.

All plots of drawdown against time showed steady-state conditions after about three minutes. These plots were matched to leaky artesian-type curves. The lithology of the Jarlemai Siltstone, a thick impermeable clayey formation, suggests that the vertical leakage from this

ward groundwater movement from the Wallal Sandstone to the confining bed. The observed respone indicates that the cone of influence has ceased expanding and that the discharge is sustained by a recharge boundary or by leakage. There is no geological or hydrological evidence to support the presence of recharge boundaries. Therefore it is concluded that the observed response results from leakage within the aquifer, caused by inhomogeneity and stratification of the sediments which together produce anisotropic conditions. This would result in greater hydraulic conductivities in a horizontal direction than occurs in the vertical. If this is the case the transmissivities derived from the analyses of hydraulic tests are applicable only for the screened interval and a corresponding mean hydraulic conductivity can be derived for that interval. This figure may then be applied to the entire aquifer thickness to derive the aquifer transmissivity.

Storage

The interstitial aquifer storage is the product of the aquifer volume and the specific yield. To derive an accurate estimate of the aquifer volume the area between adjacent isopachs of the Wallal Sandstone is multiplied by the mean thickness, and the incremental volumes are then summed to give the total volume. Table 10 shows the data required to calculate the volume of the Wallal Sandstone. The area considered is bounded on the west by line 1, on the north by the Indian Ocean, on the east by line 5, and on the south by the 20 m isopach and an east-west line from the eastern end of the 20 m isopach to line 5. This excludes the area over which the aquifer is not fully saturated and conditions are unconfined.

TABLE 10. WALLAL SANDSTONE—DATA REQUIRED TO CALCULATE THE VOLUME OF WATER HELD IN INTERSTITIAL STORAGE

Isopach interval (m)	Mean aquifer thickness (m)	Incremental area (km^2)	Incremental volume x 10^9 (m^3)
20–40	30	289·88	8·696
40–60	50	225·13	11·257
60–80	70	298·38	20·887
80–100	90	460·13	41·412
100–120	110	483·75	53·213
120–140	130	57·88	7·524
140–160	150	62·88	9·432
160–180	170	51·00	8·670
180–200	190	46·88	8·907
>200	210	123·50	25·935
Total	....	2 099·41	195·933

The specific yield was estimated to be 0.28 from laboratory experiments conducted on recompacted aquifer samples; this figure compares favourably with that quoted by Hazel (1973) of 0.27 for a medium-grained sandstone. Therefore, for estimating the volume of groundwater in storage (Q_s), specific yield (S_y) of 0.28 is adopted.

Therefore:

$$Q_s = VS_y \text{ where V is the aquifer volume}$$
$$= 195.933 \times 10^9 \times 0.28$$
$$= 54.9 \times 10^9 m^3$$

This is a very large storage, and is equivalent to approximately 275 times the annual water consumption of the Perth metropolitan supply (based on 1975-1976 figures).

Throughflow

A throughflow can be estimated for the Wallal Sandstone across the 44 m potentiometric contour using the equation Q = Kbil; the notation is given above. The mean hydraulic conductivity derived from pumping-test analyses is rounded off to 20 m/day for this calculation. The aquifer thickness along the 44 m potentiometric contour is estimated from the isopachs and Figure 13 to be 117 m, and the hydraulic gradient from Figure 13 is 4.2 x 10^{-4}. The length of section considered here is 58.5 km.

Therefore:

$$Q = 20 \times 117 \times (4.2 \times 10^{-4}) \times 58.5 \times 10^3 \times 365$$
$$= 21.0 \times 10^6 \ m^3/year$$

This figure for throughflow can be regarded as the annual safe yield as it must be supported by the average long-term recharge to the aquifer system.

Hydrochemistry

The isohalines for the Wallal Sandstone confined aquifer are shown in Figure 14. The salinity increases from about 300 mg/L TDS in the east to 13 700 mg/L TDS (private bore) in the extreme western part of the area. The sharp increase in salinity gradient in the west is thought to be

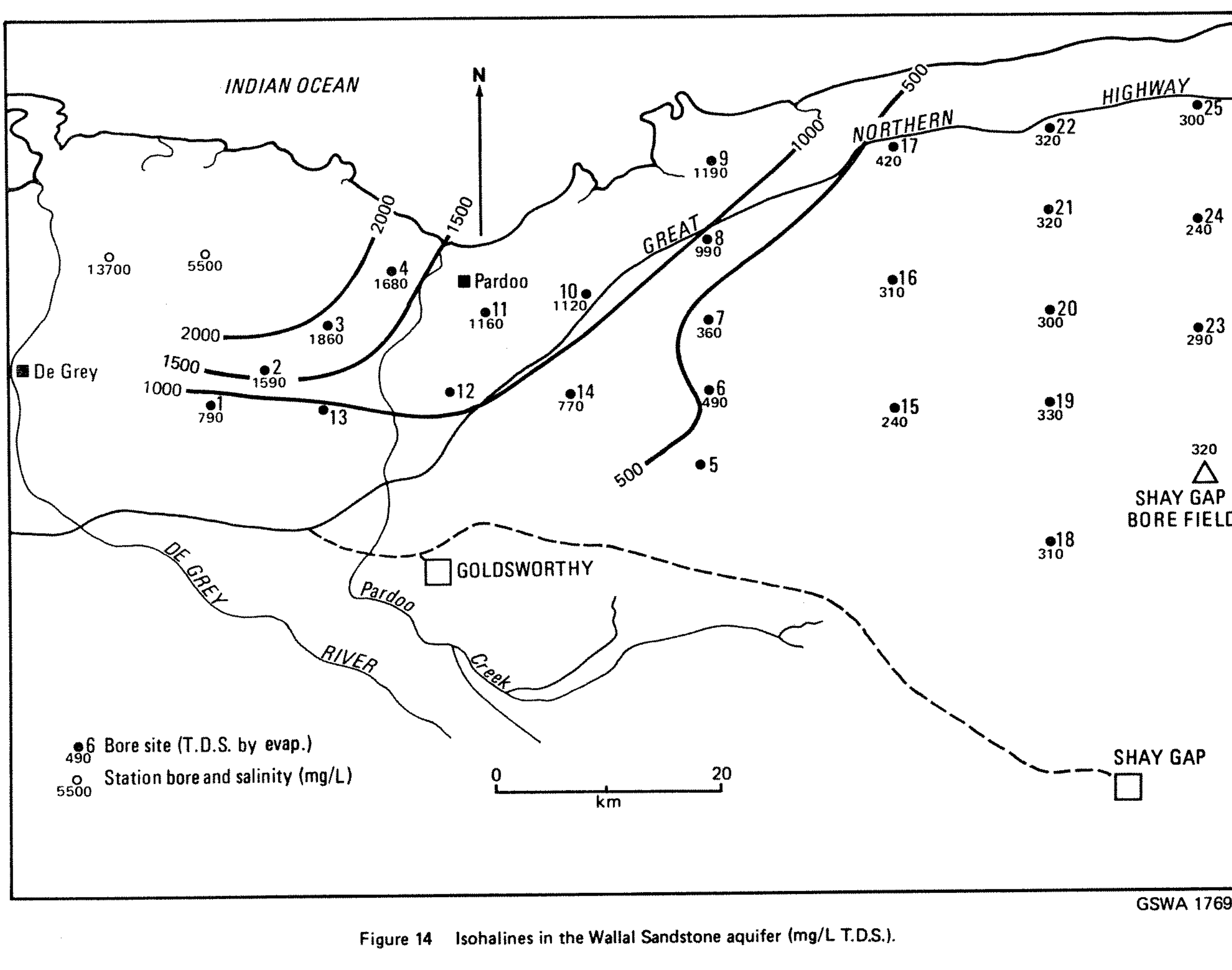

Figure 14 Isohalines in the Wallal Sandstone aquifer (mg/L T.D.S.).

due to the displacement of the saline water by fresher recharge water. It is not known whether the saline water was introduced during a high Quaternary sea level which encroached into the recharge area; or whether the aquifer was previously subjected to another source of saline intrusion.

The confined groundwater is a sodium-chloride type, with somewhat more bicarbonate in the east towards the recharge area. East of the 500 mg/L isohaline the groundwater quality is wholly acceptable for domestic consumption. However, a zone of high nitrate ion concentration does occur in an area bounded by the Shay Gap bore field and project sites 19 and 23. In this zone the nitrate concentration ranges from 23 to 26 mg/L; this is just above the acceptable limit for human consumption as defined by Hart (1974).

DEVELOPMENT

The Broome Sandstone and Wallal Sandstone aquifers contain large volumes of groundwater, much of which is suitable for domestic, irrigation or industrial use. The main constraints imposed on developing these aquifers are the remoteness of the area and the quality of the groundwater for a given use. If a production bore field is to be constructed it should develop both the Broome Sandstone and Wallal Sandstone aquifers. Besides more fully developing the total water resources this would have the effect of bringing the average nitrate concentration down to an acceptable level (subject to appropriate management). Production bores should be designed to intercept the throughflow by locating them parallel to the water table or potentiometric contours. Rates of abstraction should be appropriate to the throughflow in their vicinity.

CONCLUSIONS

This project has elucidated the stratigraphic sequence in the southwestern part of the Canning Basin and indicated the western limit of the Permian subcrop. It has also led to the discovery of an unnamed claystone unit of Bajocian age.

The major aquifers in the area are the Wallal and Broome Sandstones. The Wallal Sandstone has the greater volume of groundwater in storage and in general this is of better quality than that of the Broome Sandstone.

The full extent of the Wallal Sandstone has not been determined, but it is known to occur from De Grey Station to at least as far northeast as Anna Plains Station, a distance of 270 km. Groundwater quailty from this aquifer is acceptable for domestic purposes over more than half of the area, but varies from 300 mg/L in the southeast nearest the recharge area, to 13 000 mg/L at De Grey Station. This confined aquifer is a substantial resource and has a larger storage than any other known aquifer within the Pilbara and West Kimberley Regions of Western Australia.

The Broome Sandstone occurs throughout the investigation area and extends further east into the basin. Much of the groundwater stored in this formation is of marginal quality for domestic consumption by reason of its high salinity or nitrate content, but could be used for some industrial processes, or mixed with other water of lower salinity and nitrate content.

The large-scale development of groundwater resources in the Canning Basin sediments is unlikely in the near future due to its remote location. However, when major abstraction does take place it would be advantageous to utilize conjunctively the groundwater from the Wallal and Broome Sandstones.

Production borefield design and management, and the determination of recharge areas would be assisted by further exploratory drilling to the east and southeast. Further test pumping, under controlled conditions is also desirable to better quantify aquifer parameters and hence rate of underflow through the different parts of the area to be developed.

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AN OUTLINE OF THE CONFINED GROUNDWATER RESOURCES IN THE VICINITY OF PERTH, WESTERN AUSTRALIA

by A. D. Allen

ABSTRACT

Near Perth large confined groundwater resources occur in the Leederville, Yarragadee and Cockleshell Gully Formations of Mesozoic age. They have localized intake areas and receive recharge from rainfall and stream runoff via immediately overlying aquifers where confining beds are absent. The confined aquifers may be able to provide 50 to 80 x 10^6 m^3/y of groundwater with a salinity of less than 1 000 mg/L T.D.S. compared with a present yield of about 30 x 10^6 m^3/y. A more reliable assessment of the resources will be possible when drilling of the artesian monitoring network is completed.

INTRODUCTION

LOCATION AND TOPOGRAPHY

Confined (artesian) groundwater resources are being investigated for Perth's water supply on the Swan Coastal Plain between Gingin Brook in the north and

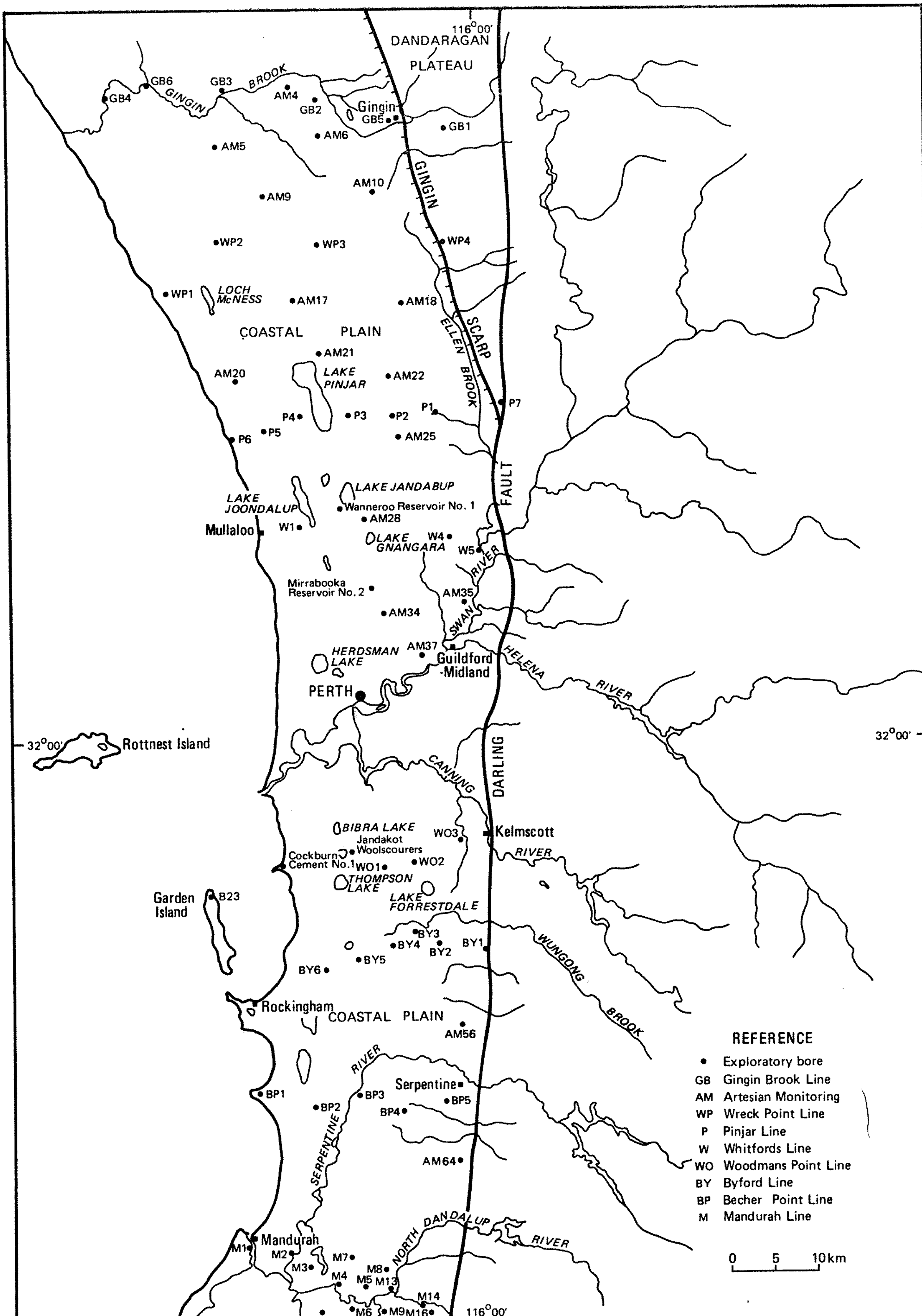

Figure 15 Locality map.

GSWA 17706

the North Dandalup River in the south. The area extends for about 65 km to the north and south of Perth, averages 25 km in width and has an area of about 3 600 km^2 (Fig. 15).

For convenience the area is referred to as the Perth area, while the areas to the north and south of the Swan River are called the northern and southern Perth areas respectively.

In the northern Perth area the Swan Coastal Plain consists of a coastal belt, about 10 km wide, of dune limestone with an irregular topography. This borders a broad ridge which reaches an elevation of about 100 m in the central part of the plain and which is flanked on the east and south by extensive low-lying areas associated with the Swan River and its tributary Ellen Brook. In the southern Perth area there is also a coastal belt which borders a gentle ridge with an elevation of about 30 m in the northern half of the area. This is bordered by low-lying areas associated with the Swan, Canning and Serpentine Rivers. In the rest of the area between the Helena and Canning Rivers and the Serpentine and North Dandalup Rivers, the coastal plain rises gently to about 70 m adjacent to the Darling Scarp.

PURPOSE AND SCOPE

The purpose of this paper is to provide an interim account of the occurrence, size, and extent of the confined groundwater resources near Perth. A more comprehensive account, possibly modifying the interpretations given in this paper will be published on completion of the exploratory drilling.

HISTORY

Artesian water (from the Leederville Formation) was first discovered in the Perth area in an exploratory bore, drilled in 1871 for coal, adjacent to the Canning River near Kelmscott (Passmore, 1912). Further drilling for artesian water was discouraged by a report by Hardman (1885). Despite this report an exploratory bore was drilled at Midland Junction by the Government in 1894-95 and encountered an artesian flow at 152 m. As a result, about 40 artesian bores were drilled in Guildford, Midland and Perth between 1895 and 1905 (Maitland, 1913).

The first artesian bore for public water supply (West Perth Station Yard bore) was drilled in 1897, and subsequently up to 1932 a further 20 bores were drilled. These produced 60 to 70 per cent of Perth's water supply until the completion of Canning Dam in 1940. A further 15 artesian bores have been drilled since 1954 and others are planned.

Systematic exploratory drilling to assess the confined groundwater resources in the Perth Basin, near Perth, was commenced by the Mines Department (G.S.W.A.) in 1961, and up to 1969 four lines of deep exploratory bores had been drilled (Table 11). At about this time it was realized that the proven surface and groundwater resources were inadequate to meet Perth's projected requirements (Hillman, 1971; O'Hara, 1973). It was also recognized that there were many advantages in having a water supply based both on surface and groundwater resources; and being able to develop groundwater resources near developing areas.

To meet increasing demand the Metropolitan Water Supply Sewerage and Drainage Board (M.W.B.) commenced a comprehensive drilling programme in 1969 to evaluate the confined and unconfined groundwater resources. The confined groundwater resources have been investigated by drilling lines of deep exploratory bores as well as a network of artesian monitoring bores which are planned to be completed by 1986.

PREVIOUS WORK

There are numerous reports which give details of the first deep bores or discuss early concepts about the geology and confined groundwater resources near Perth. Most of these are of historical interest and are not reviewed, although where relevant they are cited in this paper.

The first attempt at correlating the confined aquifers was made by Forman (1933) who distinguished three distinct 'horizons' on the basis of chemical analyses and groundwater temperatures. They were the Claremont-South Perth Horizon (equivalent to the Yarragadee Formation) and the Leederville and City Horizons (equivalent to the Leederville Formation). The City Horizon contains a mixture of water from *both* the Leederville and Yarragadee Formations; hence it was mistakenly thought to be a separate unit.

Pudovskis (1962) correlated the deep water bores with the established stratigraphy. He gave an interpretation of the structure and recognized that the Kings Park Formation filled a deep channel.

Subsequently, the most important information is given in the descriptions of the various deep drilling projects: Byford Line (Berliat, 1964), Pinjar Line (Whincup, 1966), Gingin Brook Line (Sanders, 1967), Mandurah Project (Commander, 1974), Becher Point Line (Allen, 1978), and in a general account of the hydrogeology of the Perth area by Allen (1975).

DATA

Since 1895 about 50 bores over 300 m deep and 400 bores 90 to 300 m deep have been drilled for public water supply, irrigation and exploratory projects.

The main data from the early bores are drillers' logs, head measurements, water analyses, and a few samples. Gamma logs are also available from some of these bores that are still accessible.

Geophysical logs (gamma ray, long and short normal resistivity and others), sludge samples, conventional cores and sidewall cores have been obtained from all recent exploratory and production bores. These logs, together with palaeontological results from the cores, have been used to delineate the major aquifers and to make estimates of the salinities of the groundwater that they contain.

Chemical analyses of groundwater from the production and observation bores have been made and monthly head measurements from the observation bores have been measured and are recorded in the M.W.B. computerized groundwater levels retrieval system.

GEOLOGY

SETTING

The Perth area is situated on the eastern onshore edge of the Perth Basin (Playford and others, 1976). It is underlain by more than 10 000 m of sedimentary rocks

TABLE 11. SUMMARY OF EXPLORATORY DRILLING PROJECTS

Project	Commenced	Completed	Authority	No. of bores	Range of depth (m)	Aggregate depth (m)	Remarks
Byford Line	1961	1963	G.S.W.A.	6	183–265	1 351	One bore used for observation
Mandurah Project	1961	1969	G.S.W.A.	18	96–610	3 920	Exploratory project to locate Mandurah water supply
Pinjar Line	1964	1965	G.S.W.A.	7	348–699	3 839	Bores abandoned
Gingin Brook Line	1965	1966	G.S.W.A.	6	522–796	3 982	Bores abandoned
Whitfords Line	1973	1975	M.W.B.	8	90–800	3 298	Three sites; incorporated data from existing bores; observation bores in major aquifers
Woodmans Point Line	1975	1976	M.W.B.	8	67–800	3 196	Three sites; incorporated data from existing bores; observation bores in major aquifers
Becher Point Line	1976	1977	M.W.B.	10	71–810	4 588	Five sites; observation bores in major aquifers
Artesian Monitoring Network	1976	Continuing	M.W.B.	17	116–623	6 852	Sixty-eight sites proposed; observation bores in major aquifers
Wreck Point Line	1977	1977	M.W.B.	6	165–839	3 720	Four sites; observation bores in major aquifers

separated by the Darling Fault from crystalline rocks of the Darling Scarp. The area overlies the southern end of the Dandaragan Trough, a major structural subdivision within the basin.

STRATIGRAPHY

The sequence of formations in the Perth area has been established from deep water bores, regional geological mapping and oil exploration. Those formations occurring within the upper 1 000 m of the basin and which may contain, or affect the occurrence of, low-salinity confined groundwater are given in Table 12, together with a summary of their lithology and groundwater potential.

Formation into the Cockleshell Gully and Yarragadee Formations at sites where the South Perth Shale is thin or was not deposited.

Confined groundwater may be found locally in all the formations on the coastal plain. However, in this paper only the major aquifers in the Mesozoic formations are described.

The formations containing major confined groundwater resources are, in descending order, the Leederville, Yarragadee and Cockleshell Gully Formations. The formations are multilayer aquifer systems composed of interbedded sandstone, siltstone and shale and are separated from one another by thick confining beds formed by the Osborne Formation and South Perth Shale. They may be in hydraulic interconnection as a result of erosion, faulting, or non-deposition at recharge and discharge areas but elsewhere they form discrete flow systems.

TABLE 12. NEAR-SURFACE STRATIGRAPHIC SEQUENCE—PERTH AREA

	Formal age	Group	Formation	Maximum thickness (m)	*Lithology*	*Groundwater potential*
Cainozoic	Quaternary–Late Pleistocene	Kwinana	Various	90	Sand, limestone, clay	Major non-artesian aquifer
			UNCONFORMITY			
	?Quaternary		Rockingham Sand	110	Sand	Non-artesian aquifer
			UNCONFORMITY			
	Early Tertiary		Kings Park Fm	240	Siltstone, shale, minor sand	Confining bed
			UNCONFORMITY			
Mesozoic	Late Cretaceous	Coolyena	Poison Hill Greensand Gingin Chalk .... Molecap Greensand Osborne Fm	?10 55 ?20 160	Glauconitic sand, minor silt .... Chalk—fossiliferous and glauconitic Glauconitic sand .... *Glauconitic shale and siltstone;* minor sand	Minor aquifer Confining bed Minor aquifer *Major confining bed; local* aquifers near base
			?UNCONFORMITY			
	Early Cretaceous	Warnbro	Leederville Fm .... South Perth Shale (incl. Gage Sandstone member)	300 300	Sandstone, siltstone, shale .... Shale, siltstone, minor sand at base	Major artesian aquifer Major confining bed; minor aquifer at base
			UNCONFORMITY			
	Early Cretaceous–Early Jurassic		Yarragadee Fm	2 000	Sandstone, siltstone, shale	Major artesian aquifer
	Middle Jurassic		Cadda Fm	?350	Shale, siltstone	Confining bed, not definitely known
	Early Jurassic		Cockleshell Gully Fm	2 000	Sandstone, siltstone, shale	Local artesian aquifer

STRUCTURE

The Cockleshell Gully and Yarragadee Formations have a regional dip to the east. They have been extensively faulted and occur as a complex set of fault blocks.

The Warnbro and Coolyena Groups rest unconformably on the Cockleshell Gully and Yarragadee Formations. They appear to occupy synclinal basins which have been controlled by subsidence rather than by folding. The largest of these is the Swan Syncline separated by the Pinjar Anticline from the Yanchep Syncline (Fig. 16). The structures have a northeast-southwest trend and are not known to be faulted.

The Kings Park Formation is flat-lying and occupies deep channels (probably related to former positions of the Perth Canyon) locally eroded, to a depth of about 550 m below sea level, through the Coolyena and Warnbro Groups into the underlying Yarragadee Formation.

The Rockingham Sand also occupies channels eroded into the Kings Park Formation and the Coolyena and Warnbro Groups.

The flat-lying Kwinana Group rests unconformably on the post-Early-Cretaceous formations. It conceals them, so that the distribution and nature of the underlying formations have to be obtained by geophysical methods or from boreholes.

The subcrop of the various formations beneath the Kwinana Group, and sections illustrating the structure are given in Figure 16.

HYDROGEOLOGY

RELATIONSHIP OF AQUIFERS

The Perth area has an annual rainfall of about 865 mm. This, together with local run-off from the Darling Scarp and areas to the east, maintains regional bodies of unconfined groundwater in the Kwinana Group (Allen, 1976). From these, infiltration takes place into the Leederville Formation at sites controlled by the topography and the geological structure, and in turn from the Leederville

The groundwater in the formations is under pressure except locally at the intake. In low-lying areas, especially near the major rivers, flowing artesian bores may be encountered.

LEEDERVILLE FORMATION

Description of aquifer

The Leederville Formation is a predominantly non-marine formation becoming marine in the southwestern part of the area. It is up to 300 m thick and consists of sandstone, siltstone and shale. Beds of conglomerate are common in the formation near the Darling Scarp, and in its marine facies it contains some limestone and glauconitic sand. The lenticular beds of sand in the formation usually do not exceed a thickness of 10 m and do not persist over large areas. They comprise about half the formation and vary considerably in sorting, grain size, and clay content.

In hydraulic connection and included within the aquifer are beds of glauconitic sand locally present at the base of the Osborne Formation.

The aquifer system may be confined above by thick shales and siltstones of the Osborne Formation and below by the South Perth Shale. The aquifer extends throughout the coastal plain except near the Swan Estuary where it has been eroded out prior to deposition of the Kings Park Formation.

The Leederville Formation subcrops beneath the Kwinana Group over about half of the coastal plain where the Osborne Formation has been removed by erosion (Fig. 16). In these areas it is in direct contact and hydraulic connection with the Kwinana Group.

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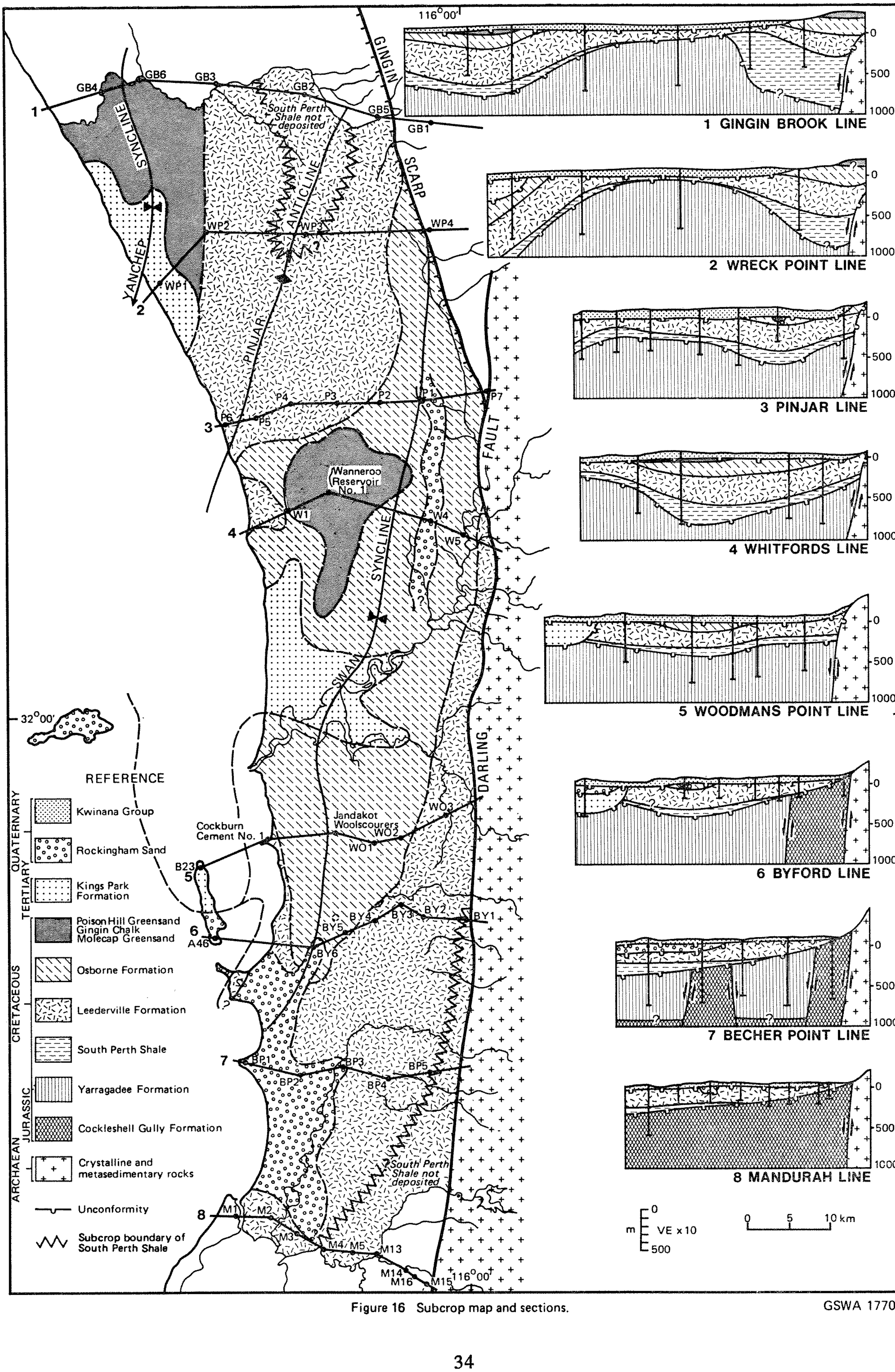

Figure 16 Subcrop map and sections.

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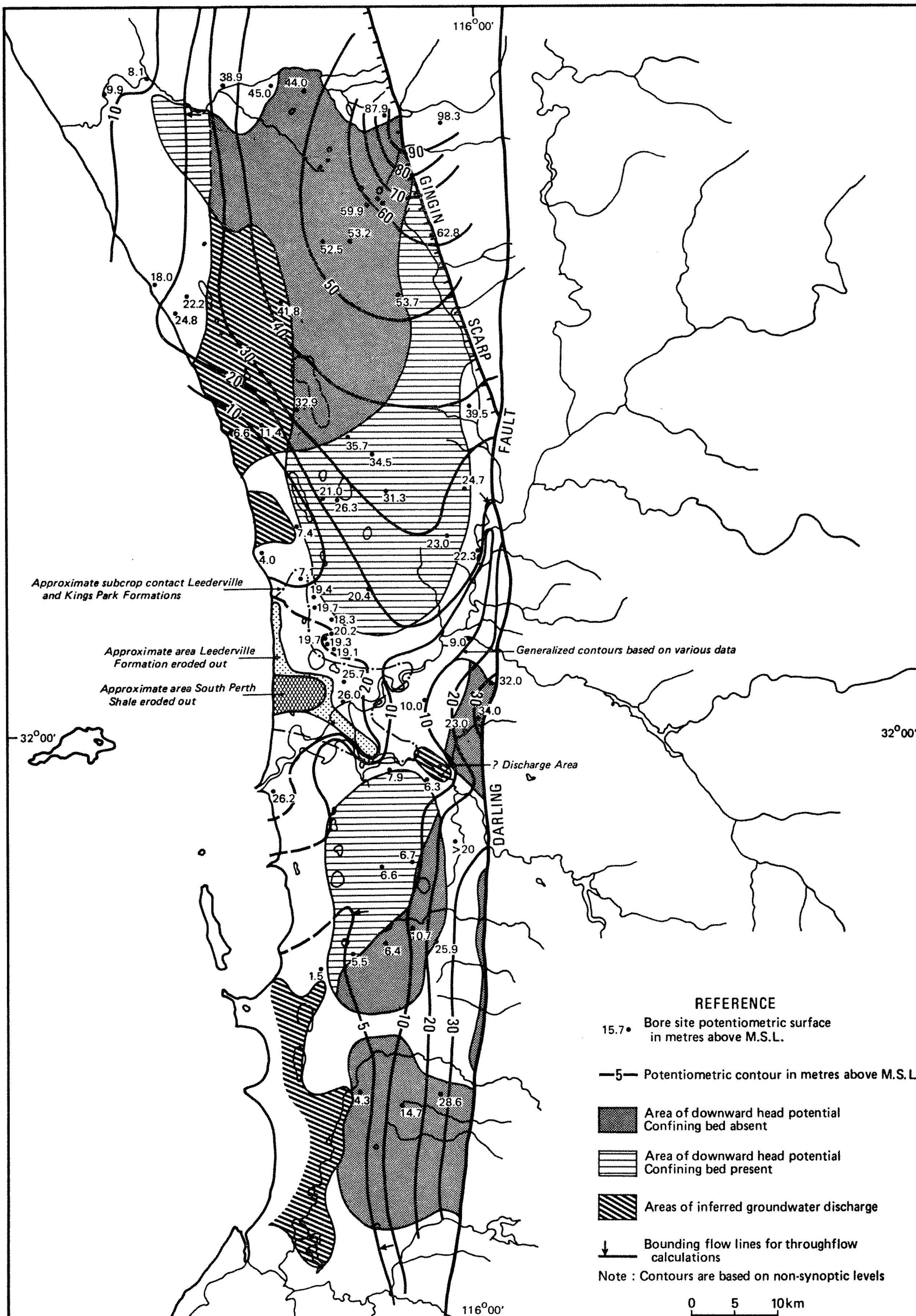

Figure 17 Leederville Formation, potentiometric contours and areas of recharge and discharge. GSWA 17708

On the crest of the Pinjar Anticline in the northern Perth area, and along the foot of the Darling Scarp in the southern Perth area (where the South Perth Shale was not deposited) it is in direct contact with the Yarragadee or Cockleshell Gully Formations (Fig. 31 Sections).

Recharge

Recharge to the formation is from the overlying Kwinana Group. The main recharge areas have been identified by overlaying the water table map for the Kwinana Group (Allen, 1976), potentiometric contours for the Leederville Formation, and the subcrop map. In the northern Perth area these occur in the northern central part of the coastal plain (600 km^2) and in the southern Perth area near the Darling Scarp (420 km^2). Small streams debouching on the Coastal Plain in the vicinity of Gingin and Serpentine may also provide recharge (Fig. 17). Other recharge occurs by upward leakage of groundwater from the Yarragadee Formation where the South Perth Shale has been eroded out near Perth. This is evident from equalized pressures in the two formations (Figs. 17 and 18) and from the chemical composition and temperature of groundwater from the Leederville Formation (Parr, 1927; Forman, 1933).

Reliable estimates of the recharge are not yet possible. In the northern Perth area the groundwater throughflow past the 20 m isopotential contour is estimated to be 75×10^6 m^3/y assuming half the formation is sand with an hydraulic conductivity of 10 m^2/d. Based on the same assumptions, groundwater flow past the 5 m contour in the southern Perth area is about 40×10^6 m^3/y. These estimates are considerably greater than would be expected from rainfall infiltration over the known recharge areas, suggesting that local streams may contribute substantially to recharge.

Storage

The area, thickness, and proportion of sand in the formation indicate that a very large volume of groundwater of variable quality is in storage within the aquifer. From isopachs of the formation (not given) the volume of the formation is estimated to be $650\,000 \times 10^6$ m^3. Assuming that half of this is sand with a specific yield of 0.10 then the volume of groundwater in storage in the formation is about $33\,000 \times 10^6$ m^3 of which about a third, $11\,000 \times 10^6$ m^3, may have a salinity less than 1 000 mg/L T.D.S.

Movement

The isopotential map (Fig. 17) indicates that groundwater flow is generally westward except near Perth and along the Swan River where there is eastward flow toward apparent discharge areas along the Swan and Canning Rivers. The configuration of the potentiometric surface is not well known in these areas and other interpretations may be possible.

The head in the aquifer system has a seasonal fluctuation of 1.5 m to 7.5 m. It is lowest in April-May and highest in October-November.

Discharge

Groundwater discharge from the Leederville Formation (Fig. 17) probably occurs between Lake Pinjar and Loch McNess, and near Mullaloo where the Osborne Formation has been removed by erosion and there is an upward head potential between the otherwise confined groundwater, and unconfined groundwater in the Kwinana Group. Other apparent discharge areas occur along the Swan valley near the Darling Scarp and in the vicinty of the Canning River. The most likely sites are at the contact between the Osborne Formation and Leederville Formation (Fig. 16). The apparent discharge area along the Canning River coincides with a notable area of saline groundwater in the Kwinana Group (Allen, 1976).

Groundwater discharge also takes place where the Rockingham Sand is deposited in a deep channel incised into the formation between Rockingham and Mandurah (Fig. 16, Section 7).

Artesian flows can be obtained along the lower areas associated with the Swan and Canning Rivers; the depression containing the linear lakes between Lake Joondalup and Loch McNess; and between Wungong Brook and Serpentine River.

Quality

Groundwater in the Leederville Formation ranges in salinity from about 180 to 3 000 mg/L T.D.S. The groundwater salinity is lowest at the intake areas and increases with depth and distance from these areas.

TABLE 13. SELECTED WATER ANALYSES

Bore Name	Chemical Lab. number	Sampling date	Conductivity mS at 20°C	pH	Turbidity APHA units	Colour HAZEN units	Odour	Free CO_2	T.D.S. Evap.	T.D.S. Cond.	Total hardness as $CaCO_3$	Total alkalinity as $CaCO_3$	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	SiO_2	Fe	Mn	Cu	Pb	As	F	B	P
								milligrams per litre																						
YARRAGADEE FORMATION																														
Whitfords No. 1	2335/75	5/2/75	340	9·0	10	<10	Oily	Nil	210	220	65	125	16	6	46	9	134	9	3	34	<1	18	·05	<·05	<·05	<·02	<·02	0·2	·10	·28
Mt. Yokine No. 1	6377/74	....	1 300	8·2	....	....	Nil	....	780	780	41	150	10	4	274	10	183	Nil	23	337	<1	19	·49	<·05	....	....	....	0·6	....	·28
Balcatta No. 1	6376/74	....	1 060	8·2	....	....	Nil	....	640	640	51	153	12	5	219	9	186	Nil	18	260	<1	21	·10	<·05	....	....	....	0·6	....	·10
Woodman Point No. 3	16524/76	14/7/76	5 450	7·5	<5	<5	Nil	17	3 000	3 490	203	273	30	31	1 070	32	332	Nil	144	1 520	<1	15	·15	<·05	<·02	<·01	<·01	1·3	<·05	·70
LEEDERVILLE FORMATION																														
Wanneroo No. 25	7961/73	12/4/73	700	6·6	<5	<10	Nil	28	420	490	91	57	17	12	113	10	70	Nil	25	190	<1	17	2·4	·15	<·05	<·02	<·02	0·2	·4	·23
Gwelup No. 135	13606/73	19/7/73	870	6·5	<5	<10	Nil	32	540	610	128	53	25	16	135	11	64	Nil	21	255	<1	19	13	·15	<·05	<·02	<·02	0·2	<·1	·01
Mounts Bay No. 1	4626/73	28/2/73	2 310	7·6	....	....	Nil	....	1 350	....	135	160	31	14	465	16	195	Nil	37	683	<1	18	·10	....	....	....	....	0·5	....	·01
Woodman Point No. 3	16042/76	8/7/76	400	6·5	<5	<5	Nil	41	230	260	31	65	4	5	66	4	79	Nil	8	75	<1	43	4·4	·28	<·02	<·01	<·01	0·1	·04	·14

The groundwater usually contains dissolved iron (0.2-15.0 mg/L) and may also contain manganese, both of which may require treatment before the water can be used for public water supply. Four selected analyses of groundwater from the Leederville Formation are given in Table 13.

The temperature of the groundwater in the Leederville Formation varies from 23.0 to 32.0°C. It shows a general increase with depth but is warmest near Perth as a result of mixing with warm water from the Yarragadee Formation.

Development

There are currently 15 M.W.B. production bores in the formation and about 400 private bores, principally in low-lying areas such as the Swan Valley where large supplies of unconfined groundwater are not available. The formation is about 100 m to 300 m deep through most of the Perth area. Bores in it are usually constructed to produce moderate to large supplies for public water supply, reticulation of public reserves, irrigation and industry. Annual usage varies with the seasonal conditions but is estimated to average about $18 \times 10^6 m^3/y$, of which about 10×10^6 m^3/y are pumped by the M.W.B.

The present abstraction is only about 15 per cent of the estimated throughflow and consequently production from the aquifer could be considerably increased.

YARRAGADEE FORMATION

Description of aquifer

The Yarragadee Formation is about 2 000 m thick. It consists of non-marine interbedded sandstone, siltstone and shale. The beds of sandstone are frequently up to 30 m thick and usually consist of medium to very coarse, feldspathic, subangular weakly-cemented sand. The formation also contains thick pyritic and micaceous siltstone as well as thin-bedded sections of rapidly alternating sandstone and siltstone.

The discontinuous Gage Sandstone Member at the base of the South Perth Shale contains groundwater in hydraulic connection with the Yarragadee Formation and for this reason is considered as part of the Yarragadee aquifer system.

Groundwater in the formation is possibly confined below by the Cadda Formation, and is confined above by the South Perth Shale. It is in hydraulic continuity with groundwater in the Leederville Formation where the South Perth Shale is absent on the crest of the Pinjar Anticline, and adjacent to the Darling Scarp in the southern Perth area. In the latter area there is probably also hydraulic continuity between adjacent fault blocks of the Yarragadee and Cockleshell Gully Formations.

The Yarragadee Formation extends throughout the Perth area at a depth of 200 m to 500 m below sea level, except in part of the southern Perth area, where it has been removed by erosion (Fig. 18).

Recharge

Recharge to the Yarragadee Formation is by downward leakage from the Leederville Formation where the South Perth Shale is absent. The approximate extent of the intake areas was determined by overlaying the isopotential maps for the Yarragadee and Leederville Formations and comparing them with the known extent of the South Perth Shale. The only intake area that has been identified is approximately 80 km^2 on the crest of the Pinjar Anticline (Fig. 18). In this area groundwater throughflow past the 40 m isopotential is about $13 \times 10^6 m^3/y$, assuming the low-salinity groundwater occurs in the upper 200 m of the aquifer, and that half the formation was sand with an hydraulic conductivity of 10 m^2/d. This throughflow appears too large to result only from recharge over the intake area, and presumably some of the groundwater is derived from further north or from recharge by local streams.

Storage

There is insufficient data to estimate the very large volume of groundwater in storage in the Yarragadee Formation. Most of this groundwater is brackish except in the northern Perth area where the upper 200 m (Whincup, 1966) of the Yarragadee Formation over an area of about 750 km^2 contains groundwater with a salinity less than 1 000 mg/L T.D.S. Assuming that half the formation is sand with a specific yield of 0.10 then the volume of groundwater in storage less than 1 000 mg/L T.D.S. is about $7\,500 \times 10^6 m^3$.

Movement

The regional groundwater movement is toward the southwest (Fig. 18). The configuration of the potentiometric surface near Perth is uncertain but does not appear to reflect any major lowering of the potentiometric surface resulting from pumping or discharge into the Leederville Formation.

The potentiometric surface is generally 5 m to 25 m higher in the northern Perth area than in the southern Perth area reflecting the effect of the regional topography. In the southern Perth area the potentiometric surface has a very low gradient, probably reflecting slow rates of recharge and a high transmissivity for the formation (Allen, 1978).

The potentiometric surface varies in phase with the rainfall. It reaches its lowest level in March-April and highest level in September-October. Under natural conditions it may vary seasonally by about 5 m.

Discharge

The chemical composition and temperature of the groundwater (Forman, 1933) together with equalization of potentiometric heads between the Yarragadee and Leederville Formations near Perth (Figs. 17 and 18) indicate that groundwater discharge takes place possibly along preferred paths around the contact with the Kings Park Formation where the South Perth Shale has been eroded away.

Groundwater discharge may also occur offshore. A large submarine spring reported at 'Fish Rock' or 'The Dummies' on the Fremantle side of the Parmelia Bank near Woodman's Point (Christie, 1912a, b) may be a discharge site. The spring is reputed to have been seen disturbing the surface of the sea between 1879 and 1907 and to have ceased flowing as a result of pumping artesian bores around Perth. Its reported location is close to the inferred contact with the Kings Park Formation.

A hot 'spring' formerly located on the foreshore of the Swan River near Sunset Men's Home in Dalkeith resulted from the escape of groundwater from a bore completed in the Yarragadee Formation. The bore was drilled in 1908 and was finally plugged in 1956.

Flowing artesian bores can be expected at most sites with an elevation less than 25 m R.L., with the exception of parts of the southern Perth area.

The upward head differential between the Yarragadee and Leederville Formations has caused some interaquifer flow within boreholes. Changes in salinity described by Parr (1927) occurring in Loftus Street No. 1 and No. 2 bores may be attributed to this, as well as variations in salinity observed in Mounts Bay No. 1 bore.

Quality

Groundwater in the Yarragadee Formation ranges in salinity from 120 to 7 500 mg/L T.D.S. with an average salinity of about 3 000 mg/L T.D.S. Groundwater with a salinity less than 1 000 mg/L is restricted to the northern Perth area in a poorly defined strip extending from about Perth northwards to near Gingin. The distribution of the low-salinity groundwater may result from a preferred flow path between the intake area and the discharge area near Perth.

The low-salinity groundwater occurs in the upper 200 to 500 m of the formation. The lowest salinity groundwater obtained is 120 mg/L T.D.S. from near Lake Pinjar. This is the lowest salinity groundwater known from any aquifer in the Perth area and may be groundwater recharged during past conditions of higher rainfall.

In offshore oil exploration wells and beneath Rottnest Island the groundwater in the formation is believed to have a salinity of 7 500 to 60 000 mg/L T.D.S. (Playford and Leech, 1977).

Unlike groundwater from the other major aquifers in the Perth area the groundwater from the Yarragadee Formation usually has a very low concentration of dissolved iron and does not require treatment. Selected analyses from the Yarragadee Formation are given in Table 13.

The temperature of groundwater from the formation ranges from 21° to 44°C. It is warmest in the vicinity of Perth and coolest in bores of the Becher Point Line in the southern Perth area.

Development

The depth at which the Yarragadee Formation occurs, and legislation restricting depth of bores to 150 m below sea level in the Metropolitan area, have ensured that the formation is mainly used for public water supply. The

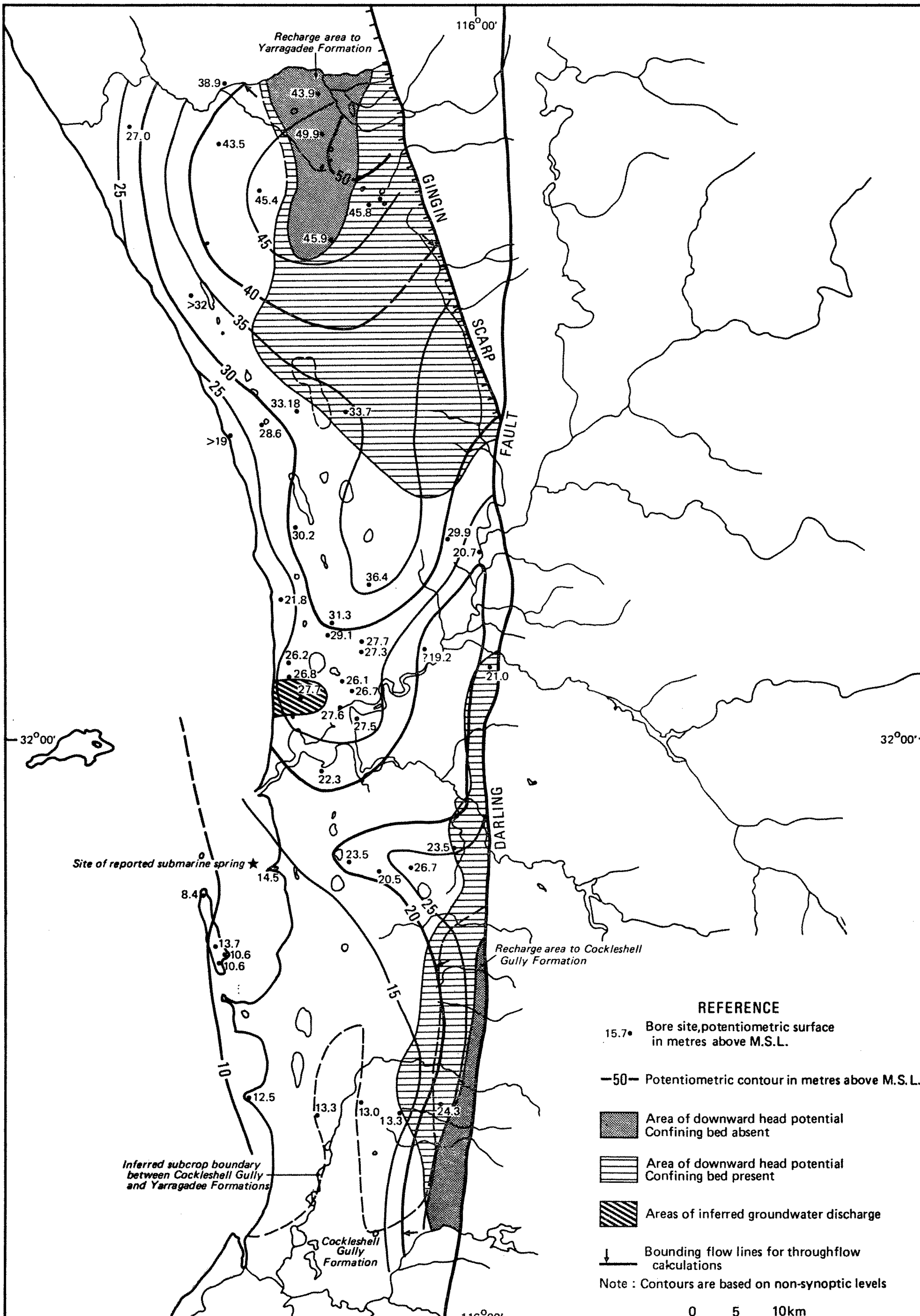

Figure 18 Yarragadee Formation, potentiometric contours and areas of recharge and discharge. GSWA 17709

M.W.B. has 12 production bores in the formation and there are 4 private bores. Six former deep bores in the formation have been plugged and abandoned.

The present annual abstraction from the formation varies depending on seasonal conditions. It is estimated that the present average production is about 10 x 10^6 m^3/y of which 8 x 10^6 m^3/y is by the M.W.B.

Since 1970 abstraction has caused the potentiometric head in the aquifer to decline at a rate ranging from 0.2 to 2.3 m/y. The cause of this has been the commissioning of new bores and the fact that abstraction is concentrated within an area of only 300 km^2. Some pumping water levels are below sea level but on cessation of pumping the potentiometric head recovers to above sea level. This indicates that there is only localized lowering of the potentiometric surface and no immediate danger of sea-water intrusion.

The exploratory drilling has proven the existence of a large volume of groundwater with a salinity less than 1 000 mg/L T.D.S. in the northern Perth area. The throughflow calculations indicate scope for further abstraction from this resource. In addition there are extremely large brackish-water resources which may also be developed.

COCKLESHELL GULLY FORMATION

Description of aquifer

The Cockleshell Gully Formation is about 2 000 m thick. It consists of non-marine interbedded sandstone, siltstone, coal measures, and shale which locally may be up to 300 m thick. The sandstones are usually slightly clayey, medium to coarse, and occur in beds up to 30 m thick.

The formation extends at depth throughout the Perth area but is at shallow depth and prospective for groundwater only in the south and southeast of the southern Perth area. It is extensively faulted so that the Yarragadee Formation may be brought into juxtaposition with it as shown by drilling on the Becher Point Line (Fig. 16). Near Mandurah the Cockleshell Gully Formation is overlain by the South Perth Shale, while further to the east it is directly overlain by the Leederville Formation (Allen, 1978).

Recharge

Recharge to the aquifer is by vertical leakage from the Leederville Formation and is inferred to occur over an area of about 60 km^2 (Fig. 18) adjacent to the Darling Scarp between about Serpentine and Pinjarra (Allen, 1978). Groundwater throughflow past the 25 m contour is estimated to be 35 x 10^6 m^3/y assuming the low salinity groundwater is in the upper 300 m of the formation (Allen, 1978), and that half the formation is sand with an hydraulic conductivity of 10 m^2/d. Some of the throughflow may originate from additional recharge from streamflow, and possibly a small amount from lateral leakage across the Darling Fault.

Storage

The subsurface area of the Cockleshell Gully Formation which contains groundwater with a salinity less than 1 000 mg/L T.D.S. is not known. In Becher Point No. 5 low salinity water extends to a depth of about 300 m in beds of sandstone with an aggregate thickness of about 100 m. This suggests that a fairly substantial groundwater resource may be present in the vicinity.

Movement

Groundwater in the Cockleshell Gully Formation is believed to be in hydraulic continuity with groundwater in the Yarragadee Formation (Fig. 18). Groundwater movement is presumably westward though it is possible that faulting may have produced a groundwater compartment in which the flow may be southwestward towards Pinjarra.

Discharge

Groundwater discharge occurs, via the Yarragadee Formation and overlying formations, offshore.

Quality

Groundwater in the formation on the Becher Point Line ranges from about 270 to 3 000 mg/L T.D.S. (Allen, 1978). Uncontaminated samples from the formation have not yet been obtained and consequently the dissolved iron content is not known.

Development

Apart from about 6 low-yielding private bores the formation is undeveloped. Further south near Pinjarra (Forth, 1974) the Alcoa Alumina Refinery abstracts about 2 x 10^6 m^3/y and has caused a large and widespread lowering in the potentiometric surface.

CONCLUSIONS

The assessment of the exploratory drilling carried out so far has provided a general understanding of the geology and the occurrence, size and extent of the confined groundwater resources. More reliable quantitative assessment of the resources and the solution of some remaining hydrogeological problems should be possible when drilling is completed for the artesian monitoring network.

Tentative calculations indicate that the confined aquifers have an aggregate throughflow of about 163 x 10^6 m^3/y and contain, in storage, more than 18 500 x 10^6 m^3 of groundwater with a salinity less than 1 000 mg/L T.D.S. In addition there are extremely large brackish groundwater resources, particularly in the Yarragadee Formation.

On the basis of the throughflow calculations possibly 50 to 180 x 10^6 m^3/y of groundwater could be abstracted from the confined aquifers, compared with the present abstraction of about 30 x 10^6 m^3/y. The remainder would be necessary to stabilize the saltwater interface. Considerably larger volumes of groundwater could be obtained if there was deliberate mining of the resources.

ACKNOWLEDGEMENTS

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SEDIMENTOLOGY OF THE TUMBLAGOODA SANDSTONE (SILURIAN) IN THE LOWER MURCHISON RIVER AREA, WESTERN AUSTRALIA: A PRELIMINARY INTERPRETATION

by R. M. Hocking

ABSTRACT

The Tumblagooda Sandstone is a thick sandy "red-bed" sequence of Silurian age which is present in the northern Perth Basin and most of the western portion of the Carnarvon Basin. Sedimentation was dominated at all times by terrigenous clastic material, which in the southern Carnarvon Basin was derived from a tectonically active source to the southeast on the Yilgarn Block. Varied sedimentary structures, trace fossils, and grain-size characteristics enable four broad facies to be distinguished. These can be equated to low-input braided fluviatile, high-input braided fluviatile, high-input tidal-flat, and tidally influenced shallow-marine environments. Sedimentation oscillated between these environments and produced a sequence greater than 3 000 m thick before the advent of chemical and evaporite sedimentation in the Late Silurian.

INTRODUCTION

The Tumblagooda Sandstone is a "red-bed" sequence which consists of feldspathic to quartz arenites with subordinate siltstones and granule to pebble conglomerate. It is only exposed in the northern Perth and southern Carnarvon Basins between the Geraldton and lower Murchison River areas (Fig. 19), and has only been penetrated by bores north of the area of outcrop, the northernmost being Wandagee 1 in the central Carnarvon Basin. The overlying Dirk Hartog Formation was penetrated in Marrilla 1 and Pendock 1, suggesting that the Tumblagooda Sandstone may extend as far north as Exmouth Gulf. It has been studied by several workers (Clarke and Teichert, 1948; Condon, 1965; Johnstone and Playford, 1955; Playford and others, 1976) as part of regional projects, but no detailed or semi-detailed analysis of sedimentary structures and depositional environments has been attempted apart from the unpublished thesis of Mandyczewsky (1973). The present paper presents a preliminary interpretation of the depositional environments of the Tumblagooda Sandstone as exposed on the Ajana Sheet.

No body fossils are known from the Tumblagooda Sandstone in outcrop. The Dirk Hartog Formation overlies the Tumblagooda Sandstone with apparent conformity in Dirk Hartog 17B and is of Late Silurian age (Philip, 1969). Microfossils from the upper part of the Tumblagooda Sandstone in Wandagee 1 are of probable Silurian

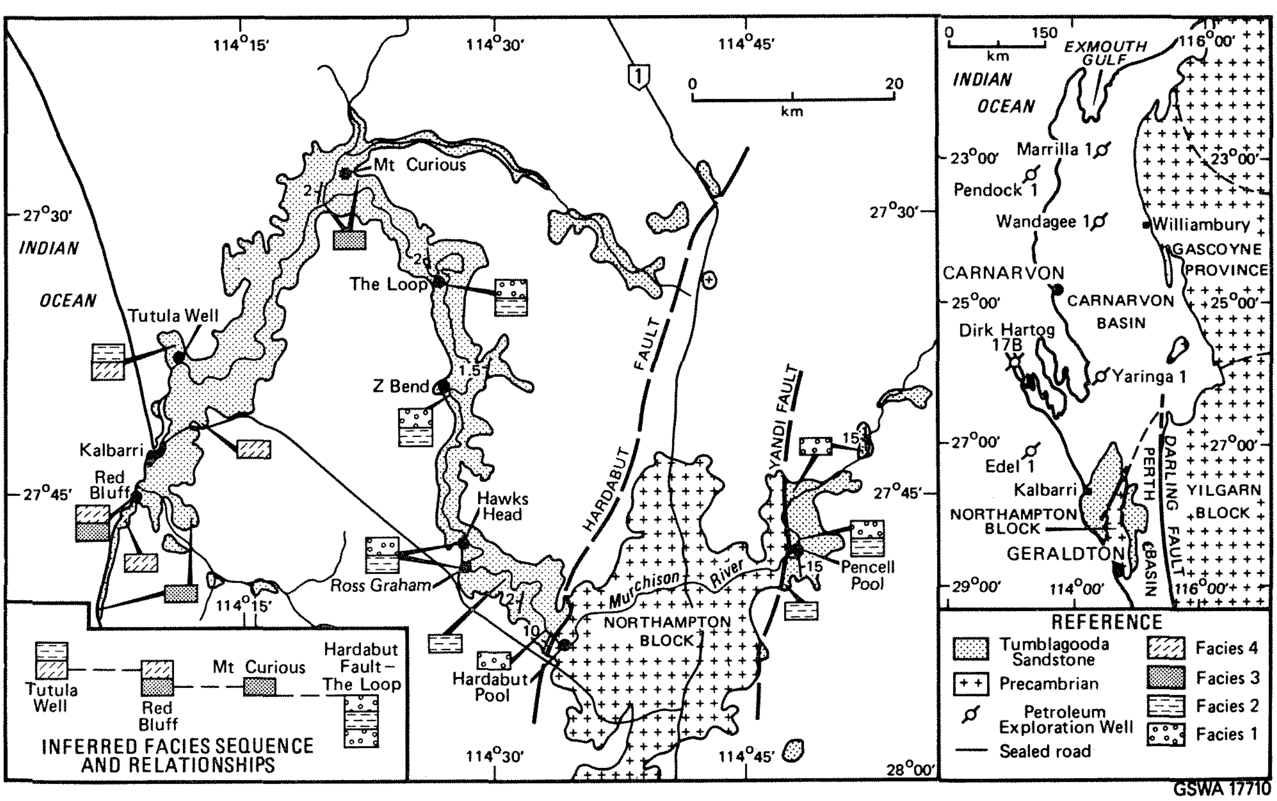

Figure 19 Outcrop distribution of the Tumblagooda Sandstone in the Perth and Carnarvon Basins, and constituent facies (where known) on Ajana Sheet.

age (B. E. Balme, *in* Playford and others, 1976), but the lower parts of the Tumblagooda Sandstone have not been dated and may conceivably be as old as Ordovician.

The base of the Tumblagooda Sandstone has not been penetrated by any oil or water wells, and is not exposed on the Ajana Sheet. On the Geraldton Sheet to the south, the Tumblagooda Sandstone crosses the Hardabut Fault (Fig. 19) without disruption, to rest directly on rocks of the Northampton Block, but a gravity survey indicates a significant thickness of sediments on the western, downthrown side of the fault beneath the outcropping Tumblagooda Sandstone (Playford and others, 1976). Thus the onlap of Tumblagooda Sandstone onto the Northampton Block might represent a limited transgression across the Hardabut Fault after cessation of the major period of movement on this fault. (As expressed now on Ajana Sheet, the Hardabut Fault reflects a later, but minor, period of reverse movement during Cainozoic times, which uplifted the block west of the fault and formed the Hardabut Anticline.)

The type section, along the Murchison River downstream from the Hardabut Fault, is 1 070 m thick, and the thickest drilled section, 2 500 m, is in Edel 1, where the depth to magnetic basement is about 4 000 m (Megallaa, in prep.). East of the Northampton Block, Johnstone and Playford (1955) measured a poorly exposed section of Tumblagooda Sandstone more than 3 500 m thick.

FACIES WITHIN THE TUMBLAGOODA SANDSTONE

The Tumblagooda Sandstone is divisible into four broad facies, based on exposures west of the Hardabut Fault. Diagrammatic sections of these facies, showing significant sedimentary features, and their distribution, relationships and order of succession (where known) are shown in Figures 19 and 20. Palaeocurrent patterns for each of the facies are shown in Figure 21. There is a fault south of Mount Curious, of unknown magnitude, which may affect the relationships between the eastern and western parts of the sequence, but movement on the fault is here assumed to be minor, and facies are extrapolated across it.

Facies 1

This consists of medium-grained, well-sorted and rounded, felspathic sandstone to quartz sandstone, with sporadic quartz granules and pebbles in more westerly exposures. In eastern exposures, as at Pencell Pool, the grain size and pebble content is greater, and some coarse lenses are present. The facies is ubiquitously crossbedded, with foresets in places oversteepened. Crossbedding is at two scales: small cross-sets 20 cm thick, and large troughs up to 10 m thick consisting of a number of smaller cross-sets. Palaeocurrents, measured mostly on trough cusps, are very consistent and have a mean direction of 315°. Scouring at the base of cross-sets is common, but there is minimal scouring on a local scale at the basal contact of the facies with the underlying Facies 2 between the Loop and Hawks Head. No trace fossils have been found.

The unimodel, low-scatter palaeocurrent pattern of this facies is suggestive of a low-sinuosity, braided fluviatile environment (Selley, 1968). The textural maturity of the sandstone is atypical of fluviatile deposits, but the hydrologic conditions which prevailed in the Silurian offer one explanation. Schumm (1968) argued that in these conditions, prior to the appearance of significant terrestrial vegetation, wide braided streams proliferated with unconfined channels downstream from source areas. With only moderate sediment input, alluvial deposits would have been constantly levelled and sorted as streams moved over and down the slopes, producing relatively mature sands. This process would have been accentuated in the Tumblagooda Sandstone, which with its large areal extent could not have had a consistently high palaeoslope. Oversteepening of cross-sets could be partially due to downcurrent drag during flooding, and partially due to earthquake shocks temporarily fluidizing waterlogged sand (Hendry and Stauffer, 1977; Allen and Banks, 1972).

A second explanation is to consider that some of the sand in Facies 1 was derived from the weathering of already mature sandstones of the Badgeradda Group or other Proterozoic sandstones marginal to the Yilgarn Block, although the feldspar content of Facies 1 sandstones renders this explanation less likely.

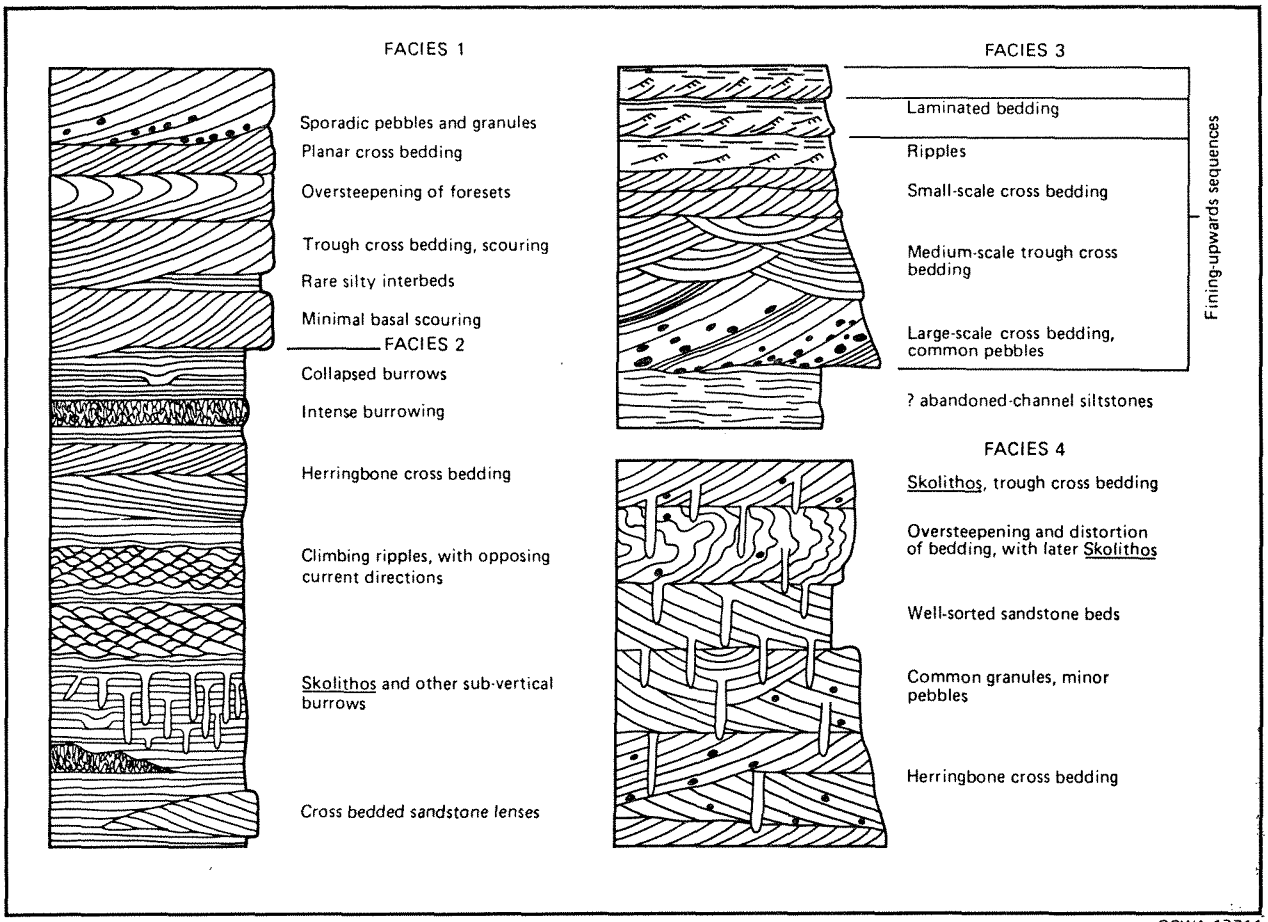

Figure 20 Diagrammatic sections of facies within the Tumblagooda Sandstone, showing diagnostic features. Scale variable.

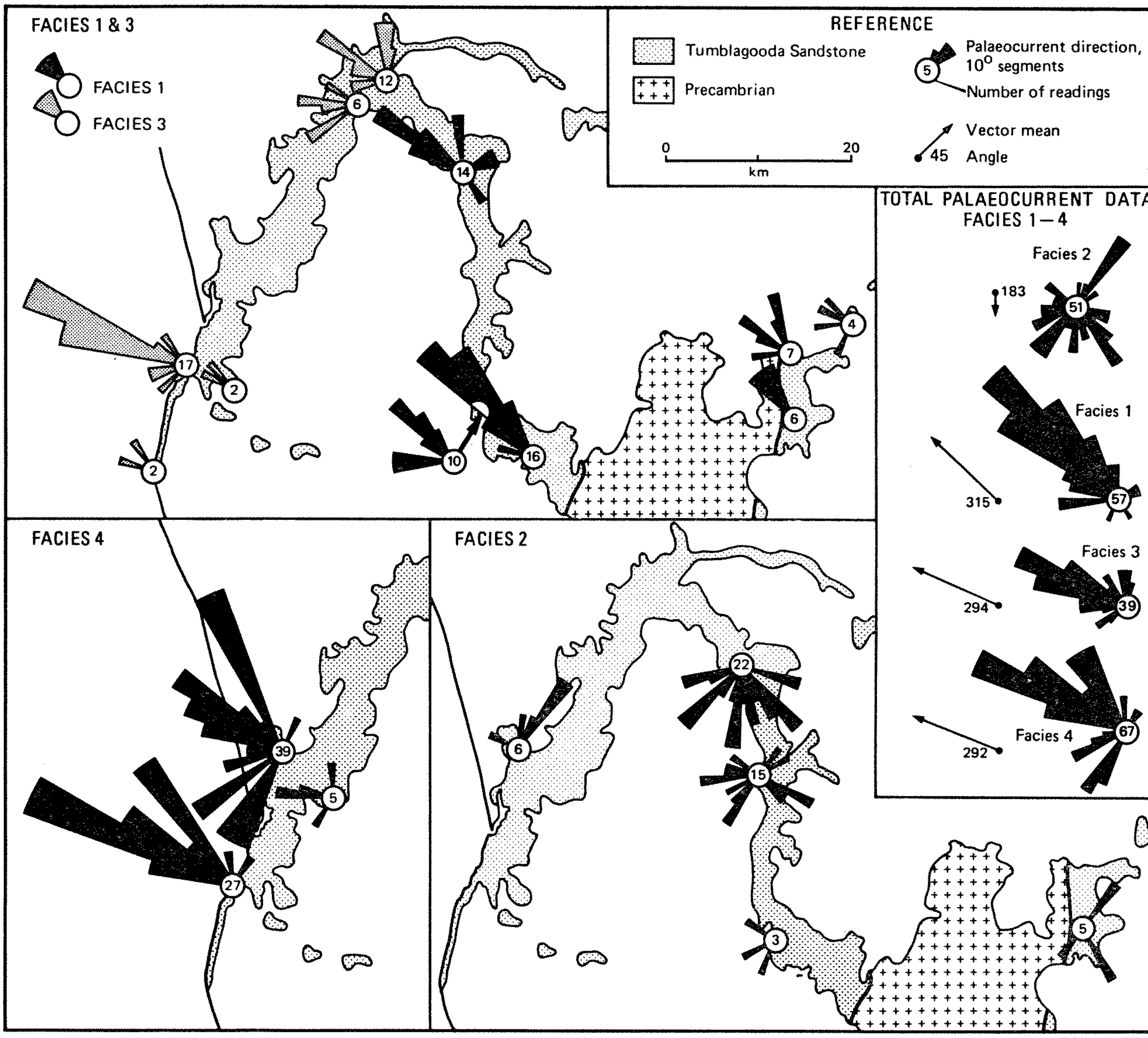

Figure 21 Palaeocurrent patterns within the Tumblagooda Sandstone. Length of arc segments proportional to number of readings.

Facies 2

This consists of thin-bedded, red and white silty sandstone and fine-grained sandstone, with some cross-bedded lenses. Some beds are intensely bioturbated, mostly by vertical and subvertical burrows, and discrete *Skolithos* tubes, *Cruziana* furrows, *Protichnites* trails, *Rusophycus* resting hollows, *Teichichnus* burrows and *Diplocraterion* tubes (Opik, 1959) are present within the facies. Sedimentary structures not shown in Figure 20, and exposed at the Z Bend, include setulfs, which are similar to flutes but with positive relief from the bedding plane (Friedman and Sanders, 1974), and considerably d.storted bedding within a sandstone lens. "Windmarks" described by Mandyczewsky (1973) are probably setulfs.

Trace fossils in Facies 2 belong to the *Skolithos* and *Cruziana* ichnofacies of Seilacher (1967). All burrows are high-angle shelter burrows, and trails show no systematic grazing pattern. These suggest shallow-marine conditions, near to and above wave-base, grading into intertidal conditions, using the modified ichnofossil zonation of Heckel (1972). The sedimentary structures support this interpretation. Herringbone cross-stratification indicates opposing current directions (Klein, 1977) which in Facies 2 are probably tidal. The composite palaeocurrent rose for Facies 2 (Fig. 21) clearly illustrates the multiplicity of opposing current directions, and sheds further light on the depositional environment of Facies 2 when compared to the roses for the fluviatile-dominated portions of the Tumblagooda Sandstone. Assuming that the dominant fluviatile trend reflects the palaeoslope, and that the coastline was perpendicular to the palaeoslope, the southeasterly pointing trend of Facies 2 suggests currents normal to the shoreline during deposition. The southwest-northwest trend may reflect alternating longshore currents, and combined with the small southerly vector mean (Fig. 21) suggests that currents during deposition moved primarily north-south at a low angle to the shoreline, rather than directly onshore. Climbing ripples indicate a periodically strong sediment supply, and herringboned climbing ripples a periodically strong supply in a tidal situation. The setulfs described by Friedman and Sanders occurred on emergent tidal flats, and those in the Tumblagooda Sandstone may also indicate subaerial exposure, but there is no other evidence of emergence within Facies 2. Cross-bedded sandstone lenses within the facies may be winnowed tidal-channel sands, and the d.storted bedding within one at the Z Bend possibly resulted from an earthquake which triggered gravity sliding.

Facies 3

This consists of coarse- to fine-grained, generally poorly sorted sandstone, with significant siltstone and claystone interbeds, and contains several fining-upwards cycles. These cycles fine upwards both in grain-size and in the scale of the bedding. Palaeocurrents are unimodel, with a vector mean of 294° (Fig. 21). The poor sorting, variable grain size, and fining-upwards sequences in this facies suggest a fluviatile environment. The section exposed at Red Bluff is very similar to one figured in Reineck and Singh (1973, Fig. 358) from a braided-alluvial environment, and siltstone beds were probably abandoned channels. Less reworking of the sediments occurred than in Facies 1 because of higher sediment input. This may have resulted from greater tectonic activity in the source area, or from subsidence of the depositional area, which would have increased stream energy.

Facies 4

This consists of medium- to coarse-grained, poorly sorted feldspathic to quartzose sandstone, with common quartz granules and minor siltsone. It is ubiquitously trough cross-bedded, with some cross-sets oversteepened and distorted, and through most of the facies palaeocurrents were to the northwest. However, cross-sets in sporadic better sorted sand lenses indicate opposing palaeocurrents which trend north-northeast and south-southwest (Fig. 21). Large-scale scouring at the base of the troughs is visible at Red Bluff. *Skolithos* tubes are common, and near Tutula Well they cut through oversteepened cross-sets.

The presence of *Skolithos* tubes indicates that there was marine influence during deposition of this facies, but the coarse grain-size and poor sorting indicate significant differences between this environment and that of Facies 2. A high-energy, braided transport system with heavy sediment load and some marine influence appears necessary. This could occur where a braided fluviatile system was partially drowned by marine incursion, offering enough marine influence to support the animals which made *Skolithos* tubes and to occasionally rework some sediment, but not enough to rework the poorly sorted deposits.

Hereford (1977, facies E) postulated a tidal flat environment, as a whole, with high-energy braided streams continuing from nearby rivers, for apparently similar parts of the Tapeats Sandstone. Fining-upwards sequences at the top of this facies near Tutula Well may have formed in semi-confined tidal channels similar to Hereford's facies D, and represent a transition into the overlying, well-sorted, tidally deposited sandstones and siltstones of Facies 2.

SILURIAN PALAEOGEOGRAPHY

The palaeocurrent pattern for Facies 1, 3 and 4 of the Tumblagooda Sandstone is unequivocal (Fig. 21). The palaeoslope was to the northwest, and the Tumblagooda Sandstone in the area of the outcrop had a southeasterly source. In marine parts of the unit, the dominant current and sediment transport direction was subparallel to the presumed coastline (a line from south-southwest to north-northeast), with tidal influence more in a north-south than in an east-west direction. Mandyczewski (1973) obtained similar results, with a palaeocurrent azimuths of 282°, 20° and 169°, and 303° respectively in his equivalents of Facies 1, 2 and 3, and 4.

With the high feldspar content of much of the sandstone, a granitic source on the Yilgarn Block can be postulated, possibly with some input from Gascoyne Province rocks as significant tourmaline is present and the Gascoyne Province is tourmaline-rich. Streams feeding the Tumblagooda Sandstone may also have passed through some Proterozoic sandstones and provided second-generation sand which was incorporated in the texturally mature sandstone of Facies 1.

There is no apparent deflection of palaeocurrents around the Northampton Block, and no trace of garnet within the Tumblagooda Sandstone. As the Northampton Block is garnet-rich (Prider, 1958), traces of garnet could reasonably be expected in the Tumblagooda Sandstone if the block was exposed to erosion during deposition of the formation. These two facts indicate that the Northampton Block was not a major topographic feature which influenced sedimentation of the Tumblagooda Sandstone. However, rates of deposition may have been less on the block than in surrounding areas if the bounding faults moved during deposition, as seems likely.

The red colouration of much of the Tumblagooda Sandstone is, as Playford and others (1976) noted, one of its most distinctive features. This indicates that during deposition sediments were subject to strongly oxidizing conditions (Reineck and Singh, 1973). The continental origin postulated for many red-bed sequences cannot be applied to the Tumblagooda Sandstone, as the marine sediments of Facies 2 are among the reddest parts of the sesquence.

On Ajana Sheet, the throw of the Darling Fault exceeds 3 000 m, and the time of movement is probably entirely pre-Permian (Playford and others, 1976; Hocking and others, in prep.), but at least some movement postdates deposition of the Proterozoic Badgeradda Group and Nilling Beds. It seems reasonable that much of the movement took place during the deposition of the Tumblagooda Sandstone, as Playford and others (1976) suggested, and that the Darling Fault where present marked the eastern margin of the Silurian depositional basin. This fault trends approximately north-south, and palaeocurrent data indicate a palaeoslope oblique to this line. With the absence of the Tumblagooda Sandstone from bores south of Geraldton, this suggests that the present area of outcrop was quite close to the southern end of the depositional basin. In this area, streams would approach the basin from the south as well as the east, and palaeocurrent directions are interpreted as showing this.

GEOLOGICAL HISTORY

The lowermost exposed sediments of the Tumblagooda Sandstone on Ajana Sheet are relatively mature, syndepositionally reworked sandstones (Facies 1) which were deposited in a braided fluviatile environment. Much if not all of the underlying sequence was probably deposited by braided streams, and may be less mature.

A marine transgression ended this fluviatile phase, and deposition commenced in a broad, shallow-marine basin, primarily above wave-base and frequently in tidal conditions (Facies 2). There was considerable biological activity on the sea-floor, although all body fossils were destroyed, probably by the strongly oxidizing conditions.

Marine sedimentation waned, and was followed by a second phase of braided fluviatile deposition (Facies 1, repeated). The topmost marine sediments may have been removed by erosion and planation on a regional scale, because the contact is abrupt although only minimally scoured on a local scale. During this fluviatile phase, rejuvenation of the source area occurred and stream power increased. Less reworking of previous deposits took place, and less mature fluviatile sediments were deposited (Facies 3).

Subsequently, the sea level rose, relative to the land, either through eustatism or as a result of basin subsidence, and high-energy paralic sediments were deposited (Facies 4). This period was relatively brief, and transitional into another phase of shallow-marine, tidally influenced sedimentation (Facies 2, repeated).

Terrigenous input continued to dominate sedimentation until the Late Silurian, when supply waned, and chemical sediments of the Dirk Hartog Formation were deposited. These are predominantly dolomitic, but contain some evaporites, limestone and mudstone (Shannon, 1966). They are probably near-shore to sabkha deposits.

CONCLUSIONS

Present evidence suggests the Tumblagooda Sandstone was deposited in mixed shallow-marine and terrestrial environments, with deposition oscillating between high-input braided fluviatile, and tidally influenced, shallow-marine environments.

Palaeocurrents in fluviatile portions of the formation are very consistent and unimodel, indicating a northwesterly facing palaeoslope, whereas palaeocurrents in the marine portions are polymodal, and suggest that the dominant tidal influence was oblique rather than perpendicular, to the shoreline.

Sedimentation was at all times dominated by terrigenous clastics, which in the southern Carnarvon and northern Perth Basins initially originated from a southeasterly source on the Yilgarn Block, as palaeocurrent and compositional data do not indicate that the Northampton Block influenced sedimentation. The Darling Fault probably formed the eastern margin of the basin, and the main tectonic activity during sedimentation was probably centres on this fault.

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PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1978

by K. A. Crank

ABSTRACT

There was a significant increase in petroleum exploration activity in Western Australia during 1978.

Fifteen exploration wells were completed compared with eight in 1977, and one was drilling ahead at the end of the year, for a total penetration of 48 100 m, an increase of 12 771 m, or 36 per cent, compared with the previous year. Expressed in rig months, however, drilling operations were 10.3 per cent less than in 1977. Drilling was mainly offshore, in the Perth, Carnarvon, Canning, Browse and Bonaparte Gulf Basins, although three onshore wells were completed, one in the Perth Basin and two on Barrow Island. Seven development wells were completed on Barrow Island. No major discoveries were made during the year although gas shows were reported in several wells.

Geophysical activity, consisting mainly of marine seismic surveys, increased about 700 per cent compared with 1977. This increase occurred mainly on the newly granted deep-water Exmouth Plateau permits, where 25 314 line kilometres of seismic surveys were shot.

INTRODUCTION

Exploratory drilling for petroleum in Western Australia over the past two years is illustrated in the following table (excluding the aborted Geelvink No. 1 well, which was abandoned at 1 268 m and was replaced by Geelvink No. 1A). No discovery wells were drilled in 1978.

Type of Well	Wells completed		Wells drilling on 31 December	
	1977	1978	1977	1978
New Field Wildcats	7	13	3	0
New Pool Wildcats	0	2	0	0
Extension Tests	1	0	0	1
Total	8	15	3	1

Total effective drilling: 1977—35 339 m
1978—48 110 m

Geophysical survey and surface geological survey activity for 1978 is shown below. Figure 22 summarizes the seismic activity since 1967.

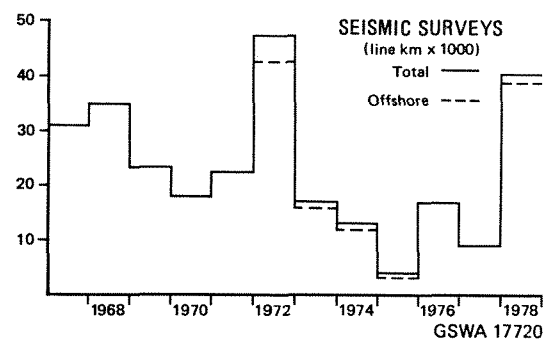

Figure 22 Seismic surveys since 1967.

Type of Survey	Line kilometres		Party months or geologist months	
	1977	1978	1977	1978
Land seismic	0	1 143	....	....
Marine seismic	5 994	38 996	....	....
Land gravity	0	459	....	....
Marine gravity	147	1 023	....	....
Aeromagnetic	0	1 847	....	....
Marine magnetic	579	2 336	....	....
Oceanographic	....	....	0	3·5
Geological	....	....	0	2
Geochemical	....	....	0	2

DRILLING

DRILLING OPERATIONS

Expressed in rig months, overall exploration operations declined by 10.3 per cent to 24.3 rig months in 1978 compared to 21.1 rig months in 1977. Offshore operations increased by 15.2 per cent compared with 1977 (21.2 compared with 8.7 rig months), and onshore exploration activity declined by 64 per cent (3.1 compared with 8.7 rig months). In addition, 4.7 rig months were spent on a seven-well development program on Barrow Island in 1978. There was no development drilling in 1977.

A total of six rigs, 4 offshore and 2 onshore, were operated. During the first half of the year, the 3-leg jack-up rig Maersk Endurer drilled the last 3 holes of a 4-well program initiated by WAPET in 1977, after which it left Western Australian waters. The drillship Regional Endeavour was active in Western Australia throughout the year except for a period in Northern Territory waters from mid-May to the end of July. Other details of rig deployment are shown in Figure 23.

Three tropical cyclones affected the Regional Endeavour operations for Woodside Petroleum Development Pty Ltd (Woodside) at the beginning of the year. The first, "Vern", caused work loss of 7 days during late January and Early February whilst drilling Jarman No. 1. Cyclone "Alby" caused a loss of 2¼ days work at the end of March whilst drilling Miller No. 1, and a week later cyclone "Brenda" caused a loss of 6½ days operational time.

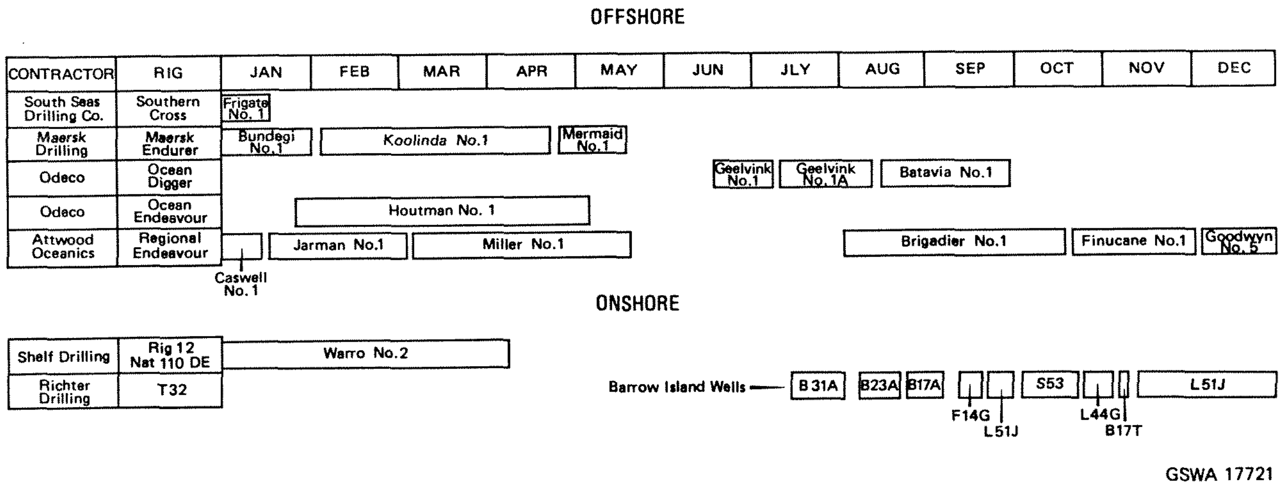

Figure 23 Rig utilization, 1978.

Figure 24 is a summary comparison of drilling operations for the 12-year period 1967-78.

WELLS COMPLETED IN 1978

The positions of wells drilled for petroleum exploration in Western Australia during 1978 are shown in Figure 25. Details relating to wells drilled during the year are given in Table 14. All petroleum exploration wells drilled in Western Australia up to the end of 1978 are listed in the Geological Survey Record 1979/1 (Crank, 1979). A summary of the principal results of drilling in each basin during the year is as follows:

Bonaparte Gulf Basin

Arco Australia Ltd completed one well, Frigate No. 1, in the offshore Bonaparte Gulf Basin in 1978. This was drilled, in WA-18-P, on a large, faulted anticlinal structure and was located 68 km southeast of Petrel No. 1 and 14 km west of Tern No. 1. No shows of gas or oil were encountered, and the well was plugged and abandoned in the Triassic at a total depth of 1 584 m.

Browse Basin

One well, Caswell No. 1, was completed in the Browse Basin by the Woodside group. It was drilled on a pre break-up horst overlain by Middle Jurassic sediments, located about 410 km north of Broome in Exploration Permit WA-34-P. The well, which was drilled in 345 m of water, reached a total depth of 4 097 m in the Lower Cretaceous. The only hydrocarbons of significance were encountered between 3 606 and 3 611 m, but testing indicated the presence of overpressured streaks, not in vertical communication, and the well was plugged and abandoned.

Canning Basin

The Woodside group also drilled one well in the Canning Basin during the year, Jarman No. 1 in WA-1-P. This was located in the Beagle Sub-basin on the north-west flank of the Cossigny Trough. It was drilled to test a very large anticlinal structure and reached a total depth of 2 906 m in the Middle Jurassic, but no significant hydrocarbon shows were encountered.

Carnarvon Basin

As has been the case over the last ten years the most active drilling area has been the offshore Carnarvon Basin. Seven exploration wells were completed and one extension test, Goodwyn No. 5, was drilling at the end of the year. Two onshore new pool wildcats were drilled on Barrow Island, as well as seven development wells within the Barrow Island field.

Three exploration wells were drilled by Woodside: Miller No. 1, Brigadier No. 1, and Finucane No. 1. Miller No. 1 was drilled to 3 520 m to test the potential of Upper Triassic sands on the eastern side of the North Rankin productive area in WA-28-P. Gas-bearing sandstones were penetrated between 3 046 and 3 066 m, and between 3 111 and 3 232 m, but the well was abandoned as non-commercial.

Brigadier No. 1, in WA-90-P, was the first well to be drilled in the newly awarded permits on and adjoining the Exmouth Plateau. It was drilled on the Brigadier Trend,

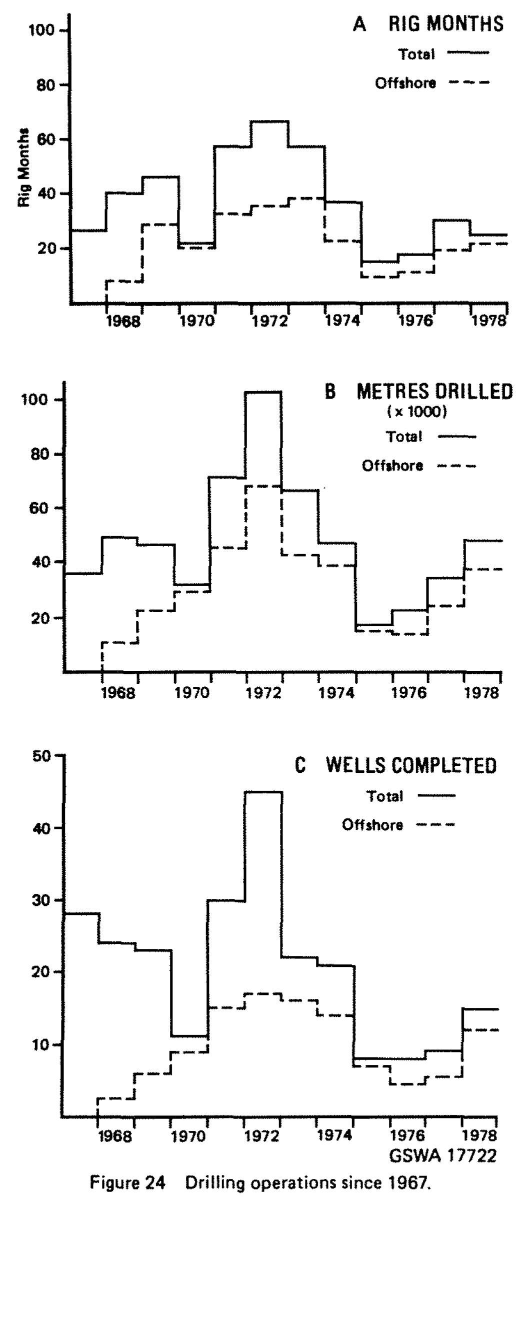

Figure 24 Drilling operations since 1967.

TABLE 14. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1978

Basin	Well	Tenement	Operating company	Type	Position		Elevation and water depth (m)			Dates			Total depth (m)	Bottomed in	Status on 31 Dec.
					Latitude South	Longitude East	GL	RT	WD	Com-menced	Reached TD	Rig released			
Perth	Warro No. 2	EP24	WAPET	NFW	30°10′05″	115°44′03″	291	299	....	20/11/77	20/2/78	5/4/78	4 854	L. Jurassic	Gas shows, p & a
	Houtman No. 1	WA-59-P	Esso	NFW	28°39′55″	113°34′35″	....	25	152	27/1/78	5/4/78	6/5/78	3 860	L. Jurassic	Gas shows, p & a
	Geelvink No. 1	WA-13-P	WAPET	NFW	29°05′47″	114°17′55″	....	30	50	30/5/78	10/6/78	13/6/78	1 268	L. Jurassic	Mechanical problems, p & a
	Geelvink No. 1A	WA-13-P	WAPET	NFW	29°05′47″	114°17′53″	....	30	51	14/6/78	2/7/78	10/8/78	3 053	? Permian	Dry, p & a
	Batavia No. 1	WA-59-P	Esso	NFW	28°53′59″	114°15′36″	....	31	53	13/8/78	20/9/78	28/9/78	2 941	? Permian	Dry, p & a
Carnarvon	Bundegi No. 1	EP41	WAPET	NFW	22°01′06″	114°09′33″	....	31	16	4/12/77	21/1/78	31/1/78	1 584	U. Triassic	Dry, p & a
Canning	Jarman No. 1	WA-1-P	Woodside	NFW	19°07′23″	117°20′42″	....	8	134	17/1/78	28/2/78	3/3/78	2 906	M. Jurassic	Dry, p & a
Carnarvon	Koolinda No. 1	WA-24-P	WAPET	NFW	21°23′46″	115°03′13″	....	31	18	4/2/78	1/4/78	24/4/78	3 732	Jurassic	Gas and oil shows, p & a
	Miller No. 1	WA-28-P	Woodside	NFW	19°34′45″	116°09′55″	....	8	121	6/3/78	12/5/78	20/5/78	3 520	U. Triassic	Gas shows, p & a
	Mermaid No. 1	WA-23-P	WAPET	NFW	20°41′55″	115°57′39″	....	31	25	27/4/78	9/5/78	16/5/78	1 271	Precambrian	Dry, p & a
	Brigadier No. 1	WA-90-P	Woodside	NFW	19°05′49″	116°08′09″	....	8	312	2/8/78	9/10/78	19/10/78	4 292	Triassic	Dry, p & a
	Finucane No. 1	WA-1-P	Woodside	NFW	19°17′25″	116°45′54″	....	8	139	21/10/78	29/11/78	3/12/78	3 301	M. Jurassic	Dry, p & a
	Barrow S53	PL1H	WAPET	NPW	20°49′05″	115°22′22″	27	38	....	7/10/78	20/10/78	22/10/78	802	L. Cretaceous	Oil shows, p & a
	Barrow L51J	PL1H	WAPET	NFW	20°49′05″	115°22′22″	40	43		11/11/78	18/12/78	....	2 135	U. Jurassic	Waiting on completion
	Goodwyn No. 5	WA-28-P	Woodside	EXT	19°40′42″	115°53′45″	....	8	129	5/12/78	....	....	2 917	....	Drilling
Browse	Caswell No. 1	WA-34-P	Woodside	NFW	14°14′29″	122°28′04″	....	8	345	16/8/77	2/1/78	13/1/78	4 090	L. Cretaceous	Gas and oil shows, p & a
Bonaparte Gulf	Frigate No. 1	WA-18-P	ARCO	NFW	13°10′48″	127°55′25″	....	2	91	4/1/78	13/1/78	17/1/78	1 584	Triassic	Dry, p & a

Woodside: Woodside Petroleum Development Pty Ltd
WAPET: West Australian Petroleum Pty Ltd
ESSO: Esso Exploration and Production Aust. Inc.
ARCO: Arco Australia Ltd

NFW: New field wildcat well
EXT: Extension test well
NPW: New pool wildcat well
p & a: Plugged and abandoned

a large structure on the northwestern edge of the Carnarvon Basin between the Victoria and Kangaroo Synclines. The total depth was 4 292 m in the Upper Triassic, but no significant shows of oil or gas were detected.

Finucane No. 1, located 25 km north-northeast of the Angel gasfield, was drilled to test a drape-closed fault block in WA-1-P, similar to those present on the Rankin Trend. Total depth was 3 301 m in probable Middle Jurassic sediments, but no hydrocarbon shows were recorded.

West Australian Petroleum Pty Ltd (WAPET) completed three offshore wells in 1978: Koolinda No. 1, Mermaid No. 1, and Bundegi No. 1, although the latter was technically located on an onshore permit, EP41.

Koolinda No. 1 was located in the Barrow Sub-basin on a large reversal on the downthrown side of the Flinders Fault System in WA-24-P. The well was drilled to a total depth of 3 732 m in the Middle Jurassic. Hydrocarbon-bearing sandstones, encountered between 2 100 and 2 305 m, were extensively drillstem tested, but the results were disappointing as no formation fluids were recovered.

The formation was considered to be tight and non-productive, and the well was abandoned.

Mermaid No. 1 was drilled to a depth of 1 271 m on the outer edge of the Lambert Shelf at the eastern margin of the Barrow Sub-basin, in Permit WA-23-P. The well was drilled to evaluate postulated stratigraphic traps in the Triassic and Upper Permian. It was drilled into Precambrian basement and no hydrocarbon shows were encountered.

Bundegi No. 1 was drilled in the shallow waters of the Exmouth Gulf within EP41 about 20 km east-northeast of Cape Range No. 1. The structure tested was an anticlinal feature on the west side of and adjacent to, the north-northeast-trending Paterson-Learmonth Fault. Possible gas-bearing sandstones were detected between 2 606 and 2 679 m. Formation-interval tests of this zone indicated multiple gas-water contacts. The gas sands were too thin to be considered economic so the well was plugged and abandoned at a total depth of 3 096 m.

Barrow L51J, drilled within PL1H (Barrow Island), was classed as a new pool wildcat and had as its main objective an extension of the "6 700-foot sand". The total depth of 2 135 m was reached on 18 December, 1978, and at the end of the year preparations were being made to test upper zones between 1 806 and 1 809 m and between 1 842 and 1 844 m, after the lower part of the well including the "6 700-foot sand" had been plugged as a dry hole.

Barrow S53 was completed on a possible closure to the northwest of the main "Windalia sand" pool on PL1H and was also classed as a new pool wildcat. The Windalia reservoir, however, did not contain significant oil saturation and the well was plugged and abandoned.

Barrow Island Development Wells

During the year seven development wells were drilled by WAPET within the Barrow Island oilfield. Three of these B17A, B23A and B31A, were completed as infill wells evaluating the "Windalia sand" reservoir. F14G, L44G and L82G were drilled to evaluate the potential of the Upper Cretaceous Gearle Siltstone, and B17T was a 76 m test of "oil shows" previously encountered in shallow Tertiary rocks in B17A.

The status of these wells at the end of the year is shown below:

Well	Total depth (m)	Status at 31 December 1978	
		(bbls oil per day)	(bbls water per day)
B17A	680	196	5
B23A	727	224	135
B31A	758	100	13
F14G	412	0	0
F82G	514	30	0
L44G	543	115	0
B17T	76	waiting on pump	
Total development drilling	3 710	....	....

Perth Basin

One onshore and three offshore wells were drilled in the Perth Basin in 1978, two by Esso and two by WAPET.

Warro No. 2, located 240 m west-northwest of Warro No. 1, was drilled by WAPET in the onshore permit EP24, to evaluate the hydrocarbon potential of Jurassic gas sands encountered in the first well, testing results

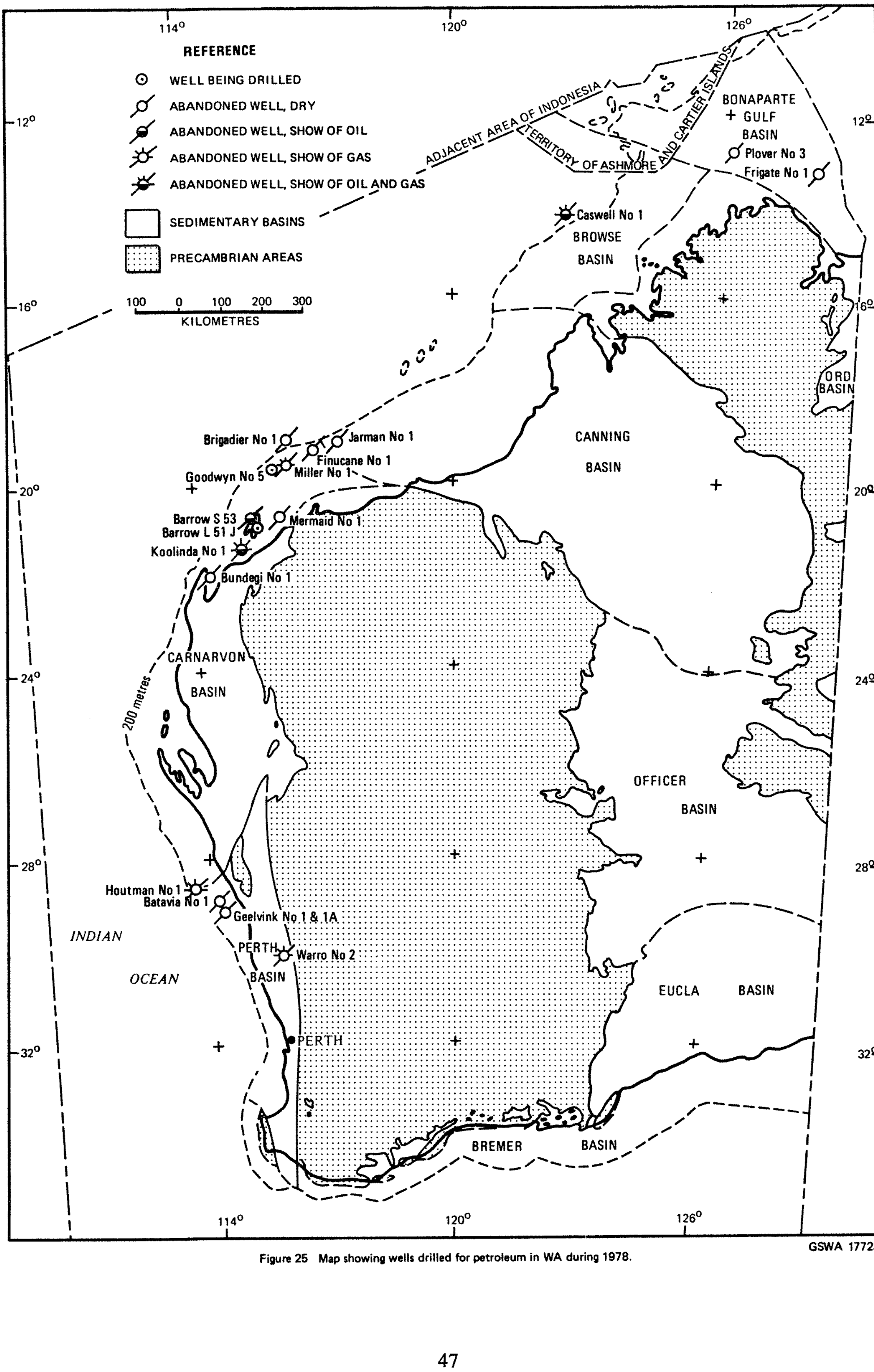

Figure 25 Map showing wells drilled for petroleum in WA during 1978.

of which had been inconclusive. The No. 2 well was abandoned at 4 854 m after testing two zones, 3 977 to 4 016 m and 4 086 to 4 120 m, which yielded only very small gas flows, 2.27×10^3 m^3/day and 2.94×10^3 m^3/day maximum respectively.

Three wells were drilled in the offshore Abrolhos Sub-basin: Houtman No. 1 and Batavia No. 1 by Esso, and Geelvink No. 1A by WAPET. Houtman No. 1 was drilled on a complex, faulted anticline west of the Abrolhos Islands in WA-59-P, with target horizons Lower Jurassic to Upper Triassic sandstones. The well did not reach these objectives and was completed at 3 860 m in the Upper Jurassic. Possible gas-bearing sandstones were penetrated between 3 340 and 3 486 m, but wireline tests, confirmed later by drillstem test results, suggested that these sandstones are low-permeability reservoirs, and the well was abandoned as uneconomic.

Esso's second well, Batavia No. 1, was drilled to the east of the Abrolhos Islands, also in WA-59-P, on a north-northwest-trending antithetic fault closure. The principal objective was basal Triassic sandstone similar to that which produces in the onshore Dongara gasfield 80 km to the southeast. No permeable reservoir sandstones were encountered and the well was plugged and abandoned at a total depth of 2 941 m.

Geelvink No. 1A was drilled by WAPET in the central part of the Abrolhos Sub-basin to test a faulted anticlinal closure with Triassic and Permian objectives. Geelvink No. 1 was abandoned at 1 268 m because of mechanical problems. The basal Triassic sandstone encountered at 2 149 to 2 169 m proved to be tight, as were the Permian sandstones below. No significant shows of oil or gas were encountered and the well was plugged and abandoned at 3 053 m.

GEOPHYSICAL SURVEYS

Geophysical surveys consisted mainly of seismic surveys which increased about 700 per cent compared to 1977. Other surveys conducted were gravity, magnetic, aeromagnetic and uphole velocity surveys.

SEISMIC

During 1978 offshore seismic surveys were conducted in the Perth Basin (809 km), Carnarvon Basin (5 028 km), Browse Basin (349 km), Canning Basin (3 073 km), Bonaparte Gulf Basin (4 420 km), and the Exmouth Plateau area (25 314 km). Onshore seismic surveys were conducted in the Perth Basin (51 km) and the Canning Basin (1 092 km). Details are as follows:

SEISMIC SURVEYS

Basin	Tenement	Company	Line (km)
Perth	PL2	West Australian Petroleum Pty Ltd	51 (onshore)
	WA-59-P	Esso Exploration and Production Aust Inc	809 (offshore)
Carnarvon	WA-1-P	Woodside Petroleum Development Pty Ltd	271 (offshore)
	WA-28-P	Woodside Petroleum Development Pty Ltd	910 (offshore)
	WA-23-P	West Australian Petroleum Pty Ltd	346 (offshore)
	WA-25-P	West Australian Petroleum Pty Ltd	424 (offshore)
	WA-58-P	Western Energy Pty Ltd	710 (offshore)
	WA-80-P	Otter Exploration NL	414 (offshore)
	WA-81-P	Continental Oil Co of Australia Ltd	1 950 (offshore)
Canning	EP97	Amax Iron Ore Corp	18 (onshore)
	EP101	Amax Iron Ore Corp	151 (onshore)
	EP102	Amax Iron Ore Corp	140 (onshore)
	EP103	Whitestone Petroleum Pty Ltd	150 (onshore)
	EP104	Esso Exploration and Production Aust Inc	633 (onshore)
	WA-79-P	Getty Oil Development Co Ltd	3 073 (offshore)

SEISMIC SURVEYS—*continued*

Basin	Tenement	Company	Line (km)
Browse	WA-33-P	Woodside Petroleum Development Pty Ltd	121 (offshore)
	WA-34-P	Woodside Petroleum Development Pty Ltd	162 (offshore)
	WA-35-P	Woodside Petroleum Development Pty Ltd	31 (offshore)
	WA-37-P	Woodside Petroleum Development Pty Ltd	34 (offshore)
Bonaparte Gulf	WA-70-P	Getty Oil Development Co Ltd	4 420 (offshore)
Exmouth Plateau area	WA-84-P	Phillips Aust Oil Co	5 344 (offshore)
	WA-90-P	Woodside Petroleum Development Pty Ltd	1 011 (offshore)
	WA 93 P	Hudbay Oil (Aust) Ltd	2 214 (offshore)
	WA-96-P	Esso Exploration and Production Aust Inc	8 980 (offshore)
	WA-97-P	Esso Exploration and Production Aust Inc	7 765 (offshore)
Total			40 139

GRAVITY

Gravity surveys carried out in conjunction with seismic surveys were as follows:

GRAVITY SURVEYS

Basin	Tenement	Company	Line (km)
Carnarvon	WA-1-P	Woodside Petroleum Development Pty Ltd	86 (offshore)
	WA-28-P	Woodside Petroleum Development Pty Ltd	248 (offshore)
Canning	EP97	Amax Iron Ore Corp	18 (onshore)
	EP101	Amax Iron Ore Corp	151 (onshore)
	EP102	Amax Iron Ore Corp	140 (onshore)
	EP103	Whitestone Petroleum Aust Ltd	150 (onshore)
Browse	WA-37-P	Woodside Petroleum Development Pty Ltd	20 (offshore)
Exmouth Plateau area	WA-93-P	Hudbay Oil (Aust) Ltd	669 (offshore)
Total			1 482

MAGNETIC

One aeromagnetic survey was flown and other magnetic surveys were conducted in conjunction with seismic surveys as follows:

MAGNETIC SURVEYS

Basin	Tenement	Company	Line (km)
Carnarvon	WA-58-P	Western Energy Pty Ltd (Aeromagnetic Survey)	1 847 (offshore)
Exmouth Plateau area	WA-84-P	Phillips Aust Oil Co	1 421 (offshore)
	WA-93-P	Hudbay Oil (Aust) Ltd	915 (offshore)
Total			4 183

OTHER SURVEYS

Esso Exploration and Production Aust Inc carried out a geological survey in the Canning Basin totalling 4 geologist months. North West Mining NL conducted a geochemical survey in the onshore Perth Basin totalling 2 party months. Other surveys included oceanographic surveys by Esso and Phillips on WA-84-P, WA-96-P and WA-97-P (3.5 party months), and an uphole velocity survey in the Perth Basin by WAPET on EP23.

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THE STRATIGRAPHY OF GINGINUP NO. 1 CENTRAL PERTH BASIN

by B. S. Ingram* and A. E. Cockbain

ABSTRACT

Ginginup No. 1, sited 3.5 km north of Gingin, was drilled in 1969 to obtain a continuously cored section through the Coolyena Group. The section penetrated was: Poison Hill Greensand (0-53.57 m), Campanian and possibly Maastrichtian; Gingin Chalk (53.57-74.75 m), Santonian-Campanian; Molecap Greensand (74.75-87.02 m), late Cenomanian-early Santonian; and Leederville Formation (87.02-102.26 m T.D.), Neocomian-Aptian.

INTRODUCTION

Ginginup No. 1 was drilled in 1969 by the Mines Department drilling section, and was sited on Mount Ginginup, some 3.5 km north of Gingin (Fig. 26). The site was selected, by G. H. Low, to provide a representative section through the Coolyena Group. The purpose of drilling the hole was to obtain a sequence of samples suitable for palaeontological (especially palynological) examination.

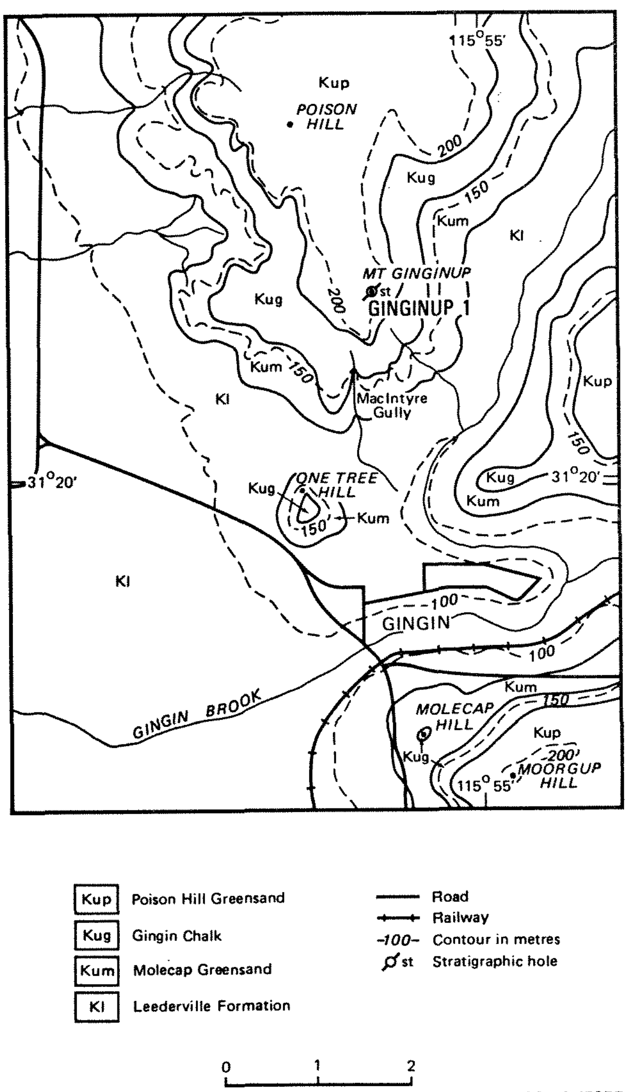

Figure 26 Solid geology sketch map of Gingin area showing position of Ginginup No. 1.

The Coolyena Group (Cockbain and Playford, 1973) consists of the Poison Hill Greensand, Gingin Chalk, Molecap Greensand and Osborne Formation. Prior to drilling Ginginup No. 1, the Gingin Chalk was considered to be of Santonian age, mainly on the evidence of pelagic crinoid fossils (Withers, 1924; 1926). The ages of the Molecap and Poison Hill Greensands were only poorly known from internal evidence. Although the Osborne Formation had been assigned to the Albian-Cenomanian on the basis of plant microfossils obtained from boreholes, the relationship between it and the Molecap Greensand was uncertain.

In order to clarify these age relationships, it was decided to drill a continuously cored hole through the Coolyena in its type area. The site selected (Fig. 26) is 1 km north of the type section of the Gingin Chalk (MacIntyre Gully) and less than 5 km from the type sections of the Poison Hill Greensand (Poison Hill) and the Molecap Greensand (Molecap Hill).

Preliminary results obtained by Ingram were used by Playford and others (1978); these included lists of plant microfossils and ages for the Molecap and Poison Hill Greensands. The Campanian to possibly Maastrichtian age of the Poison Hill Greensand is now confirmed and the Molecap Greensand is considered to be late Cenomanian to possibly early Santonian. The Santonian-Campanian age of the Gingin Chalk suggested by Playford and others (1978) is confirmed by Rexilius' (1974) detailed analysis of the planktonic foraminifers from Ginginup No. 1. Although we now know that the Molecap Greensand and Osborne Formation both extend into the Cenomanian and are therefore, in part, equivalent in age, their stratigraphic relationships are still not fully understood.

This paper summarises the stratigraphy of Ginginup No. 1. The ages of the formations are based on an examination of the microplankton by Ingram (using Evans' (1966) zonation established in the Otway Basin) and for the Gingin Chalk, on Rexilius' (1974) study of the planktonic foraminifers. Additional biostratigraphic studies of the benthonic foraminifers (N. Marshall of the University of Western Australia) and the calcareous nannofossils (S. Shafik of the Bureau of Mineral Resources) are in progress. It is hoped that all these palaeontological studies will be published shortly.

DRILLING

Ginginup No. 1 was drilled from 12 November to 16 December 1969 with a small rotary drilling rig. The hole was situated near the summit of Mount Ginginup at latitude 31°19'00"S., longitude 115°54'15"E. The hole was continuously cored to a total depth of 102.27 m using a triple-barrelled split-inner-tube core barrel. Core recovery in the relatively soft sediments averaged 64 per cent in the unweathered section below 25 m. Detailed core-recovery figures are given in Figure 27. All core is stored in the Geological Survey core library at Dianella; there is 37.8 m of 50 mm diameter core and 7.9 m of 35 mm diameter core.

STRATIGRAPHY

The sequence penetrated in Ginginup No. 1 is shown in the composite log (Fig. 27) and is summarised below:

Formation	Borehole depth (m)	Elevation (m)	Thickness (m)
Poison Hill Greensand	surface	227·18	53·57+
Gingin Chalk	53·57	173·61	21·18
Molecap Greensand	74·75	152·43	12·27
Leederville Formation	87·02	140·16	15·24+
Total depth	102·26	124·92	....

Poison Hill Greensand (0-53.57 m): The Poison Hill Greensand is weathered from the surface to a depth of about 25 m and consists of very poorly sorted, often pebbly, sandstone, which is reddish brown in colour to about 15 m, and yellowish brown below 15 m. Up to 10 per cent of clay occurs. There are some unconsolidated

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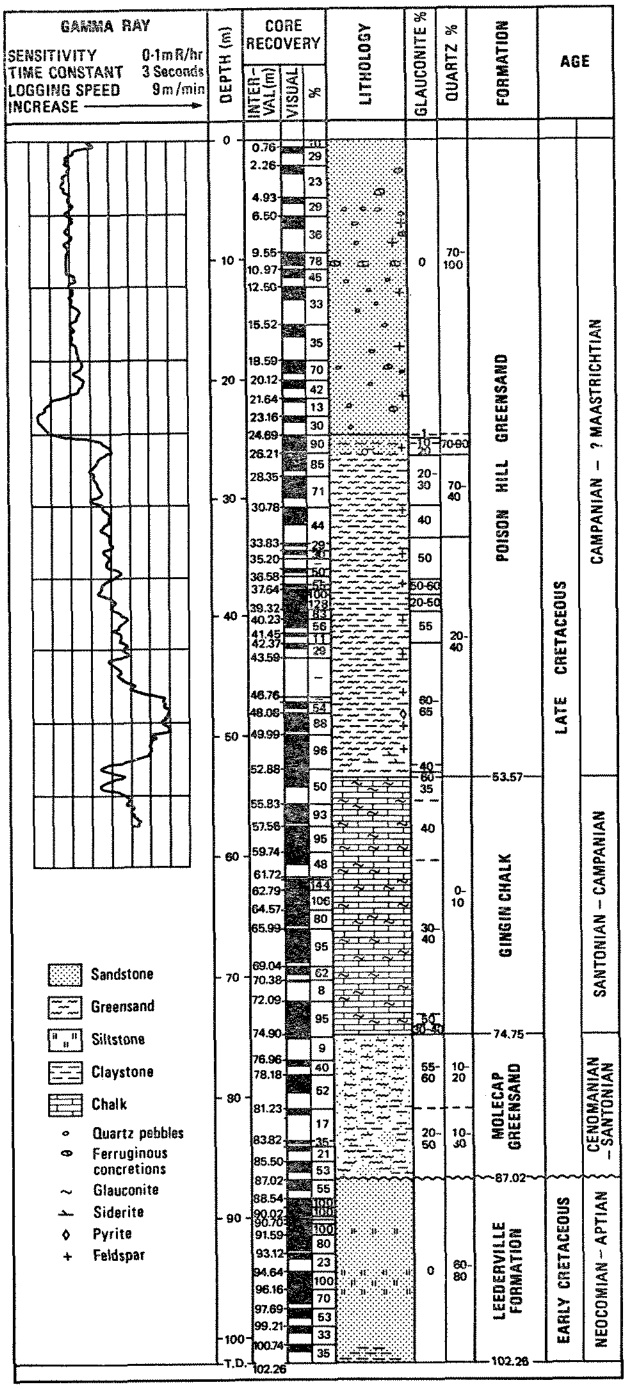

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Figure 27 Ginginup No. 1 composite log.

bands of very coarse quartz sandstone and a few hard ferruginised bands of very coarse sandstone between 30 and 80 mm thick.

Below 25 m, unweathered greensand is present. The greensand is poorly sorted (20 per cent coarse sand, 10 per cent medium sand, 50 per cent fine sand, 20 per cent silt and clay), and yellowish brown to greenish brown to greyish green in colour. Glauconite makes up to 65 per cent of the rock, and occurs mainly in the fine and medium sand fractions. Grey claystone is rare and usually occurs in lenses up to 300 mm thick. Traces of feldspar, limonite and pyrite are present and there is a 350 mm thick band near the base which contains about 30 per cent siderite.

The Poison Hill Greensand contains microplankton belonging to the *Nelsoniella aceras* and the *Xenikoon australis* zones and possibly the *Deflandrea pellucida* zone and is of Campanian age, possibly extending into the Maastrichtian.

Gingin Chalk (53.57-74.75 m): The Gingin Chalk is a greenish-grey glauconitic chalk. Glauconite ranges from 30 to 50 per cent and there is a low (less than 10 per cent) but variable amount of quartz in the rock. *Inoceramus* prisms are common at the top of the formation, but are rare elsewhere. Foraminifers are frequent; brachiopods, ostracods and crinoid and bivalve fragments were also noted. Traces of siderite and coprolites occur.

On the basis of the planktonic foraminifers the unit is Santonian-Campanian in age (Rexilius, 1974). Microplankton of the *Deflandrea cretacea* and *N. aceras* zones occur in the formation, the boundary between the two zones being about 6 m above the base of the chalk.

Molecap Greensand (74.75-87.02 m): The Molecap Greensand is divisible into two units in Ginginup No. 1. (a) 74.75-81.23 m greenish-grey poorly sorted greensand. (b) 81.23-87.02 m greensand with lenses of black claystones and coarse quartz sand.

The greensand contains up to 60 per cent glauconite, and consists of 15-25 per cent coarse sand, 25-35 per cent medium sand and 30-40 per cent fine sand. There are traces of siderite.

Microplankton from the formation belong to the *Ascodinium parvum* and *D. cretacea* zones with an unnamed assemblage between them, probably representing part of the "unclassified gap" of Evans' (1966) zonal scheme. The unit is considered to be late Cenomanian in age at the base, possibly extending into the early Santonian at the top.

Leederville Formation (87.02-102.26 m total depth): The Leederville Formation is a moderately well-sorted (5-25 per cent medium sand, 65-75 per cent fine sand, 5-25 per cent silt clay) grey silty sandstone. It is micaceous and carbonaceous and contains rare carbonaceous siltstone and silty shale.

Microfloras from the unit are poor and the age is Neocomian-Aptian.

CONCLUSIONS

The prime purpose of drilling Ginginup No. 1 was to obtain a complete sequence of samples through the Coolyena Group. This was achieved and the biostratigraphic information resulting from examination of these samples promises to be very useful. Other contributions to geology include:

1. The great depth of weathering (25 m) in the Poison Hill Greensand is confirmed. The corehole represents the thickest section (53 m) of the formation yet recorded.
2. The two-fold subdivision of the Molecap Greensand was not previously known. The lower, claystone-rich, unit is lithologically like the Osborne Formation, although the significance (if any) of this resemblance is not clear.

Comparison of Ginginup No. 1 with Gingin Brook No. 1, situated 6.7 km to the south-east, is instructive. In the latter hole, the top of the Leederville Formation is at an elevation of 9 m above sea level, and is overlain by 95 m of Osborne Formation. This is in contrast to the absence of the Osborne Formation in Ginginup No. 1, where the top of the Leederville Formation is 131 m higher. Clearly there are still gaps in our knowledge of the stratigraphy of the Coolyena Group in the Gingin area.

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RECENT FAULT SCARPS IN THE MOUNT NARRYER AREA, BYRO 1:250 000 SHEET

by I. R. Williams

ABSTRACT

Two prominent curvilinear photo-lineaments, identified as eroded fault scarps, occur near Mount Narryer, 60 km north-northeast of Meeberrie homestead.

Large mulga trees *(Acacia aneura)*, which are confined to alluvium at the base of eroded fault scarps, were sectioned for dendrochronology (counting of annual growth rings) in order to establish a minimum age for the faults. The scarps are at least 90 years old, hence the Mount Narryer fault traces are older than the Meeberrie earthquake of 1941 whose computed epicentre plots 21 km south of the fault traces. It is suggested that surface faulting of the hardpan produced favourable soil and seed-trapping conditions which induced coeval germination of mulga seeds. Consequently, the fault scarps may be little more than 90 years old.

Empirical relationships between earthquake magnitude (energy released) and surface dimensions of the fault scarp, suggest an earthquake magnitude of 6 to 7 for the faulting. Historical records describe a strong earthquake in 1885 which was felt in the Geraldton-Northampton district, about 280 km southwest of Mount Narryer (Everingham, 1968). In view of the comparable times, it is likely that this earthquake resulted from the faulting near Mount Narryer.

The discovery of similar tree-lined lineaments within 200 km of Mount Narryer and the matching of some lineaments with computed, recent earthquake epicentres suggests that the Meeberrie Seismic Zone may be more active than previously supposed.

INTRODUCTION

During routine regional mapping of the Byro 1:250 000 sheet an investigation was made of two curvilinear photo-lineaments situated 30 km east and 50 km east-northeast of Mount Narryer homestead, and roughly 60 km north-northeast of Meeberrie homestead. Reference has already been made to these lineaments by Gordon (1972, p. 31), who speculated that they represented fault scarps produced by the Meeberrie earthquake of 1941.

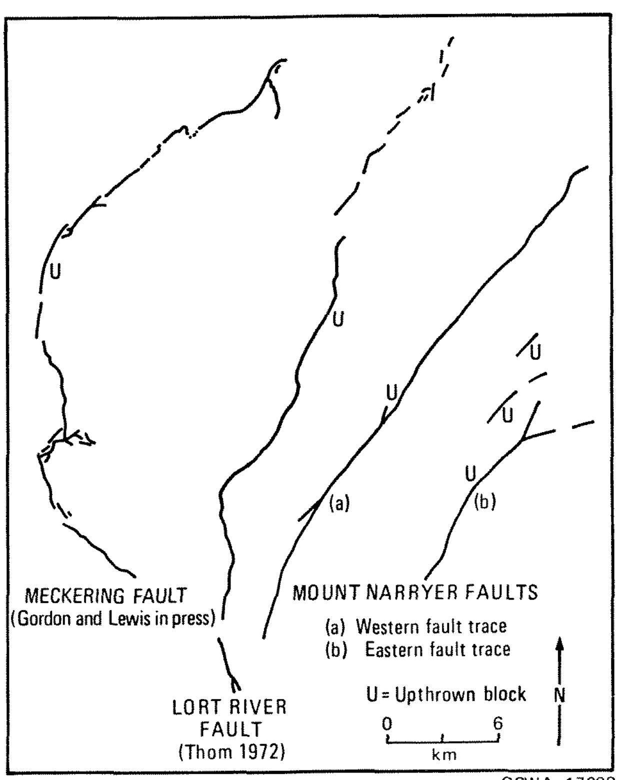

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Figure 28 Comparison of fault traces.

Knowledge of such features on the Precambrian Shield of Western Australia has been increased in recent years by studies of the Meckering (1968) and Calingiri (1970) fault traces, (Gordon and Lewis, in press). Thom (1972) has identified a comparable photo-lineament, in the Lort River area near the south coast, as a scarp generated during a recent, but unrecorded, seismic event. The similarities between the Meckering and Lort River fault scarps and the two Mount Narryer scarps are shown in Figure 28.

The discovery that the Mount Narryer lineaments did coincide with a break in slope, that their dimensions and photo-expression resembled known fault scarps, and that there is recorded evidence of active seismicity in this region (Everingham, 1968), leads to the conclusion that the lineaments are eroded fault scarps.

The dark photo-expression of the lineaments is due to dense growth of large mulgas (*Acacia aneura*) in deep alluvium at the base (downthrown side) of the eroded scarps (Fig. 30 shows the eastern fault trace). This vegetation contrasts with the open shrub and grassland on the sheet-wash colluvium adjacent to the fault traces. The fault-scarp vegetation resembles the taller and denser vegetation of the stream courses. However, in contrast to the variable size of the stream mulgas, the scarp mulgas show a uniform size that would suggest coeval germination, in which case the age of the mulgas would give a minimum age for the earthquake scarp, which may be only a few years older than the tree age.

REGIONAL GEOLOGY

Both fault traces are confined to alluvium and colluvium over hardpan in broad valleys west of the Murchison River. The underlying bedrock consists of banded gneiss (mainly paragneiss), migmatite, amphibolite and iron-formation into which is intruded various types of granitoid and mafic rocks. The Mount Narryer area, between the western and eastern fault traces, is a north-trending belt of high-grade garnet quartzite, a meta-conglomerate, and garnet-sillimanite gneiss.

The trend of the fault traces (040°) is oblique to the regional foliation in the gneiss (355-025°). The western fault trace is parallel to quartz-filled shear zones in the banded gneiss and these also extend south and north from the terminations of the western fault scarp. These shear zones (including the western fault trace) separate granulite-facies rocks to the east from amphibolite-facies rocks to the west. It is possible that the recent fracturing follows the older fractures in the gneiss-migmatite basement (Fig. 29).

SURFACE CHARACTERISTICS OF FAULT TRACES

The dimensions and salient features are summarized in the following table:

Name	Length (km)	Estimated vertical displacement	Trend	Remarks
(a) Western fault trace	32·7	1–1·5	040°	Downthrown to east
(b) Eastern fault	11·0	1·2	040°	Downthrown to east small; separate faults at northern end downthrown to west

The western fault trace lies 9.5 km west of Mount Narryer, where it passes obliquely across the Murrum Creek drainage. It is a gently arcuate trace, convex to the west. Two short faults, both about 1 km in length, splay from the western side between Walboo Well and Duffies Well.

The eastern fault trace lies 4 km east of Mount Narryer, along the west bank of the Murchison River. Again, it is convex westward, but is more arcuate than the western fault trace, and bifurcates towards the northern end.

Three short (2 km) lineaments northwest of River Well appear to be fault traces which are downthrown to the west.

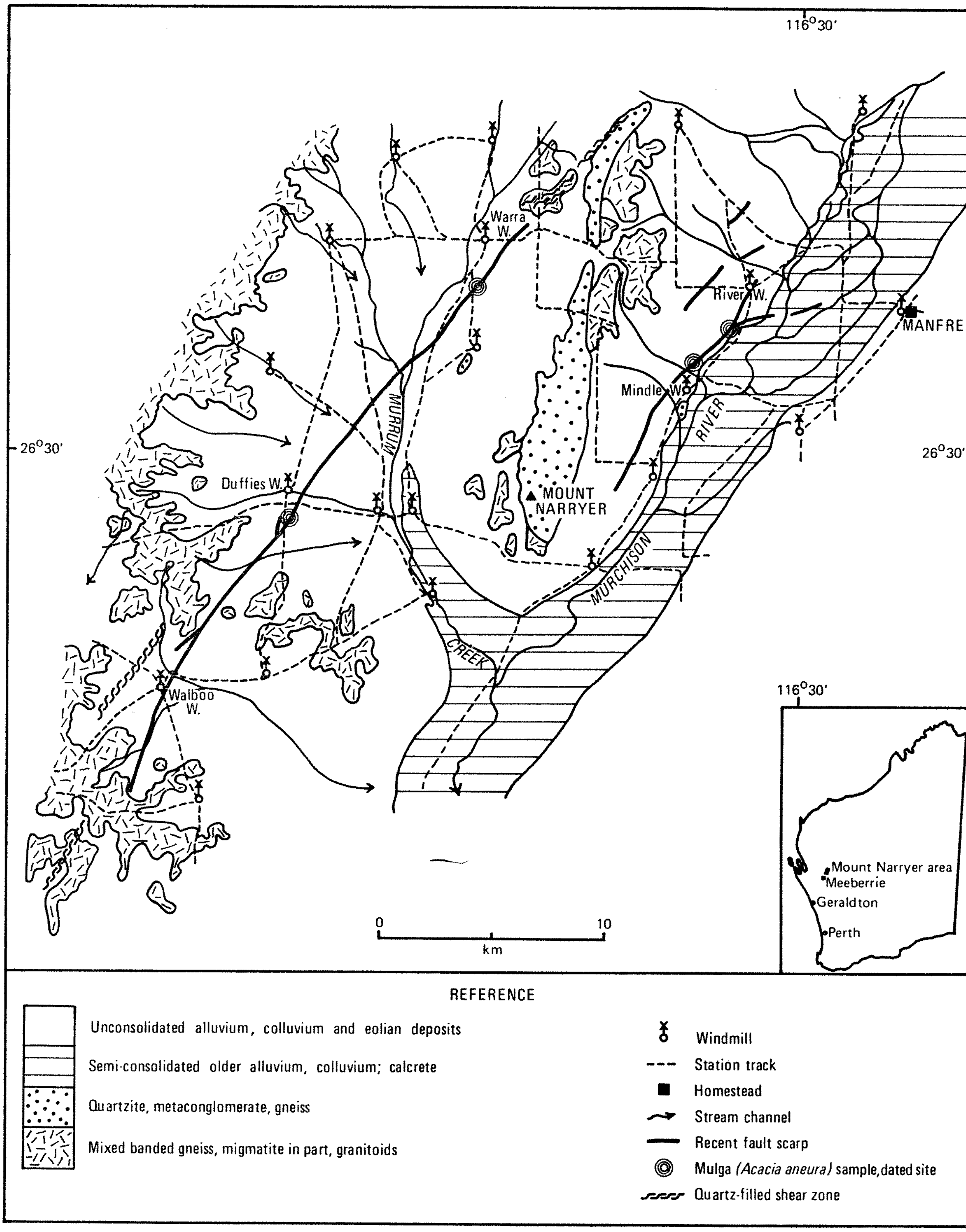

Figure 29 General geological sketch, Mount Narryer area.

The strip of dense vegetation which marks both fault traces varies from 10 m to 500 m in width. The western edge of the vegetation is very abrupt (Fig. 30) and presumably marks the actual trace of the fault. The eastern edge of the vegetation is irregular, the lineament being widest where water courses cross the scarp, and narrowest in colluvial areas close to outcrop.

Schematic cross sections of the fault including the distribution of the vegetation are given in Figure 31.

DENDROCHRONOLOGY

Four large mulga trees (*Acacia aneura*) were sampled, two from each fault trace. Polished, unvarnished sections were prepared from each tree and submitted to Mr. A. J. Hart, Forests Department, Kelmscott, for counting of annual growth rings. Check counts were carried out by Mr. B. Rockel, Forests Research Division, CSIRO, Kelmscott. The results of repeated counting are given in Table 15.

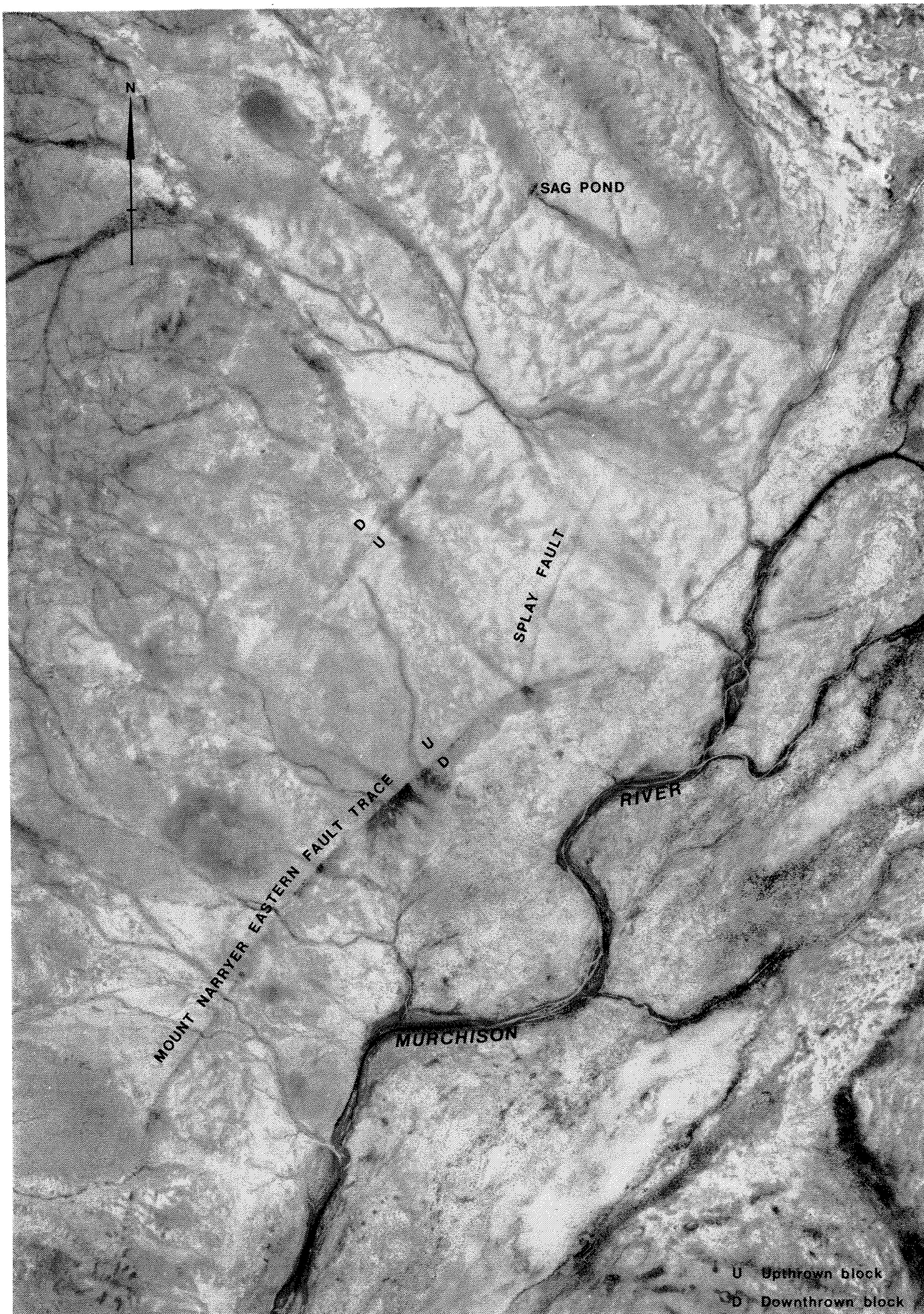

Figure 30 Aerial photo showing eastern fault trace and several smaller traces (Byro CAF 7557 Run 4, photo 088. Scale enlarged to approximately 1:57000).

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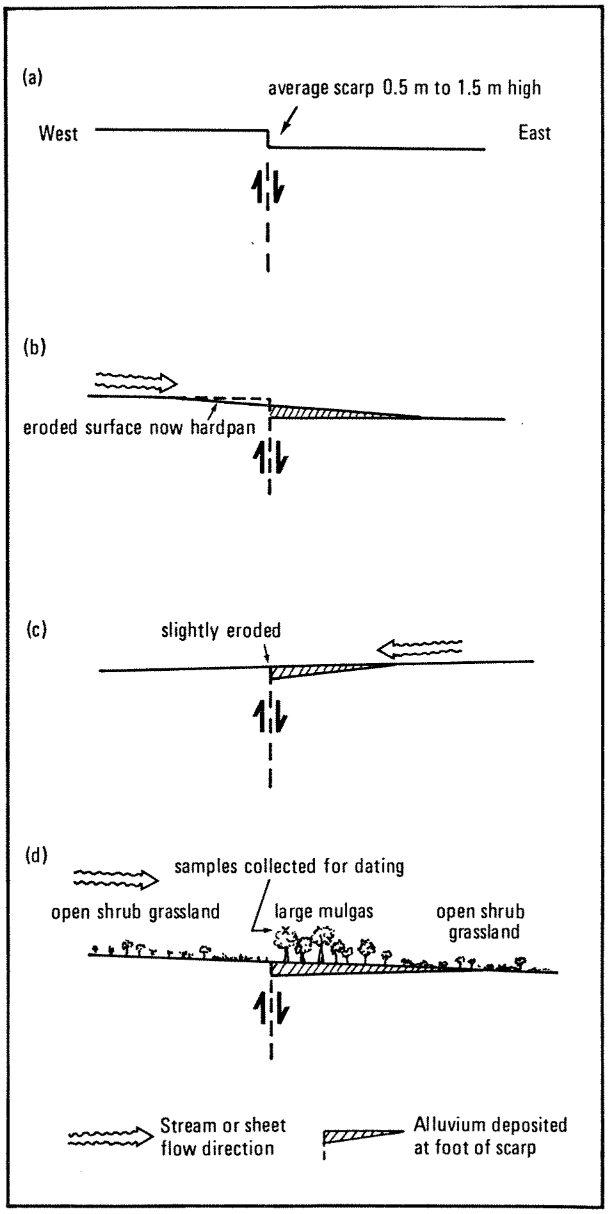

Figure 31 Schematic cross sections of eroded fault scarps, Mount Narryer area.

The estimated age range of each tree is a preferred age, or age range, subject to the constraints imposed by the difficulty of ascertaining the significance of some growth rings. Climatic variations of the Murchison area, particularly the irregular summer rainfall seem to have produced some 'false' growth rings, which have grown outside the normal growth season. Although the individual counts are not precisely consistent, even on the one sample, they all are clustered in the range of 70 to 90 years, suggesting that the fault scarps are closely related in time, if not coeval. The surface expressions of both fault traces show similar degrees of erosion.

It is concluded that the fault scarps are at least 90 years old and, subtracting from 1978, would have formed prior to 1888. Therefore the fault traces cannot be related to the Meeberrie earthquake of 1941 whose epicentre plots only 21 km south-southwest of the Mount Narryer faults (Gordon, 1972, p. 31; Denham, 1976).

SEISMIC HISTORY

The Mount Narryer area falls within seismic zones variously called Zone C (Everingham and Gregson, 1970), Zone 2—Meeberrie (Gordon, 1972), or the Meeberrie-Onslow Zone (Denham, 1976). Although it has not been as active as the South West Seismic Zone over the past 30 years (Doyle, 1971) this zone included the Meeberrie earthquake in 1941, one of the largest (magnitude 6.8) and deepest (33 km focal depth) earthquakes recorded on the Australian continent (Denham, 1976).

Besides the Meeberrie event four other computed epicentres lie within a 200 km radius of Mount Narryer (Fig. 32). Two epicentres plot near Coordewandy Hill, 85 km north of Mount Narryer. The other two epicentres both plot 180 km north-northeast of Mount Narryer (Everingham, 1968; Everingham and Parkes, 1971).

Inspection of 1972 CAF aerial photography covering these two areas revealed tree-lined lineaments similar in trend and size to the Mount Narryer fault traces. All these lineaments occur in areas of sheet wash over consolidated hardpan. These localities have not been inspected in the field.

Other probable recent fault traces have been checked in the field 30 km east-southeast of Byro homestead (20 km north of Mount Narryer). They are considered to be older than those at Mount Narryer as they strongly control the local drainage on the older colluvial hardpan unit.

M. Elias (pers. comm.) pointed out the occurrence of similar tree-lined lineaments near Wilyun Bore, 90 km east of Mount Narryer. Unlike all the other lineaments, which trend northeasterly, the Wilyun Bore lineaments trend northwesterly.

The localities of all these probable fault traces are shown in Figure 32. It is not specifically suggested that the plotted epicentres produced the visible lineaments, but merely that their close spatial relationships point to active seismic areas within the Meeberrie Seismic Zone.

An account in Geraldton and Northampton newspapers of an earthquake in January, 1885 raises some interesting speculations, particularly in view of the age of the Mount Narryer faulting. These reports indicated a felt intensity of about MMV-VI, (Modified Mercalli scale, Gordon, 1972, p. 36), and that the noise and shaking came from a northeasterly direction (Everingham and Tilbury, 1972).

TABLE 15. DENDROCHRONOLOGY, MOUNT NARRYER FAULT TRACES—AGE OF MULGA (*ACACIA ANEURA*) FROM RING COUNTING

G.S.W.A. Sample No.	Byro 1:250 000 CAF air-photo data (Run No., photo point)	Locality		Estimated age (in years)		Estimated age range (preferred) age (in years)
		Co-ordinates	Description	Observer I*	Observer II	
			Western fault trace			
60119	4-086-1022	26°26′30″S 116°21′00″E	2·5 km S Warra Well, Mount Narryer Station	88, 79	94, 72	80-85
60120	5-204-456	26°31′45″S 116°16′00″E	1·5 km S Duffies Well, Mount Narryer Station	86, 78, 83, 79	61, 76, 69	70-80
			Eastern fault trace			
60115	4-086-1018	26°27′15″S 116°28′15″E	2 km SSW River Well, Manfred Station	70	68-70	70
60116	4-086-1019	26°28′00″S 116°27′00″E	1·5 km N Mindle Well, Manfred Station	90	70-80	90

* Ring counting of prepared mulga samples carried out by Mr. A. J. Hart, Forest Department and Mr. B. Rockel, Forests Research Division, C.S.I.R.O.

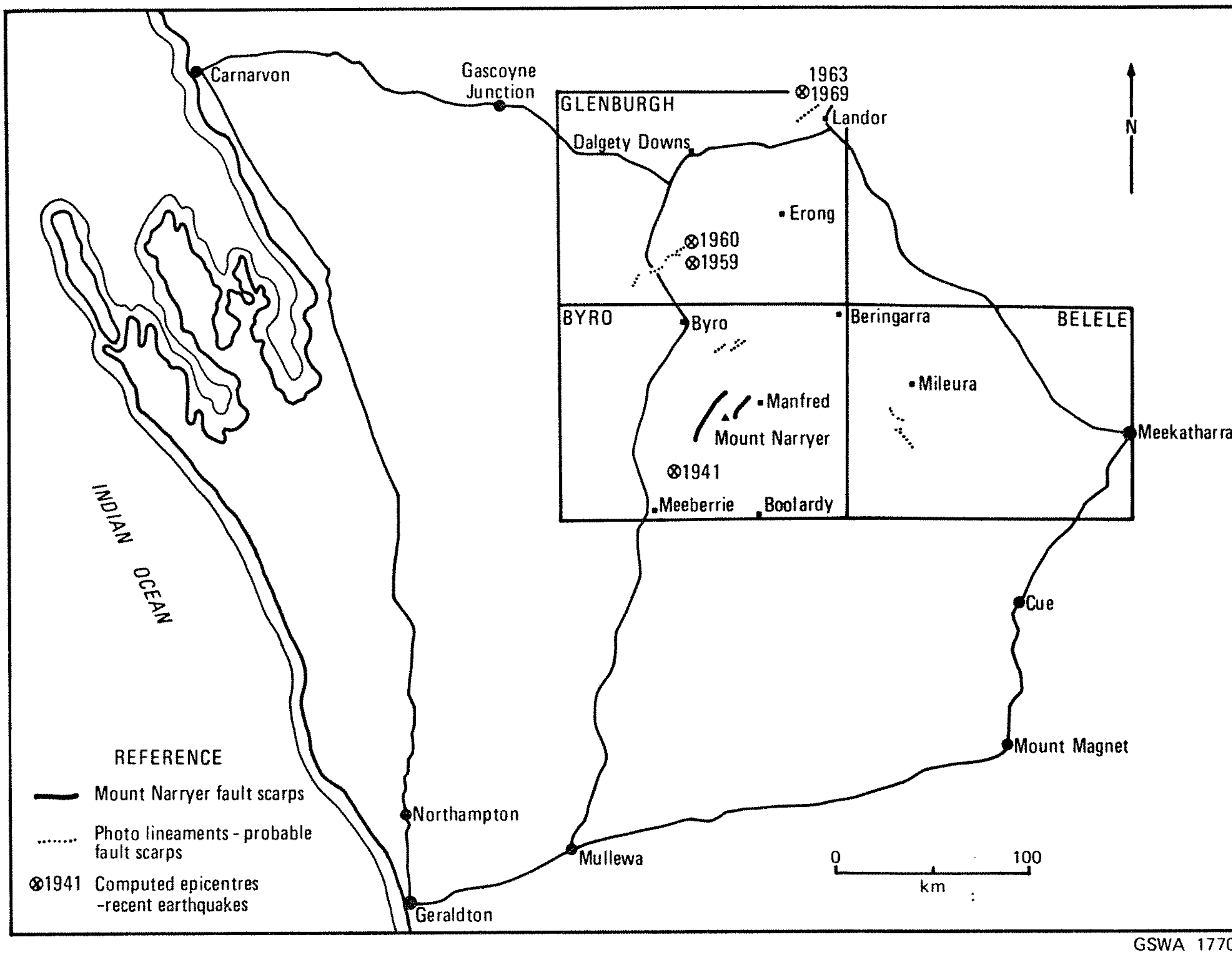

Figure 32 Location map of Mount Narryer faults, computed epicentres and photo-lineaments in relation to 1:250 000 sheets.

DISCUSSION AND CONCLUSIONS

The magnitude of an earthquake is an expression of the energy released. The Richter Scale is the best known scale for magnitude, which is measured from seismic records. Seismologists have also developed empirical relationships between earthquake magnitude and fault characteristics, based on shallow earthquakes in California and Nevada (Tocher, 1958; Bonilla, 1970), and these have been used for calculations involving the Mount Narryer faults.

In the following equations, L is the length of the fault trace in kilometres, D the maximum displacement in centimetres, and M the magnitude:

$$M = 5.65 + 0.98 \log L$$
$$M = 5.22 + 0.53 \log LD$$ (Tocher, 1958)

$$\log D = 0.57 M - 1.91$$ (Bonilla, 1970)

A fourth formula is based on 42 world-wide events:

$$\log LD^2 = 1.90 M - 7.65$$ (King and Knopoff, 1968)

The western fault trace of Mount Narryer is 32.7 km long and has an estimated maximum vertical displacement of about 1.5 metres. Substituting these values in any of the above formulae gives a magnitude of between 7.1 and 7.2.

Gordon and Lewis (in press), using these relationships for the Meckering earthquake, calculated a magnitude of 7.2-7.9 against a known magnitude (measured) of 6.8. This suggests that in the Precambrian Shield there is a tendency for the formulae to overestimate the magnitude by up to one unit.

The question now arises, would a 6 to 7 magnitude earthquake at Mount Narryer be felt in Geraldton? Richter (1958) has shown that an earthquake of such magnitude would be felt up to 400 km away, and Geraldton is only 280 km from Mount Narryer. The Meeberrie earthquake, which had a magnitude of 6.8, was felt in Geraldton with an intensity of VI on the Modified Mercalli Scale (Denham, 1976). From this it is deduced that an earthquake of estimated magnitude 6 to 7 at Mount Narryer should have been felt in Geraldton with an intensity of V-VI.

If the oldest tree growing along the degraded scarp was 90 years old in 1978, it would have germinated in 1888, only three years after the known earthquake.

The mulgas at Mount Narryer grow in alluvium derived either by erosion of the scarp and/or by ponded deposition against the scarp. During heavy rain the mixed colluvial-eolian deposits, intersected by the fault scarps, are flooded to a depth of several centimetres. This surface is underlain, at shallow depths, by an impermeable clay hardpan which is not conducive to germination. Hence, during heavy rain, seeds would normally wash across this surface into stream channels. The ruptured hardpan exposing sterile subsoil (A. J. Hart, pers. comm.) and the newly deposited alluvium would act as a seed trap and seed bed, and germination could commence following the first heavy seasonal rain after the faulting occurred.

The absence of dead trees along the eroded scarp, and the deliberate sampling of the oldest mulgas, supports the contention that the age of about 90 years is close to the initial germination of vegetation along the scarp. The time lag of mass germination after faulting would be three years, which is the average frequency of heavy cyclonic rains in this area.

It is not unreasonable to suggest, but by no means proven, that the Geraldton-Northampton earthquake of 1885 was caused by the Mount Narryer faulting.

ACKNOWLEDGMENTS

The author thanks Mr. R. P. Groom of Domus Furniture for the preparation of the mulga samples. Counting of rings was undertaken by Mr. B. Rockel, Forest Research Division, CSIRO, and Mr. A. J. Hart, Forests Department, Kelmscott, whose helpful discussions are also acknowledged.

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THE GEOLOGY OF THE PEAK HILL AREA

by R. D. Gee

ABSTRACT

A thick geosynclinal sequence of arkose, conglomerate, basalt, greywacke, sandstone and shale, possibly as much as 20 km thick, occurs in the Glengarry Sub-basin of the Nabberu Basin. This sequence is called the Glengarry Group, and eight of its constituent formations are defined and described. It is probably 2.0-1.8 b.y. old. A shallow-water clastic facies, a thick volcanic pile, and a deep turbidite trough are identified.

This sequence is unconformably overlain by the Padbury Group (probably 1.7-1.6 b.y. old), which is a chemogenic sequence with a coarse basal conglomerate called the Wilthorpe Conglomerate. The Wilthorpe Conglomerate was the coarse conglomeratic part of the Labouchere Formation as originally defined. The Labouchere Formation was previously assigned to the Padbury Group, but the revised formation is now placed in the Glengarry Group.

Metamorphosed sedimentary rocks in the vicinity of Peak Hill townsite are called the Peak Hill Metamorphic Suite, and are unconformable beneath the Glengarry Group. These metamorphics form a mantle of the Marymia Dome, which has a core of reworked Archaean basement. In the Glengarry Sub-basin, deformation is by crumpling between basement domes.

Regional correlations suggest that the Glengarry Group forms part of an ensialic geosyncline, now largely covered by the Bangemall Group, between the Hamersley Basin and the Yilgarn Block.

INTRODUCTION

Two main problems outlined by Bunting and others (1977) in their preliminary synthesis of the Proterozic stratigraphy and structure along the northern margin of the Yilgarn Block were the relationship of the Padbury Group to the older rocks of the Glengarry Sub-basin, and the stratigraphic relationships within that older sequence. In an attempt to clarify these problems, the area surrounding Peak Hill has been re-mapped, and the Proterozoic stratigraphy in the eastern part of Robinson Range Sheet has been re-examined. This paper summarizes this reappraisal, and establishes a stratigraphic framework which should serve as the basis for continuing studies in the western part of the Nabberu Basin.

EVOLUTION OF STRATIGRAPHIC CONCEPTS

MacLeod (1970) erected the first stratigraphy for the area when he introduced the terms "Peak Hill, Horseshoe, Labouchere and Robinson Range Beds". Although recognizing the possibility of a Proterozoic age, he opted for an Archaean age. During mapping of the Robinson Range Sheet, Barnett (1975) identified this entire succession as having the overall features of a Proterozoic basin. He formalized some of the stratigraphic units, and included them in the Padbury Group, which was defined to include only those units which formed a continuous sequence.

Subsequently, evidence emerged for the existence of a thick sequence older than the Padbury Group, which until its stratigraphy could be clarified, was termed the "pre-Padbury" by Elias and Williams 1977, Williams and others 1978, and the "Glengarry axial sequence" by Bunting and others (1977). The most compelling evidence at that stage was the exposed unconformity between conglomerate assigned to the Labouchere Formation and granitoid of the Yarlarweelor Gneiss Belt. Williams and others (1978) also pointed out that the "pre-Padbury" displayed a more complex structure and a higher grade of metamorphism than the Padbury Group.

During selective remapping on the Peak Hill sheet, it became evident that an unconformity lay *within* rocks assigned to the Labouchere Formation, and as the type section of the Labouchere Formation falls within the "pre-Padbury", some terminological revision is now necessary.

PROTEROZOIC STRATIGRAPHY

EARLY PROTEROZOIC METASEDIMENTARY INLIERS

Peak Hill Metamorphic Suite

This is the metasedimentary sequence in the area within a 7 km radius of the Peak Hill townsite. It occurs unconformably below the Glengarry Group, and does not display the high metamorphic grades and the advanced gneissic fabrics of the Archaean parts of the Marymia Dome. The suite corresponds more-or-less to the "Peak Hill Beds" of MacLeod (1970). It represents a sequence of terrigenous clastics, chert and carbonate, which have been repeatedly deformed and metamorphosed to upper greenschist facies. Its age is uncertain, but is presumed to represent Early Proterozoic sedimentation, tectonism, and metamorphism.

The western part of the exposed area is quartz-muscovite-magnetite schist, interlayered with flaggy quartzite. The quartzite is fine grained, has lepidoblastic texture (elongate quartz in a metamorphic mosaic), and contains minor amounts of potash feldspar, biotite, and muscovite. Lamination is defined by grain-size variations on a millimetre scale, and by stylolitic carbonaceous stringers. No evidence of cross-bedding is evident. A distinctive feature is the presence of moulds of a fibrous lenticular mineral having a radiating habit similar to gypsum (selenite). These features suggest that the quartzite is metamorphosed chert.

Calc-silicate schist and granofels contain albite, calcite, epidote and quartz in a granoblastic mosaic. Biotite and chlorite impart a foliation. Poikiloblastic garnet and magnetite are also present. These rocks are metamorphosed calcareous siltstones, and indicate upper greenschist facies.

The eastern part of the Peak Hill Metamorphic Suite is more homogeneous than the western part, and is not so obviously metasedimentary. Mostly the rocks are retrogressed and granulated quartz-muscovite-plagioclase-sericite gneiss, some of which is banded paragneiss and some of which is probably sheared granitoid. Porphyritic adamellite occurs 15 km east of Peak Hill townsite, but its relationship to the metasedimentary sequence, whether intrusive or unconformable, is unknown.

Sequence at Horseshoe Lights

Stratigraphically below the Thaduna Greywacke at Horseshoe Lights is a sequence that does not fit conveniently into the regional stratigraphy. The rocks here are quartzite, quartz-muscovite-sericite schist, garnetiferous felsic agglomerate and lapilli tuff of mafic composition. The fabric in the pelitic schist demonstrates repeated deformation, and together with the metamorphic grade suggests that the pelites and volcanics correlate with the Peak Hill Metamorphic Suite.

It is possible that the quartzite at the Horseshoe Lights Mine is equivalent to the base of the Glengarry Group, and that the overlying arkose and greywacke are the Doolgunna Arkose and Thaduna Greywacke respectively. There is certainly a contrast in deformation and fabric on either side of the quartzite; and an unconformity is inferred, although there is no direct evidence of this. Nevertheless, this is the interpretation placed on Figure 33, but the metamorphic rocks are not specifically assigned to the Peak Hill Metamorphic Suite.

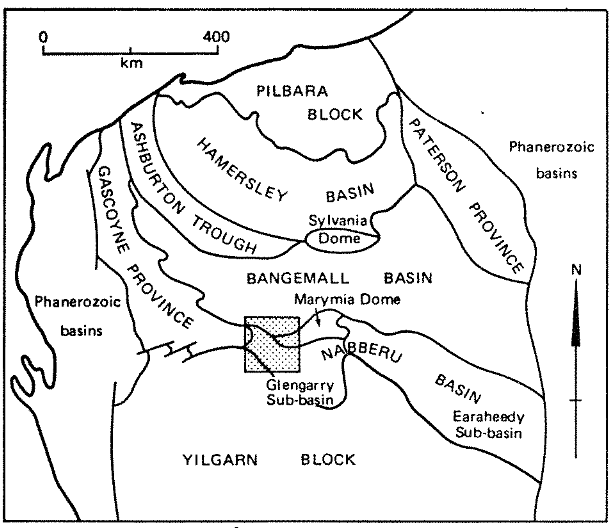

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Figure 33 Location diagram showing relation of area to tectonic units in the northern part of the Western Australian Shield.

GLENGARRY GROUP

Definition

The Glengarry Group is a newly defined group, of greywacke, terriginous clastics, carbonate and volcanics that unconformably overlies Archaean basement, and is unconformably overlain by the Padbury Group in the Glengarry Sub-basin. It includes what has been informally termed the "Axial Sequence" and "pre-Padbury" by previous writers, and also includes most of what has previously been termed the Labouchere Formation.

Basal formations of the Glengarry Group

The base of the Glengarry Group is exposed more or less continuously along the southern margin of the Glengarry Sub-basin, where the orthoquartzitic Finlayson Sandstone (Elias, Bunting, and Wharton 1979) rests unconformably on Archaean granite of the Yilgarn Block. Over most of its extent, the Finlayson Sandstone is overlain by the Maraloou Formation—a calcareous shale sequence. Together, these two formations constitute the shelf facies of the Glengarry Group in the southern part of the sub-basin.

Within the Glengarry Sub-basin is a basement high of Archaean granite, called the Goodin Dome. This is unconformably overlain by a sandstone similar to the Finlayson Sandstone. Physical continuity cannot be established between them, and furthermore the sandstone at Goodin Dome is overlain by a thick arkose unit, which marks the appearance of the axial sequence in the northern part of the Glengarry Sub-basin. For these reasons, this sandstone blanketing the Goodin Dome is given a new name, Juderina Sandstone.

On the northern margin of the Glengarry Sub-basin a continuous basal orthoquartzite unconformably overlies the basement, and is conformably overlain by the same arkose unit as around the Goodin Dome. This orthoquartzite is also placed in the Juderina Sandstone. Previously this northern boundary has been interpreted as a fault (Bunting and others 1977), but in view of the stratigraphic consistency, it is more properly regarded as a folded, but essentially intact, unconformity.

The Juderina Sandstone on the edge of the Marymia Dome extends westerly toward the Peak Hill mine area, where it passes into a boulder conglomerate of comparable thickness to the Juderina Sanstone and retains the same stratigraphic position. This unit is termed the Crispin Conglomerate.

Crispin Conglomerate

The Crispin Conglomerate is that formation of boulder pebble and granule conglomerate and coarse sandstone which occurs at the base of the Glengarry Group, where it overlies the Peak Hill Metamorphic Suite. It extends in an arc of continuous exposure from a point 5 km south of Peak Hill townsite, eastward to the vicinity of the old Saint Crispin gold mine. It is about 200 m thick.

The lower part is schistose, sericitic granule conglomerate and coarse sandstone, which contains abundant pebbles and boulders of metamorphic-textured quartzite averaging 0.1 m in diameter and ranging up to 1.5 m in diameter. The matrix is schistose, and the generally well-rounded boulders are now prolate ellipsoids because of tectonic flattening and stretching in the cleavage.

Toward the top of the formation, pebbles become sparse, and the rock is simply a schistose, sericitic granule conglomerate and sandstone, in which low-angle trough cross-bedding is recognizable. The sericite is mainly derived by granulation of abundant detrital muscovite. A fluvial origin is envisaged for the Crispin Conglomerate.

Juderina Sandstone

The Juderina Sandstone is a well-bedded orthoquartzitic sandstone at the base of the Glengarry Group around the northern part of the Goodin Dome. Its type area is 3 km north of Juderina Bore (119°12′E, 25°53′S), where it is 30 m thick.

Around the Goodin Dome, the bedding in the sandstone is strictly conformable with the contact over a distance of 3 km, and is only disturbed by post-depositional faulting. Where visible, the contact is sharp, non-conglomeratic, and totally without intrusive features. Dolerite dykes occur in the granite, but are absent in the Juderina Sandstone.

The correlate of the Juderina Sandstone, along the southern margin of the Marymia Dome is 50 m thick. The beds in the lowermost metre are of feldspathic sandstone containing small pebbles of vein quartz, which are now flattened and stretched. Angular discordance occurs between the underlying gneiss and the sandstone.

The sandstone has a recognizable sedimentary texture, together with cross-bedding and ripple marks. In the region adjacent to the Marymia Dome, it appears to be a facies variant of the Crispin Conglomerate, the facies change correlating with a change of basement type from Archaean gneiss to the Peak Hill Metamorphic Suite. The Juderina Sandstone is interpreted as a transgressive shoreline deposit developed on a flat unconformity surface.

Finlayson Sandstone

The Finlayson Sandstone (Elias, Bunting and Wharton, 1979) extends into the area of Figure 33 only at the locality 10 km southwest of Mikhaburra where it is a ripple-marked and cross-bedded orthoquartzite 10 m thick resting unconformably on granite of the Yilgarn Block.

At this locality, the basal orthoquartzite is overlain by an alternation of sandstone and slaty siltstone about 100 m thick. Overlying this is magnetite-bearing sandstone and quartzose-feldspathic microconglomerate, which marks the appearance of the Doolgunna Arkose.

Doolgunna Arkose

The Doolgunna Arkose is a thick sequence of medium- to coarse-grained arkose and minor quartz-pebble conglomerate and argillaceous siltstone, which on the southern side of the Glengarry Sub-basin appears to lie conformably above the basal orthoquartzite, and which is conformable with the overlying Karalundi Formation. Around the northern margin of the Goodin Dome, there is a gap in exposure between the Juderina Sandstone and the arkose, but on the northern side of the sub-basin, the correlate of the Juderina Sandstone passes upward into arkose by the appearance of arkose beds within the sandstone.

In the type area, 14 km southeast of Ruby Well Find, arkose is spectacularly exposed in breakaway country, as it is in the area 13 km northeast of Doolgunna (off the area of Fig. 34). It is invariably deeply weathered and has the topographic expression of deeply weathered granite. It weathers in buff and reddish-brown colours.

Individual arkose beds may be stacked one upon the other, or separated by thin shale beds. Arkose beds range in thickness from less than 1 m up to 4 m, and display gross upward-fining grading, bottom scouring of the shale,

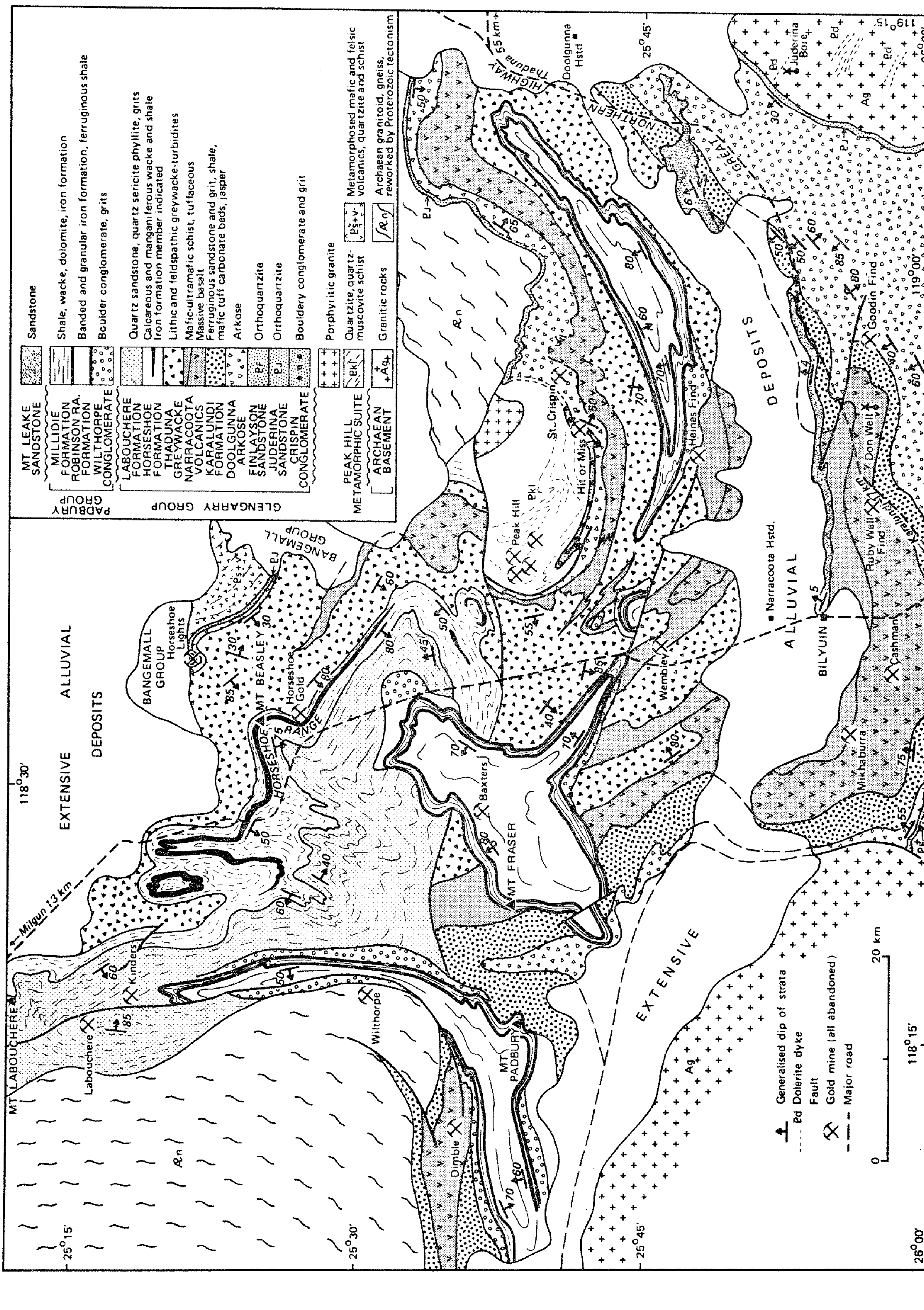

Figure 34 Geological map of parts of Peak Hill and Robinson Range 1:250 000 sheets

and diffuse, trough-type cross-bedding. The lower parts of the arkose beds may contain rounded clasts of vein quartz, up to 20 mm in diameter, and fragments of the underlying shale, but the bulk of each bed consists of angular quartz, microcline and plagioclase up to 10 mm in diameter. Feldspar grains are as abundant as quartz, and the rocks are true arkose.

Strangely, no granite clasts are found, and it appears that the source granite was disaggregated into consituent crystals, perhaps by a balance of deep chemical leaching and rapid mechanical breakdown.

The Doolgunna Arkose is continuous throughout this part of the Glengarry Sub-basin, but there are rapid thickness variations. It is possibly 5 km thick around the northern part of the Goodin Dome, about 1 000 m thick along the southern margin of the Marymia Dome, and only a few hundred metres thick at the western end of the Marymia Dome. East of the area of Figure 34, in the Doolgunna-Thaduna area, mapping has established that the Doolgunna Arkose passes laterally into the Thaduna Greywacke.

The Doolgunna Arkose is considered to be a thick clastic wedge emanating from the Goodin Dome, and spreading extensively through the Glengarry Sub-basin. It is interpreted as a complex piedmont deposit, involving fluvial, shallow-marine and possibly lacustrine processes. Although a close spatial connection exists between the arkose and the granite, the two rocks have not been found in contact. Presumably the Juderina Sandstone must be missing in some areas.

Karalundi Formation

The Karalundi Formation is a mixed clastic-carbonate-chert-tuff sequence, about 1 500 m thick, lying conformably between Doolgunna Arkose and the Narracoota Volcanics in the southern part of the Glengarry Sub-basin. The type area is along the east-west fence line 11 km north-northwest of Karalundi (south of the area of Fig. 34), and good exposures occur adjacent to the Great Northern Highway between 8 and 12 km north from Karalundi along the highway.

The base is the single layer of fine-grained, massively bedded orthoquartzite which is exposed 3 km southwest of Don Well. Above this is an interbedded sequence of feldspathic sandstone, kaolinitic siltstone and thin orthoquartzite. This association becomes more ferruginous higher in the sequence.

Medium- to fine-grained, poorly sorted, ferruginous, black sandstone is the most distinctive rock in this formation. It contains both well-rounded and angular quartz grains, and feldspar clasts set in a hard, black cement. Upward-fining beds, convolute lamination, and cement angle cross-bedding are common in these beds, which appear to be shallow-water marine deposits. These rocks are interbedded with ferruginous and siliceous shales, which commonly contain silty lenses with ripple-drift lamination.

Basaltic tuff, minor pillow basalt, and carbonate beds appear in the upper part, being conspicuous in the section 11 km north-northwest of Karalundi. The tuffs are clearly waterlain, being well bedded, with upward fining grading, and planar and ripple-drift lamination. They contain fragments of shale and basalt in a matrix of fine chlorite, epidote, saussuritized plagioclase, calcite, ilmenite, and magnetite. Calcite also occurs as large idioblastic authigenic crystals.

Carbonate beds range from only a few centimetres to several metres thick, and are either finely laminated (commonly with cross-lamination) or oolitic.

Another distinctive rock is hematite-magnetite jasper, which occurs as steeply inclined pipes up to 20 m in diameter. It has a distinctive colloform texture due to grain-size differences in the cherty material, these differences being outlined by cellular patterns of hematite staining. Euhedral magnetite is abundant, commonly forming clusters within or around the cellular structures. Veins of identical material also penetrate the interpillow material in the basalt. These jasper pipes are interpreted as colloidal hydrothermal deposits formed in fumarolic pipes associated with the basalt volcanism.

The top of the formation is taken as the continuous bed of ferruginous, cherty sandstone which extends for 10 km southwest from Ruby Well Find.

The Karalundi Formation represents a transition from fluvial to shallow-water marine environments, and records the commencement of basalt volcanism.

Narracoota Volcanics

At the lower stratigraphic levels, the Narracoota Volcanics is a massive basalt, and at upper levels mafic-ultramafic phyllite. It conformably overlies the Karalundi Formation in the type area which is specified as the Mikhaburra-Cashman area, 10 to 15 km south of Narracoota.

Basalt, about 4 km thick, is exposed in this area. It is generally massive, but is sheared in some places. Pillowed and fragmental types are also present. The basalts are usually altered; the clinopyroxene shows varying degrees of alteration to actinolite, and the plagioclase to saussurite. More advanced alteration produces actinolite, epidote, clinozoisite, albite and calcite.

At Mikhaburra, at the top of the main pile of massive basalt, is a volcanoclastic sequence of quartz-chlorite phyllite which displays clastic textures, interbedded with clay-pellet quartz sandstone and feldspathic-lithic greywacke. This horizon seems to mark a change to predominantly mafic-ultramafic pyroclastic volcanics, which occur extensively in the general area northeast and northwest of Narracoota.

Although some of this rock is simply sheared basalt, much of it is talc-tremoite-chlorite phyllite with only minor amounts of altered feldspar, and characterized by a fragmental texture on a scale of millimetres. The fragments are usually of similar material to the matrix. Despite the intense shearing, some of these rocks still exhibit remnants of devitrified glass fragments.

The total thickness of the Narracoota Volcanics is about 6 km, but the complex deformation in the upper part makes an accurate estimate impossible. However, the formation does seem to have its maximum thickness along an axis from Ruby Well Find through Mikhaburra, perhaps extending into the Dimble area. In this latter area, Elias and Williams (1977) record considerable amounts of magnesian lavas, containing olivine, skeletal clinopyroxene, and devitrified glass. The Narracoota Volcanics lens out in the Doolgunna and Horseshoe areas by interfingering with Thaduna Greywacke.

Thaduna Greywacke

Extensive areas of greywacke, covered by a thin veneer of alluvium, but excellently exposed in water courses, have been encountered within and to the north of the major synclinorial axis (Fig. 34). These rocks, which bear a striking resemblance to the Thaduna Beds (MacLeod, 1970), hold a constant stratigraphic relationship to the Narracoota Volcanics in the area shown in the central part of Figure 33, and interfinger with the greywacke in the distal parts of the volcanic pile.

Additional field investigations between Doolgunna and Thaduna show that the Doolgunna-Karalundi-Narracoota stratigraphic interval passes laterally into a thick sequence of greywacke. Consequently the greywacke discussed here appears to be the same litho-stratigraphic unit as the undefined Thaduna Beds. For the present, it is convenient to use Thaduna Greywacke as a formal term to include all this greywacke in the Glengarry Sub-basin. The type locality of the Thaduna Greywacke is taken as the area surrounding the Thaduna Mine.

The Thaduna Greywacke is a thick turbidite sequence consisting of graded beds of coarse- to fine-grained lithic and feldspathic wacke with subordinate interbedded slaty mudstone. Like the arkose, the greywacke is invariable deeply weathered, exhibiting red, purple, buff and chocolate colours. The wacke beds contain a variety of sedimentary structures, such as single and multiple graded cycles, shale intraclasts, flute marks, load casts, convolute lamination and slumping. Individual wacke beds are generally of the order of 1 to 2 m thick.

Identifiable lithic fragments include basalt, jasper and shale, but the deep weathering limits petrographic study. Feldspar is abundant as discrete clasts and as matrix, but the relative contributions of microline and plagioclase are unknown. The only petrological descriptions of these rocks are of drill core from Thaduna by Trendall (1970). He described: lithic fragments of shale, tuff, lava, and siltstone; clasts of epidote, amphibole, quartz and albite; and matrices rich in chlorite and hematite. Such assemblages are consistent with derivation from the Narracoota Volcanics.

These rocks are interpreted as proximal turbidites marking a deep trough marginal to a rapidly accumulating submarine basalt pile.

Horseshoe Formation

The Horeshoe Formation is the unit of carbonate-cemented greywacke, shale and banded ironstone that occurs in a section extending for 3 km west from the Horseshoe gold mine, across the Horseshoe Range. It is used in the same sense as the 'Horseshoe Beds' of MacLeod (1970). No specific base is defined, as it is transitional upwards from the correlate of the Thaduna Greywacke, but for mapping puroses it is taken as the sudden break in slope at the eastern side of the Horseshoe Range. The top is taken as the base of the prominent orthoquartzite which marks the base of the conformably overlying Labouchere Formation. It is about 1 000 m thick.

The lowermost 300 m on the eastern slopes of Horseshoe Range is an interbedded dark-grey-green greywacke and chloritic shale, interbedded on a scale of centimetres up to about one metre. A typical greywacke bed is graded in the lower part, and planar laminated in the upper part. Rare fragments of chert, gneiss and sericitic shale occur up to one centimetre in diameter. The rock is composed of about equal proportions of quartz, microcline, and lamellae-twinned albite-oligoclase, in single-crystal grains up to 2 mm in diameter. Detrital flakes of muscovite and biotite are also present. The matrix contains fine chips of all the above minerals, together with opaques, chlorite and sericite and abundant carbonate cement.

The interbeds are of laminated green shale composed of fine quartz, biotite, chlorite and magnetite. Both greywacke and shale are stained by manganese dioxide. These rocks differ from the Thaduna Greywacke because of their finer bedding features, their darker colour, and a modal composition which indicates derivation from granitic and metamorphic terrain, rather than from mafic volcanics.

The most prominent member at Horseshoe Range is an iron-formation. At Mount Beasley, it is 250 m thick, and consists of three bands of iron-formation, each about 40 m thick, intercalated in quartz-chlorite-magnetite shale. These prominent bands consist of beds of chert-magnetite-?stilpnomelane iron-formation, green shale, and chert, alternating on a scale of 20 to 100 mm. Each bed shows lamination on a scale of millimetres.

Above the iron-formation is about 500 m of more calcareous, manganiferous shale and greywacke, which at Horseshoe Range is heavily replaced by supergene manganese and iron oxides. This upper part is better exposed in the areas 10 to 15 km to the south, where there is calcareous greywacke and shale similar to the lower part.

The iron-formation member has a limited strike extent of 50 km, and 25 km south-southeast of Mount Beasley, it thins to a number of beds or iron-formation less than 1 m thick.

The Horseshoe Formation marks the filling of the deep geosynclinal trough, the cessation of volcanogenic sedimentation, and a transient period of quiet shallow-water sedimentation during which chemical sediments precipitated in isolated depressions.

Labouchere Formation

The unconformity that marks the top of the Glengarry Group is now known to occur within what has previously been called the 'Labouchere Formation' within the Padbury Group. The major part of this formation is in conformable sequence with the Glengarry Group, and the coarse conglomerate at the top of the formation as originally defiined is now regarded as the basal unit of the Padbury Group, the Wilthorpe Conglomerate.

In accordance with the original usage of MacLeod (1970) and the intention of Barnett (1975) the name Labouchere Formation is now applied to the thick sequence of sandstone and slaty sericitic siltstone that can be traced from the type area at Mount Labouchere to the Horseshoe Range, where it conformably overlies the Horseshoe Formation.

At Mount Labouchere, the formation consists of medium-to coarse-grained orthoquartzite at the base, overlain by an interbedded sequence of quartzose feldspathic wacke and phyllitic shale, in which the wacke becomes better sorted and the shale proportion increase at higher levels. The term 'wacke' was used to indicate sandstones containing more than 10 per cent matrix, which in this rock is sericitic and argillaceous. However, they are not related in any way to greywacke turbidites, and in order to preserve the distinction, the term sandstone is used in this paper.

The section is 5 000 m thick in the Mount Labouchere area but is incomplete because of faulting. The greatest thickness occurs in the area 30 km south-southeast of Mount Labouchere, where an additional 2 000 m of sericitic slate with siltstone and sandstone appears, before being cut out by the unconformity at the base of the Padbury Group.

The sequence on the western side of the Horseshoe Range is comparable to that at Mount Labouchere. The basal quartz, which is the most conspicuous marker horizon in the Glengarry Group, is again about 300 m thick, but has become better sorted and contains thin, shale interbeds. It is medium grained, with well-rounded quartz grains and sparse feldspar in a siliceous cement. The beds range from 0.1 to 3 m in thickness, and low-angle trough cross-bedding and linguoid ripple marks are present.

The overlying sequence consists of beds of argillaceous sandstone, some with detrital muscovite and feldspar, intervals of sericitic quartz siltstone with thin interbeds of ripple-marked clean sandstone, and fine-grained sericitic and laminated mudstone (now phyllite in places).

Cross-bedding of various types, such as small linguoid ripples, and planar and tangential megaripples occur within normally planar beds which range from 0.1 up to 1.5 m in thickness. These features, together with the presence of shale, indicate that the Labouchere Formation was deposited on a marine shelf. The sedimentary structures record sediment-dispersal currents.

PADBURY GROUP

The definiton of the Padbury Group (Barnett, 1975) is amended to exclude the Labouchere Formation (and the Horseshoe Formation) and to include the newly defined Wilthorpe Conglomerate. Barnett (1975) noted that the topmost 1 000 m of what he refferd to as the "Labouchere Formation" consisted of conglomerate and quartzose-feldspathic granule sandstone, and it is only this conglomeratic unit, the Wilthorpe Conglomerate, that remains in the Padbury Group.

Evidence for regional unconformity below the Padbury Group

Unconformity between the Padbury and Glengarry Groups is indicated by the following evidence.

1. A proven unconformity lies between the Wilthorpe Conglomerate and basement gneiss at locality 118° 18′20″E, 25°28′40″S.
2. Discontinuous lenses of boulder conglomerate (correlated with the Wilthorpe Conglomerate) occur at several other localities (Fig. 34) immediately below the Robinson Range Formation.
3. Angular discordance on the local and regional scale, between bedding in the Wilthorpe Conglomerate and cleavage in underlying phyllite is observable, although the unconformity surface itself is not exposed.
4. The Wilthorpe Conglomerate and the Robinson Range Formation overlie a variety of rock types which represent different stratigraphic levels in the Glengarry Group.
5. The Wilthorpe Conglomerate contains clasts of distinctive rocks which can be matched with particular stratigraphic units low in the Glengarry Group.
6. There is a contrast between the Glengarry Group which contains several generations of cleavage and phyllitic schistosity, as well as metamorphic garnet, muscovite, biotite and tremolite, and the Padbury Group which generally has only one cleavage and is unmetamorphosed.

Wilthorpe Conglomerate

The type area of the Wilthorpe Conglomerate lies 5 km east-northeast of the Wilthorpe Mining Centre. Here it consists of boulder and cobble conglomerate, passing upward through feldspathic sandstone with abundant pebble beds into siltstone and shale with thin, white chert layers, and is finally conformably overlain by the Robinson Range Formation. This predominantly conglomeratic unit occurs more or less continuously around the Padbury Syncline.

At the unconformity locality on the western side of the Padbury Syncline large boulders up to 1 m in diameter directly overlie the unconformity, and together with granite clasts form a conglomerate with a matrix of feldspathic sandstone containing abundant detrital muscovite. Clasts within the body of the Wilthorpe Conglomerate consist predominantly of fine-grained silica- or hematite-cemented orthoquartzite, that can be matched with the Karalundi Formation, and with Finlayson-type sandstone. Clasts of vein quartz and lepidoblastic-textured metamorphic quartzite are also common. Seldom do the coarse conglomerates actually outcrop; they are usually expressed as talus slopes of well-rounded boulders up to 3 m in diameter. The coarse conglomerate beds appear to be up to 100 m thick.

The conglomeratic sandstone occurs in lensoid units, several metres thick, which define a crude stratification. Imbrication of pebbles and low-angle trough-type cross-bedding are evident. There is commonly an upward fining of all clasts within the sedimentation unit.

The conglomeratic rocks have a cleavage, and the pebbles are deformed by brittle-style cracking, a feature common to all occurrences of the Wilthorpe Conglomerate. Some pebbles, however, show some evidence of stretching, flattening, and mineral lineation, but their fabric is not consistent with respect to the cleavage, and some of these deformed pebbles also participated in the sedimentary imbrication. It is suggested that at least some of these pebbles are recycled from an older, previously stretched conglomerate.

The Wilthorpe Conglomerate has its maximum thickness of about 1 000 m around the Padbury Syncline, an area adjacent to the Yarlarweelor Gneiss Belt. It is only intermittently exposed beneath the Robinson Range Formation further east, and is commonly covered by scree of iron-formation.

One area of reasonably good exposure below the Robinson Range Formation on the northern side of the Robinson Syncline consists of finely interbedded white chert and hematitic and sericitic shale with rare pebbles, which passes conformably up into the iron-formation. At another locality in the southeast part of the Millidie Syncline (118°34'00"E, 25°42'30"S) a similar chert-shale sequence contains interbeds up to 10 m thick of flaggy cross-bedded sandstone and pebbly siltstone containing well-rounded clasts of orthoquartzite up to 0.1 m in diameter.

These features suggest a discontinuous development of the conglomeratic phase, and furthermore, the fluvial features lead to the suggestion that the Wilthorpe Conglomerate records the position of large rivers that spread out over a peneplaned surface over which chert and ferruginous silts were elsewhere being deposited.

Robinson Range Formation

In the western part of the area, the Robinson Range Formation consists of a prominent layer of finely laminated chert-magnetite banded iron-formation, underlain by hematitic shale, which contains thin beds of banded iron-formation, and overlain by laminated chlorite-hematite shale. Barnett (1975) noted an upper zone in the main iron-formation layer in which bedding is indistinct, and clastic textures are apparent.

This feature is most characteristic of the Robinson Range Formation in the Robinson Syncline, where two regionally concordant ridges are separated by magnetite-bearing hematite-sericite shale. The lower unit is a true banded iron-formation, but the upper unit is a granular iron-formation with discontinuous bedding on the outcrop scale.

The granular iron-formation is characterized by lenses of granular and oolitic chert 10-20 mm thick, more continuous beds of the same thickness or red jasper, and beds of clastic ironstone up to 1 m thick. Clasts in the ironstone include spherical granules of chert 0.5 mm in diameter, fine grained hematitic shale, green chloritic shale, chert, and specular hematite up to 10 mm in diameter, and larger fragments of jasper. All clasts appear to have been derived from the immediate sedimentary environment. None of the original Fe-silicate mineralogy is preserved.

These rocks bear a striking similarity to the granular iron-formations of the Frere Formation in the eastern part of the Earaheedy Sub-basin, rock which Hall and Goode (1978) interpret as precipitates of iron silicates and chert in a shallow-marine environment disturbed by current activity. The lithological similarity is the basis of the proposed correlation of the Padbury and Earaheedy Groups (Bunting and others, 1976).

Millidie Formation

This is the higest stratigraphic unit of the Padbury Group, and is best exposed in the Millidie Syncline, where there is at least 1 500 m of feldspathic wacke, with sandstone, chert, dolomite, sericitic and hematitic shale and granular iron-formation. Exposure in the Padbury and Robinson Synclines is particularly poor, there being only iron- and manganese- stained shale and sandstone, with extensive developement of calcrete, presumably over dolomite.

Mount Leake Sandstone

Gently dipping beds of orthoquartzitic sandstone occur in a line of exposures from Bilyuin to Mount Leake. These beds unconformably overlie the vertically dipping Glengarry Group, the unconformity being well exposed on the southern slopes of Mount Leake. This unit is defined as the Mount Leake Sandstone and has its type section at Mount Leake (119°09'30"E, 25°47'00"S) where it is 15 m thick.

Characteristically it supports a chalcedonic cap with large colloform and breccia structures of uncertain origin, but it is suggested that the rock originally had a carbonate cement. Below this cap, the rock is a silica-cemented, fine-grained, well-sorted and well-rounded orthoquartzite, commonly containing small rounded flakes of glauconite. It is flaggy bedded, and abounds in trough crossbedding. Resting directly on the unconformity at Mount Leake is a thin stromatolite layer that has been totally replaced by chert.

The stratigraphic relations of the Mount Leake Sandstone are unknown; it could be an outlier of Bangemall Group, or part of a westerly extension of the Earaheedy Group, or a remnant of a new sedimentary sequence, as yet unidentified in the Glengarry Sub-basin.

TECTONIC DEVELOPMENT

Geosynclinal phase

Reconstruction of the Glengarry Sub-basin is shown in Figure 35. It is postulated that the almost continuous blanket of basal sandstone and conglomerate is broken

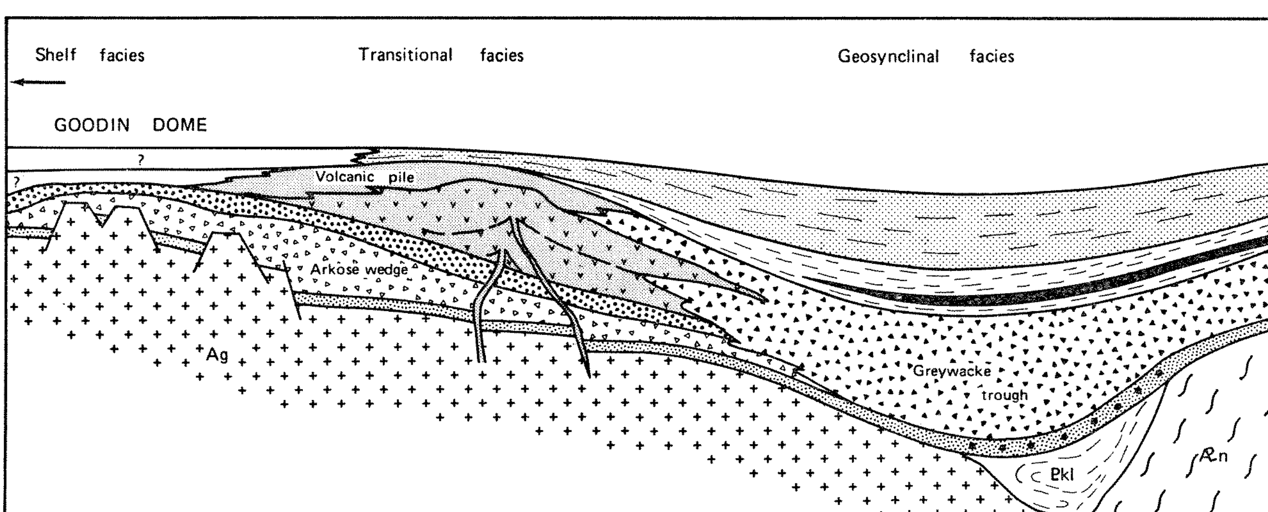

Figure 35 Diagrammatic section of the Glengarry Sub-basin from Goodin Dome northward to Horseshoe area, showing distribution of facies, and relationship of arkose wedges, volcanic pile and greywacke trough. Symbols are same as in Figure 34.

only over the Goodin Dome, where block-faulting elevated granite into a palaeo-high which was the source for the arkose wedges.

A deep geosynclinal trough developed across the northern margin of the cratonic Yilgarn Block, possibly located on a major crustal suture between different types of Archaean basement. The relationship between the geosynclinal and stable-shelf facies is not discussed here, however, it is worth noting that the Karalundi Formation appear to mark the transition from shelf to trough. The thick volcanic pile is localized along the hinge line of basin development. Calcareous shale, shallow-water conglomeratic sandstone, tuff and basalt lava were laid down here. At the same time, volcanogenic debris slumped off the volcanic pile, and was transported into the trough by dense turbidity currents to form greywacke.

The deposition of carbonate-cemented greywacke and a lens of banded iron-formation marks the termination of rapid subsidence and the filling of the trough. Then followed a period of vigorous fluvial and near-shore arenaceous sedimentation.

Main Deformation Phase

Bunting and others (1977) and Williams and others (1978) have previously interpreted deformation in terms of Archaean basement domes, driven by upward-rising Proterozoic granites. This picture is consistent with the revised stratigraphy, and it is further evident from the complex depositional and deformational history that this was a long-continuing episodic process.

Identification of an overall coherent structure in the Glengarry Group is obscured by the strong deformation, both before and after deposition of the Padbury Group. However, regional facings reveal a synclinorium more-or-less coincident with the synclinorium expressed by the Padbury Group. Contacts of the Glengarry Group with the metamorphic rocks of the Marymia Dome are still intact, but possibly as much as 10 km of stratigraphic thickness is absent adjacent to the bulbous end of the Yarlarweelor Gneiss Belt; this points to the region being a major shear zone. Infolded and metamorphosed remnants of the Glengarry Group occur in this reworked basement area. A 1.7 b.y. age for metamorphic muscovite (Williams and others, 1978) dates the main metamorphic event of the Glengarry Group. Consistent with the polyphase deformation, evidence of strain-slip and crenulation cleavage overprinting slaty cleavage is ubiquitous, but regional examples of refolded structures have not been identified. One of the most conspicuous pre-Padbury structures is the major east-west fault that emanates from a strong shear zone between the Yarlarweelor Gneiss Belt and the Yilgarn Block and extends to the western end of the Marymia Dome (Fig. 36). The nature of displacement on this fault is uncertain.

Second phase sedimentation and deformation

Following the orogenic climax, there was a period of uplift, erosion, and peneplanation, and then the Padbury Group was deposited as an upward-fining sequence of fluvial clastics and chemogenic rocks. The appearance of greywacke in the Millidie Formation indicates a return to active basinal sedimentation, but the record of this is incomplete.

Deformation of the Padbury Group followed the same earlier pattern—compression between reactivated basement domes and the stable basement of the Yilgarn Block (Fig. 36). Upright, near-isoclinal folds, spectacularly outlined by the Robinson Range Formation, are clearly related to basement domes. The Padbury Syncline is arcuate around the end of the Yarlarweelor Gneiss Belt; the Robinson Syncline is arcuate about the Marymia Dome; and the amoeba-shaped Millidie Syncline is crumpled between the two domes.

The last recorded tectonic event in the Yarlarweelor Gneiss Belt is the emplacement of Proterozoic granite dated about 1.6 to 1.5 b.y. (Williams and others, 1978). This event dates the deformation of the Padbury Group, and hence places a younger age limit on Padbury Group sedimentation.

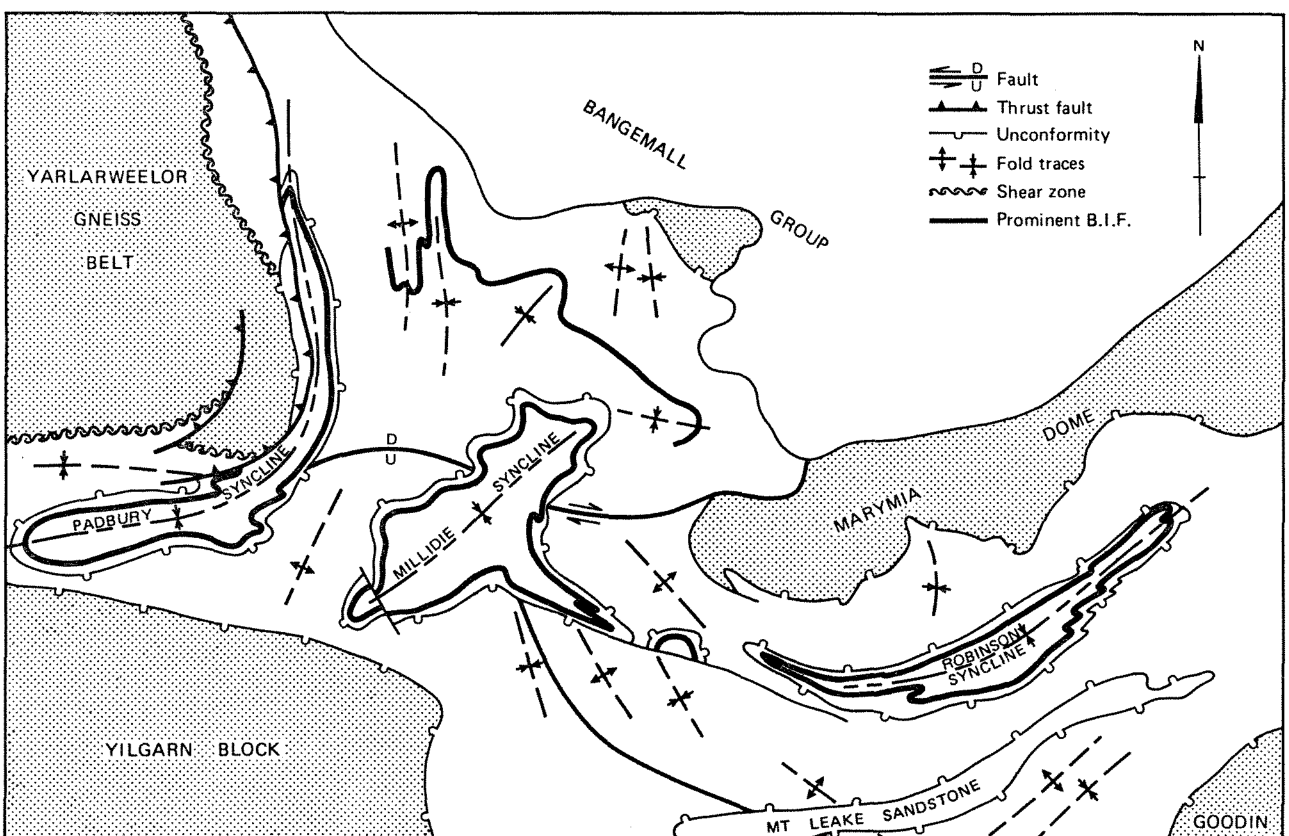

Figure 36 Structural map,showing relationship of regional folds to basement highs and domes (shaded). The area of this figure is the same as Figure 34.

IMPLICATIONS FOR THE PROTEROZOIC GEOLOGY OF W.A.

The identification of a major unconformity between the Padbury Group and the Glengarry Group, and the discovery of abundant granular iron-formations in the Padbury Group, which are similar to those in the Earaheedy Group, supports the proposal of Bunting and others (1977) that the Earaheedy Group in the eastern part of the Nabberu Basin unconformably overlies the Glengarry Group. No additional evidence is forthcoming from this present study to clarify the ages of the various sedimentary sequences, but the conclusions are consistent with the previously suggested ages of 1.7 to 1.6 b.y. for the Padbury Group and 1.8 to 2.0 for the Glengarry Group (Williams and others, 1978).

It is not the intention of this paper to present a tectonic synthesis of the northern margin of the Yilgarn Block, as this requires elucidation of the relationships between the geosynclinal and stable-shelf facies of the Glengarry Group, and an examination of the easterly extension of the Glengarry Group toward the Earaheedy Group. However, it is appropriate to examine possible relationships with other major sequences on the Precambrian Shield of Western Australia.

Most striking is the gross lithological similarity of the Glengarry and Wyloo Groups, both of which are thick geosynclinal sequences containing arkose, greywacke, carbonates and basalt. These two sequences have a comparable age, the Wyloo Group being later than the Woongarra Volcanics (Trendall, 1979), and hence younger than 2.0 b.y. (Arriens, 1976). Furthermore, there is almost a physical continuity between the two sequences, expressed by the infolded belts of Proterozoic metamorphic rocks throughout the Gascoyne Province Williams and others, 1979). This reconstruction points to an elongate belt of thick greywacke and volcanic fill of geosynclinal dimensions occupying the broad area between the Hamersley Basin and the Yilgarn Block, and suggests the emergence of a major, and hitherto unrecognized, tectonic element in the Western Australian Shield.

Relatively small elongate belts of fluvial sandstone and conglomerate occur throughout the Gascoyne Province (Williams, Williams, and Chin, 1979). They uncoformably overlie the metamorphic rocks, and clearly post date the orogenic climax, however they have been deformed during the emplacement of the Proterozoic orogenic granitoids. These sediments may correlate, by virtue of their similar tectonic setting, with the Padbury Group.

These broad chronostratigraphic relations, together with the currently accepted ages for the basement units in the Western Australian Shield, are shown diagramatically in Figure 37. This figure presents a model for the Proterozoic tectonic evolution for the region between the two stable Archaean cratons in the Western Australian Shield.

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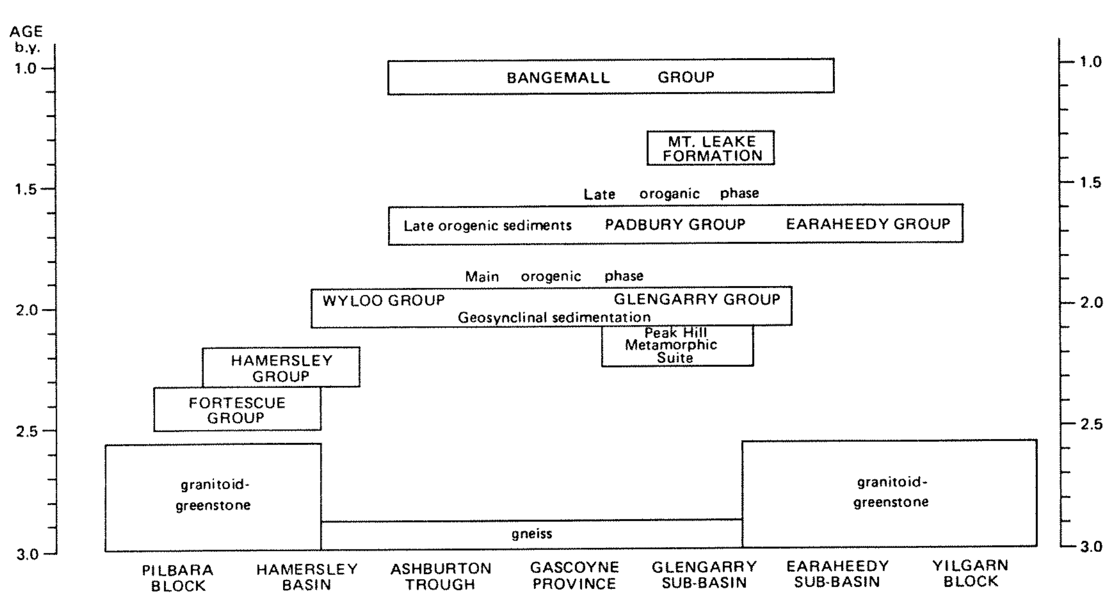

Figure 37 Diagram showing relationships of Padbury and Glengarry Groups to other major sedimentary and tectonic events in the region between the Pilbara and Yilgarn Blocks

A REVISION OF THE MOUNT BRUCE SUPERGROUP

by A. F. Trendall

ABSTRACT

All published accounts of the Proterozoic Hamersley Basin accept the stratigraphic framework established by MacLeod and others (1963), in which three consecutive groups, in ascending order the Fortescue, Hamersley, and Wyloo Groups, together constitute the Mount Bruce Supergroup, and represent the total content of the basin. Re-examination of the stratigraphy of the lower part of the Wyloo Group within a small area at the southwestern margin of the basin has revealed complexities which prevent continuing and consistent use of the established nomenclature, and the following revisions are proposed:

1. The lowest formation of the original Wyloo Group, the Turee Creek Formation, is raised to group status.
2. The lowest formation of the newly erected Turee Creek Group, locally containing the boulder-bearing and possibly glacigene Meteorite Bore Member, is defined as the Kungarra Formation.
3. The lowest formation of the revised Wyloo Group is the newly defined Beasley River Quartzite, the basal Three Corner Conglomerate Member of which marks the unconformity between the Wyloo Group and the underlying Hamersley and Turee Creek Groups.
4. The Mount Bruce Supergroup is consequently revised to exclude the revised Wyloo Group.

These revisions are consistent with the concept that the revised Wyloo Group (which constitutes the greater part of the Wyloo Group as hitherto accepted) was laid down in the Ashburton Trough (Gee, 1979), a belt of crustal subsidence to the south of, younger than, and tectonically distinct from the Hamersley Basin.

INTRODUCTION

In a initial report of striated and faceted boulders from the "Wyloo Group" (Trendall, 1976), it was noted that further work was planned in support of a more complete description of the occurrence. It was envisaged that this would include details of the stratigraphic status and extent of the mixtite containing the boulders. Work in 1976 showed that the stratigraphy of the mixtite could not adequately be described within the existing nomenclature of the "Wyloo Group", and in 1977 and 1978, the lower units of the group were re-examined over a slightly wider area, extending from the southwestern corner of the Mount Bruce 1:250 000 Sheet area to the adjacent southeastern part of the Wyloo Sheet area.

The purpose of this paper is to report the results of this wider study, which has led to a substantial stratigraphic revision of the lower part of the "Wyloo Group", and in consequence to a reassessment of the "Mount Bruce Supergroup".

In order to avoid confusion as to whether a revised stratigraphic name is used in this paper with a pre-revision or post-revision connotation, all revised names used in a pre-revision sense are placed between inverted commas. Thus "Beasley River Quartzite" means some or all, according to context, of the rocks represented on a map as such or referred to as such, in a previous publication. Beasley River Quartzite, without inverted commas, means the rocks defined and represented as such in this paper.

This revision is made at a time when the Council of the Geological Society of Australia has accepted a recommendation from its Stratigraphic Nomenclature Committee to replace the Australian Code of Stratigraphic Nomenclature (GSA, 1964) by the International Stratigraphic Guide (Hedberg, 1976). At the time of writing the procedural details of this transition are unclear, and for the purpose of this paper the requirements of the Australian Code are accepted as the criteria for determining the present validity of names already in use, while the International Guide is employed in the process of revision.

PRESENT STATUS OF THE "WYLOO GROUP"

Attention has previously been drawn (Trendall, 1975) to the fact that the constituent formations of the "Wyloo Group", the uppermost of the three groups which form Halligan and Daniels' (1964) "Mount Bruce Supergroup", have never been properly established in accordance with the Australian Code of Stratigraphic Nomenclature (GSA, 1964). Article 19 of this Code required that a new formation be 'explicitly defined at the time of its proposal'. A critical omission from all early references to these formations was that of any described type sections or localities. In terms of Articles 11 and 12 of the Code, none is therefore a valid unit, or can consequently be regarded as validly or formally named. It follows that the "Wyloo Group" itself has the same status.

The name "Wyloo Group", and the names of many of its constituent units, have nevertheless been widely and usefully applied since their roughly concurrent introduction by MacLeod and others (1963), Halligan and Daniels (1964), and de la Hunty (1965). These authors' stratigraphic intentions were generally clear through the representation of their named units on accompanying maps. From these publications, and from the later publication of further 1:250 000 scale maps with extensive "Wyloo Group" outcrop (Daniels, 1968, 1970), the name came to cover all the sedimentary and associated volcanic rocks stratigraphically above the Hamersley Group and below the Bangemall Group, with the exception of certain specifically separated groups such as the Bresnahan and Mount Minnie Groups.

In this sense the group reached the state of subdivision shown in the left hand column of Table 16, in which the revisions made in this paper are also summarised.

JUSTIFICATION FOR REVISION

Within the area whose re-examination is reported here:

(i) the "Turee Creek Formation" is overlain with marked unconformity by the "Beasley River Quartzite",

(ii) parts of the "Beasley River Quartzite" are continuously mappable into the underlying "Turee Creek Formation", and

(iii) different parts of the "Beasley River Quartzite" are separated by a major unconformity.

The first point formally precludes the permissibility of retaining both formations within the same group (GSA, 1964), while the second two points make it essential that some defining type sections be established.

THE AREA USED AS A BASIS FOR REVISION

The geology of the area selected as a basis for "Wyloo Group" revision is shown in Figure 38. The map there presented is generalized from the published Wyloo (Daniels, 1970) and Mount Bruce (de la Hunty, 1965) 1:250 000 Sheets, with boundaries interpolated across areas of Tertiary or later cover. The dominant structure of the area is the east-west anticline which culminates in the Wyloo and Rocklea Domes; the name Wyloo-Rocklea Anticline is suggested for it. Its northern limb forms the south limb of a complementary syncline, the Duck Creek-Brockman Syncline, which has a sub-parallel, but more irregular, axial trend. Similarly, its southern limb forms, in the east of the illustrated area, the northern limb of the complementary Hardey Syncline. All these folds are cut by southwesterly trending faults. Two of these, which together exert a stronger effect than others on the structural trends shown, are here called jointly the Menindee Fault Zone. Two subareas, whose outlines are shown on Figure 38 are described in more detail below and are used as a basis for definition of the new stratigraphic names used in this paper. The western subarea is called the Wyloo Dome subarea, and that to the east the Hardey Syncline subarea.

Within the area of Figure 38 no lateral stratigraphic variation is known to exist within the Hamersley Group, as established by MacLeod and others (1963) and elaborated by Trendall and Blockley (1970), other than local absence of the uppermost part caused by the unconformable overlap of the Wyloo Group. Although the thicknesses of some Hamersley Group formations are obviously reduced locally, this occurs where it is credibly attributable to tectonic strain, as for example along the eastern margin of the Menindee Fault Zone.

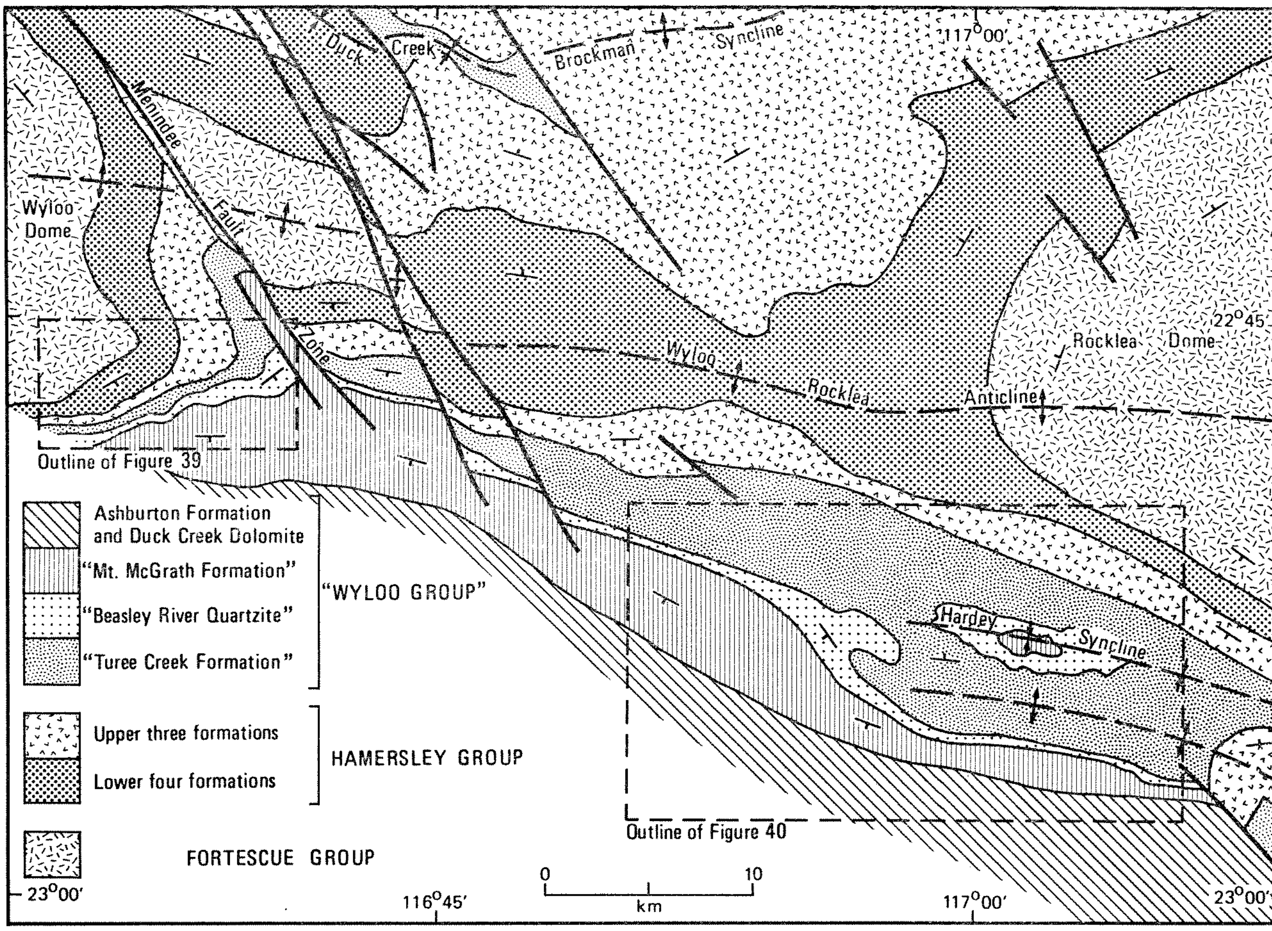

Figure 38 Geological map of the area in this paper as basis for revision of the Mount Bruce Supergroup. The outlines of the Wyloo Dome (Fig. 39) and Hardey Syncline (Fig. 40) subareas are also shown.

WYLOO DOME SUBAREA

A revised geological map of this area appears in Figure 39. For this map, the nominal 1:50 000—scale (airphoto) line compilations used for reduction to the 1:250 000 scale of the published map (Daniels, 1970) were used as a base, and alterations were made only to re-examined boundaries. Consequent modifications, apparent from a comparison of Figures 38 and 39, affect mainly the "Turee Creek Formation" and "Beasley River Quartzite" of Figure 38, which are there represented as stratigraphically concordant and continuous. The revised geological map of Figure 39 serves as a basis for definition below of the revised Beasley River Quartzite and its basal Three Corner Conglomerate Member, which unconformably overlies, from west to east and in ascending stratigraphic order, the Woongarra Volcanics and the Boolgeeda Iron Formation of the Hamersley Group, and the newly established Kungarra Formation of the Turee Creek Group.

BEASLEY RIVER QUARTZITE

Preliminary note

The type section defined here is, in fact, a 'lectostratotype' in the sense of Hedberg (1976, p. 26): a stratotype selected later in the absence of an adequately designated original stratotype.

Type section (stratotype)

The position of the designated type section is shown on Figure 39. Its base is in a deeply incised valley which drains south-southeast at 22°46′50″ South, 116°37′47″ East. This point is 86 mm on a bearing of 350°50′ from the principal point of 1957 air photo, Wyloo, Run 15 No. 5817. From it, the section extends for a distance of about 700 m on a bearing of approximately 160°; for the first 500 m, the excellent exposures along the sides and in the floor of the valley define the type section, but the remaining part of the section then continues over a sharp ridge while the valley bends abruptly westwards.

The basal 100 m of the Beasley River Quartzite consists of the Three Corner Conglomerate Member, details of which appear further below. This conglomerate is succeeded upwards by 240 m of massive, white or pale-green, well-cemented orthoquartzite, with an average dip of about 35° to the south-southeast. The quartzite is well bedded in units mainly 0.2 to 1 m thick, but some sections are more flaggy, and in others the quartzite is glassy with barely detectable bedding. Cross-bedding is common, with sets mainly 0.2 to 0.4 m thick, and ripple marks are locally present. The quartzite is well jointed, but forms steep cliffs on either side of the valley. This continuous section of massive quartzite is succeeded by about 12 m of greenish-grey, very finely laminated shale. This is in turn overlain by about 8 m of conglomerate with closely packed angular and rounded pebbles of black and white chert up to 80 mm across. Above this conglomerate, a further 50 m of massive white quartzite is lithologically similar to that of the main central quartzite.

The total thickness of the Beasley River Quartzite in the type section is thus about 400 m, including the basal Three Corner Conglomerate Member. Some minor folding in the upper part, and uncertainties in determination of the true average dip, give this figure an uncertainty of about 10%.

To the south of the type section, the uppermost quartzite of the Beasley River Quartzite is separated from a thick well-exposed dolerite sill by an exposure gap of a few metres. South of this, only thin, grey, silty quartzite and shale associated with the lower part of the Cheela Springs Basalt are present; no discordance has been shown to exist between the two units.

The type section is most conveniently reached by leaving the main Nanutarra-Tom Price road about 4 km west of the turn-off to Meningee Well and driving about 3 km across country in a north-northeasterly direction; it is then necessary to walk for about 2 km to the top of the type section.

Derivation of name

Although the selected type section lies some 35 km west-northwest of the lower part of the Beasley River, there is little doubt either of its correlation with the reference section established below, which is closer to the river, or

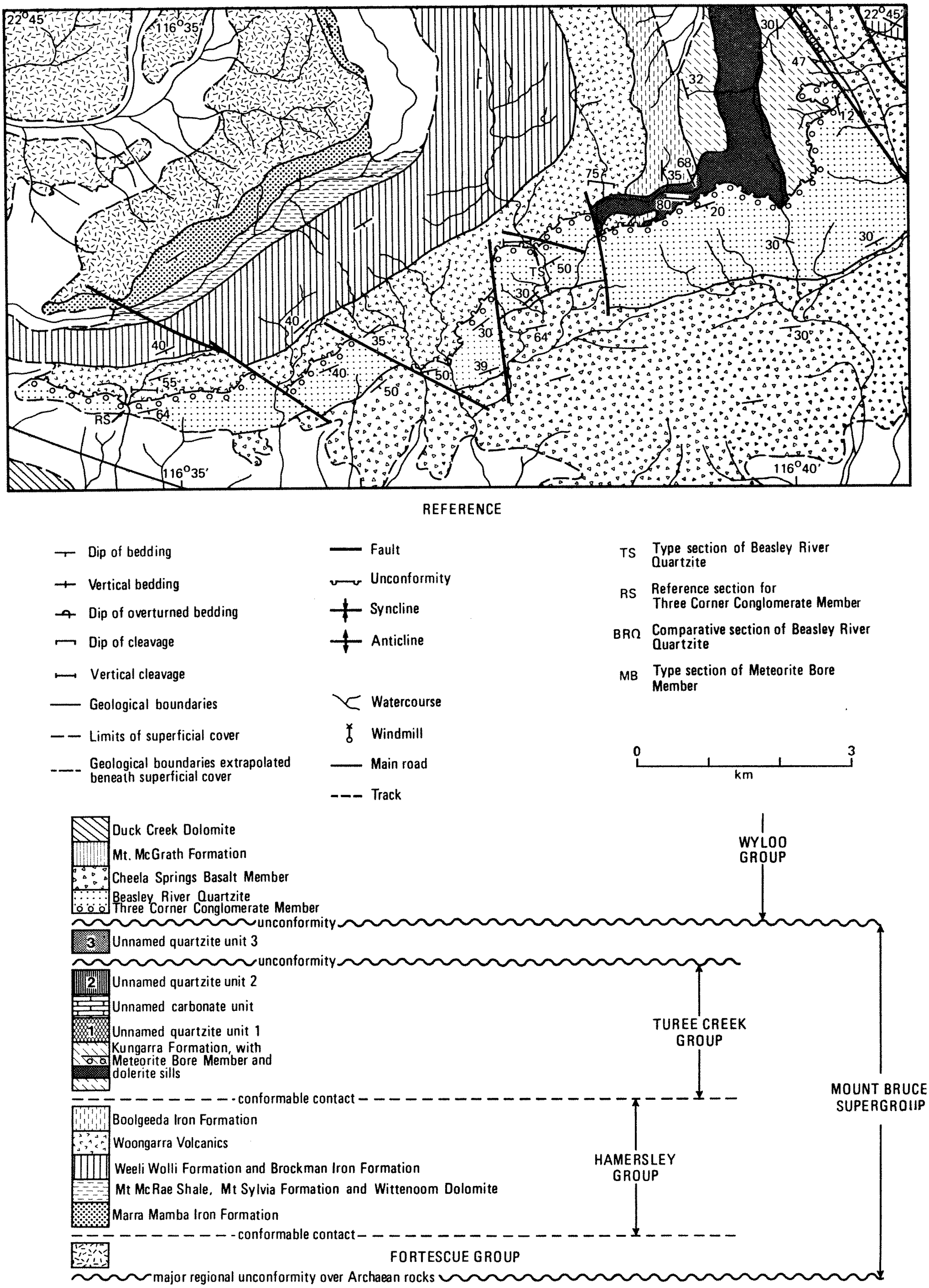

Figure 39 Geological map of the Proterozoic rocks of the Wyloo Dome subarea; superficial deposits are left blank. See Figure 38 for location.

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that it represents the "Beasley River Quartzite" as stratigraphically intended by Daniels (1970). The name is therefore retained.

THREE CORNER CONGLOMERATE MEMBER

Type section (stratotype)

The Three Corner Conglomerate Member forms the lower-most part of the Beasley River Quartzite, the base of which has been specified above, and is marked on Figure 39. Although the member at the type section is known from regional stratigraphy to be unconformable over the Woongarra Volcanics, this relationship cannot be established at the contact: the underlying Woongarra Volcanics consist of autobrecciated rhyolite with a strong, vertical, east-west cleavage, and no disconcordantly truncated primary structure can be seen. The contact can be established on both slopes of the valley to within a few metres, and dips south-southwest at about 40°.

The conglomerate immediately above the base consists almost entirely of close-packed fragments of cherty, banded iron-formation (BIF) characteristic of that present in the Weeli Wolli Formation of the Hamersley Group. Striking red and black, or red and white definition of both mesobands and microbands is common. Most such fragments are between 0.02 and 0.1 m across, but some reach a length of about 0.2 m. They are mainly platy, with their length parallel to both the bedding of the conglomerate and the internal banding, but the latter may be oblique or perpendicular to the clast length. All are angular, with somewhat abraded edges. Clasts not clearly identifiable as derived from the Weeli Wolli Formation include boulders derived from the Woongarra Volcanics, and clasts possibly derived from other (lower) iron-formations of the Hamersley Group. The clasts of Woongarra Volcanics tend to be more rounded than the BIF fragments, and reach a greatest length of 0.4 m. All the clasts are strikingly close packed, and pressure-solution embayment is common between fragments of differing type. The interstices are occupied by a coarse angular sand of BIF debris.

Apart from its expression by a long-axis orientation of the clasts there is no clear stratification in the lower parts of the conglomerate, although a blocky parting in beds 2 to 4 m thick may represent a primary bedding structure. However, with increasing distance above the base there is a gradual increase in frequency of partings of coarse, often cross-bedded, ferruginous sandstone 0.1 to 0.3 m thick. The appearance of these beds is associated with a steady but slight decrease in the average clast size to about 50 mm, due mainly to a decrease in the largest size fraction.

Within the lower 60 m of the member these textural transitions are gradual, but above this interval there is a relatively abrupt change in facies. The upper 40 m of the member consists of coarse-grained, often cross-bedded grey quartzite with scattered pebbles of BIF debris, interbedded with pebbly conglomerate. Measured dips range from 35° to 44° to the south-southeast throughout the type section. At the top of the member, the transition to the white or pale-green orthoquartzite of the main body of the Beasley River Quartzite is again relatively abrupt.

Reference section (hypostratotype)

The following reference section is established because of the relative inaccessibility of the type section, which was selected because the complete thickness of the Beasley River Quartzite is exposed there. At this reference section the Three Corner Conglomerate Member is as well exposed, and stratigraphically almost identical to, the type section, but the overlying quartzite is truncated.

The base of the reference section (Fig. 39) lies in a deeply incised valley draining southwards at 22°47′58″ South, 116°34′36″ East. This point is 72 mm on a bearing of 300° from the principal point of 1957 air photo, Wyloo Run 15, No. 5816. As at the type section, the conglomerate unconformably overlies intensely cleaved rhyolite of the Woongarra Volcanics; the cleavage dips at 75° to the south. The contact dips at about 60° to the south-southeast. The lithology of the member is as described for the type section. However, the lower unstratified or weakly stratified conglomerate is here 80 m rather than 60 m thick; the upper, pebbly quartzite and conglomerate is 40 m thick at both localities. Dip is consistently concordant with the lower contact, at 60° to the south-southeast. Conformably overlying the member are about 50 m of flaggy yellow and brown quartzite terminated by a fault contact exposed in the right bank of the creek.

This reference section lies about 800 m north of the main Nanutarra-Tom Price road, 8 km west of the Menindee Bore turn-off, and is very easily accessible from it.

Derivation of name

The name is derived from Three Corner Bore, which lies 6 km from this reference section on a bearing of 282°; note that this bore is shown about 1 km too far east on the published 1:250 000 map (Daniels, 1970).

KUNGARRA FORMATION

On Figure 38, the siltstone, fine sandstone, and greywacke which concordantly overlie the Boolgeeda Iron Formation are correlated with the Kungarra Formation of the Turee Creek Group. These respectively new and revised names are defined below.

HARDEY SYNCLINE SUBAREA

A revised geological map of this area appears in Figure 40, the Reference column for which is included on Figure 39. Like Figure 39, this map is based on the airphoto-scale line compilations of Daniels (1970) west of longitude 117° East and of de la Hunty (1965) east of this longitude, with amendments only in restricted re-examined areas. The stratigraphy and structure of this subarea are clear from the map and the accompanying cross-sections of Figure 41. From the comparison of Figures 38 and 40 the amendments on the latter map involve, as for the Wyloo Dome subarea, a reinterpretation of the simple, stratigraphically concordant, and continuous relationship of the "Turee Creek Formation" and "Beasley River Quartzite". This subarea serves as a basis for upgrading the earlier "Turee Creek Formation" to group status and for establishing newly named units within it, as set out below.

TUREE CREEK GROUP

This major unit, herein raised to group from formation status, is defined as including the Kungarra Formation, which is defined below, and other sediments which overlie that formation in this subarea. These include the unnamed quartzite units 1 and 2, and the unnamed carbonate unit shown in Figures 40 and 41. They are not formally named and defined here because sufficient work has not yet been done to support full descriptions and some details of relationships remain uncertain. Unnamed quartzite unit 1 consists of both massive and flaggy white to pale-brown quartzite, locally with festoon cross-bedding. Quartzite unit 2 is more massive and glassy, and shows sporadic development of pebble conglomerate with abundant red chert debris. The estimated thicknesses of these unnamed units are shown graphically in Figure 42.

KUNGARRA FORMATION

Preliminary note

This formation is equivalent to most of the rocks represented as "Turee Creek Formation" on published 1:250 000 maps covering the Hamersley Basin.

Type area

Because of the normally poor exposure of this formation it is impracticable to designate a single type section. A type area is therefore defined as that part of the northern limb of the Hardey Syncline, between the vicinity of the Beasley River to the east and that of the Kungarra Gorge to the west, and between the top of the south-dipping Boolgeeda Iron Formation to the north and the base of the ridge-forming quartzite shown as unnamed quartzite unit 1 on Figure 40 to the south. The greater part of this area appears in Figure 40.

The lower part of the formation is particularly poorly exposed. The base crops out immediately south of Woongarra Pool, on the Beasley River at 22°53′ South, 117°06′ East (Trendall, 1976, pp. 38-39). Here 3 to 4 m of greenish flaggy siltstone dips south-southwest at 80° and conformably overlies the top of the Boolgeeda Iron Formation. The upper part of the formation is well exposed at the western end of the type area (Fig. 40) and also at the eastern end in the axial part of the Hardey Syncline. Apart from the Meteorite Bore Member, described below, the formation consists of a monotonous sequence of greyish-green siltstone, fine-grained greywacke, and fine-grained sandstone, in which the normally thin bedding is weakly defined by slight colour changes. Thin carbonates

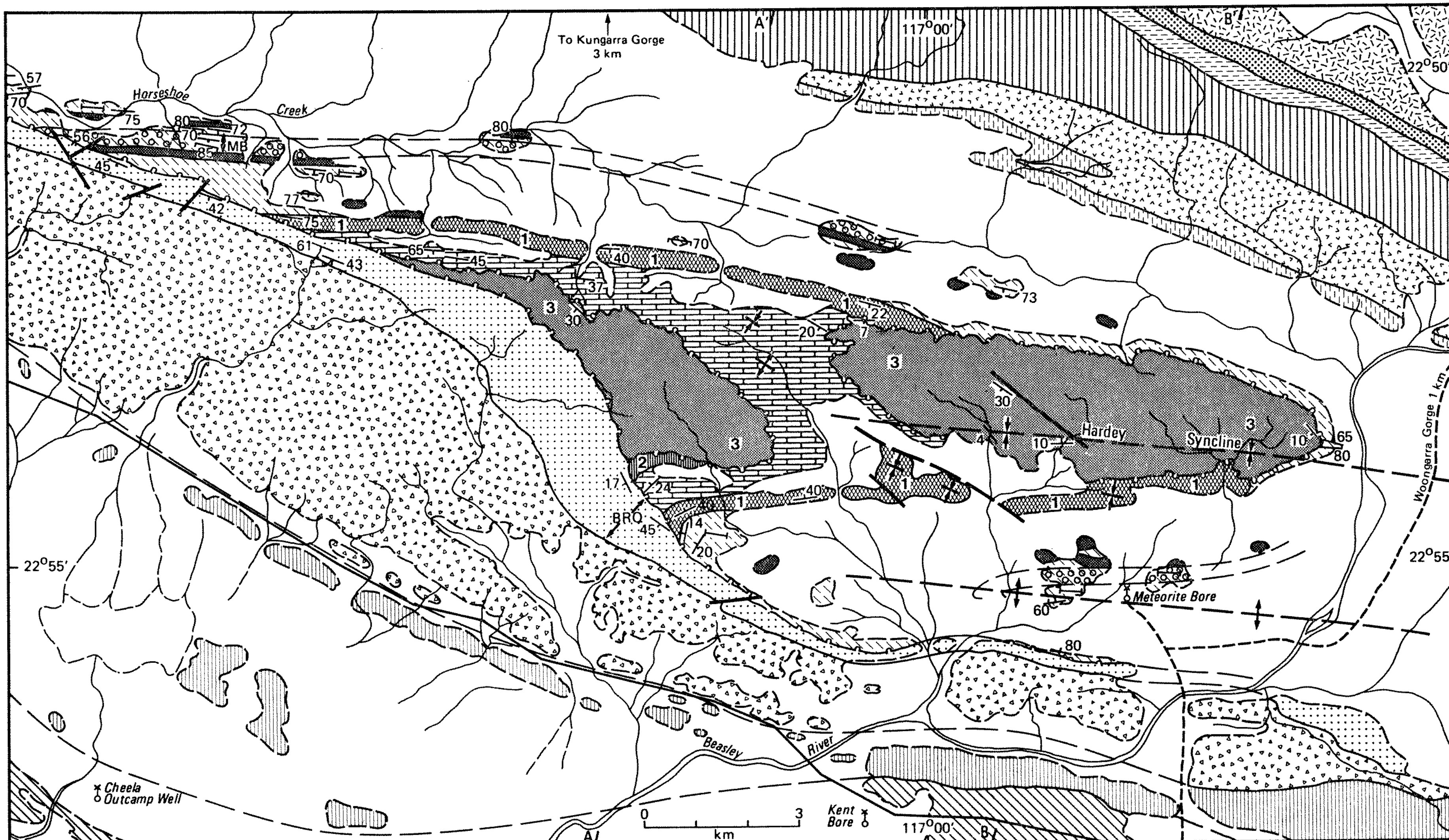

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Figure 40 Geological map of the Proterozoic rocks of the Hardey Syncline subarea; superficial deposits are left blank. See Figure 38 for location. The reference for this figure is included on Figure 39.

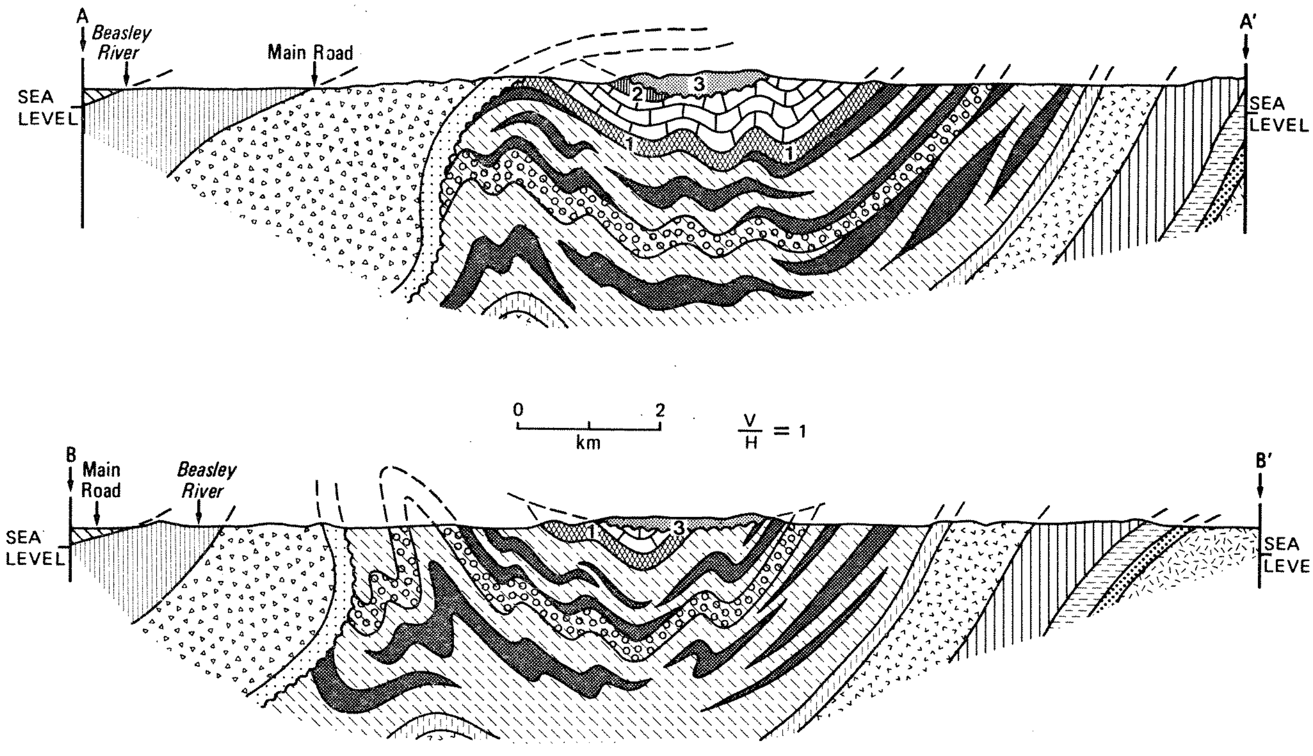

Figure 41 Vertical cross-sections along the lines marked A-A' and B-B' on Figure 40. Stratigraphic units are marked as in the reference of Figure 39.

are interbedded with siltstones in the higher parts of the formation. Throughout the type area, the formation has a strong cleavage, close to vertical and striking roughly east-west, which is normally more conspicuous than the bedding. The transition at the top of the formation to the unnamed quartzite unit 1 shown on Figure 40 is taken to be a stratigraphically concordant one because of its parallel outcrop with the Meteorite Bore Member. Dolerite sills are abundant within the formation, and probably form between 10 and 20% of its thickness.

Although minor folding is present locally, it is likely from the width of the outcrop area and the likely average dip that this formation has a total thickness of about 3 km.

Local correlation

The folding of the Kungarra Formation with the underlying Hamersley Group defines the Hardey Syncline, and the formation together with the Meteorite Bore Member, is continuously mappable, over the south side of the Syncline, as shown in Figures 40 and 41. Within the area of Figure 38, but *excluding* the area of Figures 39 and 40, the Kungarra Formation is probably equivalent to the previously mapped "Turee Creek Formation". This equivalence outside the area of Figure 37 has already been mentioned above.

Derivation of name

The name is derived from Kungarra Gorge (Fig. 40).

METEORITE BORE MEMBER

Type section

The type section is located at 22° 50′ 48″ South, 116° 52′ 12″ East, among steep rocky exposures on the south side of Horseshoe Creek; its position is marked on Figure 40. The member consists of mixtite (Schermerhorn, 1966), a form of conglomerate in which scattered boulders with a wide size range are sparsely and randomly distributed within a matrix of greenish-grey siltstone. In the type section, bedding is not visible, but bedding in the siltstone and fine sandstone of the Kungarra Formation, above and below the member, dips steeply to the south. The outcrop width of about 320 m gives a true stratigraphic thickness for the member of about 300 m.

The lithology of the mixtite at the type section is closely similar to that of the mixtite near Meteorite Bore described by Trendall (1976b), except that the contained clasts are smaller and less abundant. Boulders of fine sandstone, and a lesser proportion of acid volcanic rock, are evenly scattered through the silty matrix. Most of the sandstone boulders are tabular; the remainder, and all of the volcanic boulders, are roughly equant. They reach a length of up to 0.3 m, but most have greatest dimensions in the range 0.05 to 0.1 m. All have their shortest dimension perpendicular to the roughly vertical and east-west striking cleavage which is strongly developed at this locality.

A small proportion of both sandstone and volcanic clasts exhibit striation or grooving of a type suggestive of glacial origin.

Local correlation

The constant thickness and lithology of this member from its point of emergence from beneath the basal unconformity of the Beasley River Quartzite, eastwards through the type section (Fig. 40), and the close correspondence in both thickness and lithology between this mixtite on the north limb of the Hardey Syncline with that of the south limb, in the vicinity of Meteorite Bore, make it reasonable to suggest that a single continuous mixtite bed exists, as shown in Figures 41 and 42. Although the member may be expected to crop out in the hillslope exposures of the Kungarra Formation below the cliffs formed by the unnamed quartzite unit 3 in the axial area of the Hardey Syncline, it has not so far been seen, or sought, there.

Derivation of name

The name is derived from Meteorite Bore (Fig. 40).

STRATIGRAPHIC SYNTHESIS

The newly named units described above are displayed in column format in Figure 42, where approximate thicknesses and nominal lithologies of other stratigraphic units included on Figure 40 are also shown. The relationships of these are apparent from these two figures and from the cross-sections of Figure 41.

A key point in the comparative columns of Figure 42 lies in the correlation of the Beasley River Quartzite between the Wyloo Dome and the Hardey Syncline subareas. Although the basal Three Corner Conglomerate Member is almost continuous within the Wyloo Dome subarea it can be seen from Figure 39 that there is a central part of the outcrop of the Beasley River Quartzite, just east of a fault, from which it is absent. It is not certain whether this absence is a tectonic effect related to the fault, or whether this part of the quartzite was draped

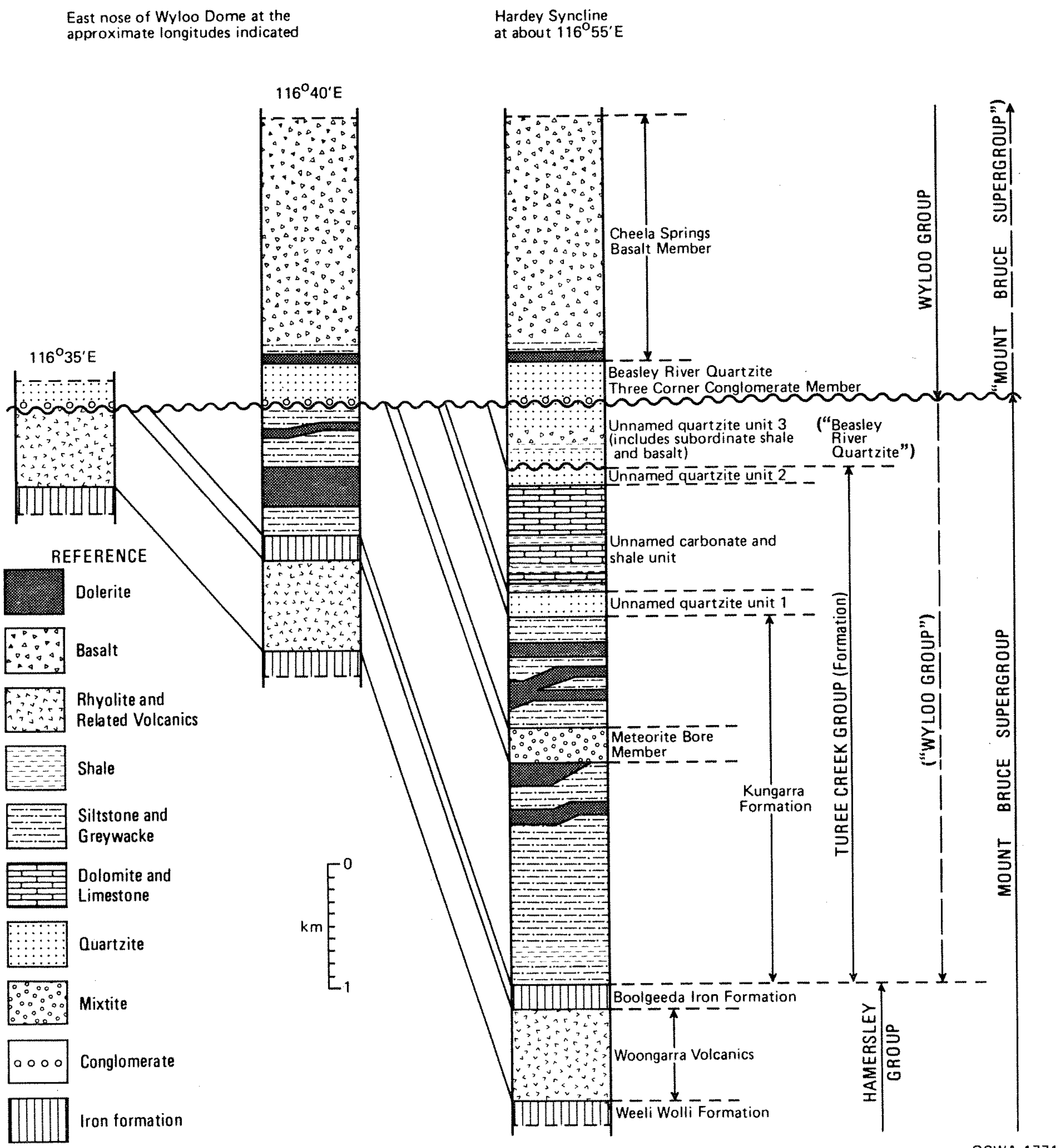

Figure 42 Comparative stratigraphic columns for two localities of Figure 39 and one of Figure 40. The nomenclatural revisions of this paper are displayed by showing the pre-revision nomenclature within brackets, and by pecked lines.

over a hill on an irregular palaeosurface of the Woongarra Volcanics. It may be that both possible reasons are partly true. However that may be, its absence indicates that the presence of the basal Three Corner Conglomerate Member is not an indispensible requirement for correlation of the Beasley River Quartzite beyond the area of Figure 39. An immediate difficulty occurs in eastward correlation of the quartzite across the Menindee Fault Zone. Slivers of conglomerate are preserved within the multiple bounding faults marking the western edge of this zone. One of them appears on Figure 38. Immediately east of the Menindee Fault Zone, no conglomerate is present at the base of the quartzite immediately succeeding the Kungurra Formation, but pervasive strain adjacent to the fault makes it uncertain whether the exposed succession is complete. Farther east, more faults prevent continuous lithostratigraphic correlation, and it is not until the northwestern part of the Hardey Syncline subarea (Fig. 40) is reached that there is reasonable stratigraphic continuity. The correlation with the Beasley River Quartzite of the quartzite marked as such on Figure 40 is based on the close lithological correspondence of the section marked "BRQ" with the type section. Although this section was not measured on the ground, the total thickness of the formation is estimated from air photos as 370 m, within which the basal coarse conglomerate, which is lithologically indistinguishable from the material of the lower part of the Three Corner Conglomerate type and reference sections, has an estimated thickness of 20 m. The continuity of this conglomerate has not been examined in detail, but it is certainly absent where the Beasley River Quartzite overlies the unnamed quartzite unit I, one kilometre to the southeast of the base of the "BRQ" section, and also to the northeast, for at least 7 km eastwards from the western edge of Figure 40; it is possible either that the dolomite below the "BRQ" section formed a valley in which conglomerate was preferentially deposited, or that the basal conglomerate has been sheared out by faulting at a shallow angle to the bedding during folding.

Two other stratigraphic amendments within the two subareas which will be apparent by comparison of Figures 39 and 40 with Figure 38 are both concerned with the identity of the "Mount McGrath Formation". The absence of a defined type section for this formation is particularly confusing, as preliminary work suggests that there is even more doubt about the correlation between its different outcrop areas than there has been for the "Beasley River Quartzite". Horwitz's (1978, Fig. 1) omission of the "Mount McGrath Formation", in displaying the stratigraphy of a part of the Wyloo Dome to the west of Figures 38 and 39, and outside the scope of this paper, appears to reflect a similar doubt concerning its status. It is likely that what appears on published maps as the "Cheela Springs Basalt Member" of the "Mount McGrath Formation" will need to be defined with formation status.

STRUCTURE AND SEDIMENTATION

Although it appears complex in detail, the structure of the area of Figure 37 may be envisaged simply as related to a system of open east-west folds of the granitic crust underlying the whole supracrustal sequence, and the *concurrent* development of a set of northwest-southeast faults, representing one of the two sets of oblique conjugate fractures that may be expected to develop. A diagrammatic simplification of the Wyloo-Rocklea Anticline illustrates this concept in Figure 43A. The real structural situation may be developed from this simple model by providing for branching or anastomosing of the faults, and for movement on them to be variously right-lateral vertical or with a rotational component due to fold shape differences between adjacent fault-bounded blocks. These possibilities are shown in Figure 43B.

An advantage of the model of Figure 43B, is that it provides an explanation both for the Menindee Fault Zone, as explained in the caption, and for the way in which many of the faults parallel to it (Figs. 39 and 40) die out along their length. Where this takes place towards the northwest it is seen as a result of rotational movement; where

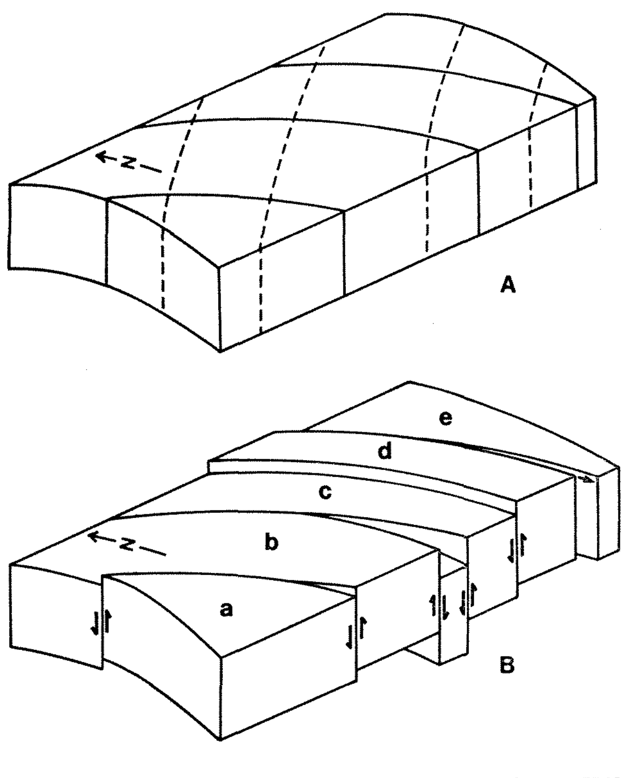

Figure 43 Block diagrams showing the suggested general relationship between folding and faulting in the area described. The Minindee Fault Zone is interpreted as a pinched graben akin to that between the blocks marked 'b' and 'c'.

it takes place toward the southwest this may additionally be due to the contemporaneity of faulting and deposition, higher formations of the Wyloo Group covering faulted lower formations.

The concept of tectonic and depositional contemporaneity gains support from the Hardey Syncline subarea, where it appears that the preservation of a thick section of the Turee Creek Group above the Kungarra Formation, and of a still higher quartzite (unnamed quartzite 3) below the Beasley River Quartzite, is related to continuing intensification of the Hardey Syncline from its initiation, probably during deposition of the Kungarra Formation, up to and beyond the deposition of the Beasley River Quartzite.

The presence of the volcanic clasts, almost certainly derived from the Woongarra Volcanics, in the Meteorite Bore Member indicates that, locally, deposition was not continuous during the transition from the Hamersley Group into and through the Turee Creek Group. However, it is not known whether the Kungarra Formation was deposited over the whole of the southwestern part of the Hamersley Basin, and the boulders in the Meteorite Bore Member came from the northern part, or whether, within the southwestern part, there was some degree of concurrent erosion of continuously developing anticlinal areas during deposition in the synclines. Certainly, in the Wyloo Dome subarea (Fig. 39), the most complete stratigraphic section occurs in the crestal area of the anticline, while the southern limb shows erosion to successively lower stratigraphic levels, so that the relationship between deposition and structure may not be simple.

Whatever the detailed nature of this relationship, the lithology and extent of the Three Corner Conglomerate Member argue strongly for its status as the record of a unique catastrophic event, involving the abrupt deposition of an enormous volume of coarse, angular, iron-formation debris. Both the coarseness and the angularity of this debris preclude the possibility of transport over a substantial distance, and a debris slide off the crest of a nearby rapidly rising anticline seems the best explanation of these features.

With the necessary exclusion of the "Turee Creek Formation" from the Wyloo Group, the stratigraphic record of this event is now seen as an appropriate marker for the base for the revised Wyloo Group, and for the initiation of the main tectonism accompanying the development of the Ashburton Trough, in which it was deposited. The Mount Bruce Supergroup, if it is to continue to designate the contents of the Hamersley Basin, is consequently revised to exclude the revised Wyloo Group, and to include the Turee Creek Group and higher unnamed units below the Beasley River Quartzite.

REGIONAL IMPLICATIONS

The new definitions presented above, taken together with the demonstration that within the limited area of Figure 38, the Beasley River Quartzite is markedly discordant over the Turee Creek Group, and the unnamed quartzite unit 3 raise problems for future application of stratigraphic nomenclature to other areas of "Wyloo Group" outcrop. In the initial regional mapping of the Wyloo (Daniels, 1970), Mount Bruce (de la Hunty, 1965), and Turee Creek (Daniels, 1968) Sheets, it was accepted that within the "Wyloo Group" the "Beasley River Quartzite" everywhere overlay the "Turee Creek Formation" conformably. As this concept must now be abandoned, the grounds for correlation of any outcrop of "Beasley River Quartzite" with the Beasley River Quartzite as here defined need careful individual appraisal, especially where there is no prospect of mappable continuity or near-continuity. In the outlier of "Wyloo Group" rocks forming the core of the Turee Creek Syncline, for example, the quartzite units cannot be correlated confidently with either the Turee Creek Group or the Wyloo Group as here defined, and judgement on their stratigraphic position must be withheld until more detailed work has been carried out.

ACKNOWLEDGEMENTS

Mr. R. Halligan, who was responsible for the initial 1:250 000 mapping of the southeast part of Wyloo (Daniels, 1970), observed and noted the discordant base of the Beasley River Quartzite in the Hardey Syncline subarea in 1962; his helpful comments and advice during preparation of this paper are acknowledged with thanks.

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TABLE 16. SUMMARY OF STRATIGRAPHIC REVISIONS IN THIS PAPER

"Wyloo Group" of MacLeod and others (1963), Halligan and Daniels (1964), de la Hunty (1965) and Daniels (1968, 1970)	Names applied in this paper to outcrop areas allocated in published maps to the units of the "Wyloo Group" shown in the left hand column	
	Wyloo Sheet (Daniels, 1970)	Mount Bruce Sheet (de la Hunty, 1965)
Capricorn Formation	Not on these sheets	
Ashburton Formation (including Mudong Member)	Part re-allocated (Fig. 40) to Mount McGrath Formation	No change
Duck Creek Dolomite	No change	No change
Mount McGrath Formation, locally subdivided into:	Incorporated into Cheela Springs Basalt Member	
"Karlathundra Conglomerate Member"	Not used by Daniels (1970)....	Combined as Mount McGrath Formation on Figure 40.
"Coolbye Shale Member"	Not used by Daniels (1970)....	
"Cheela Springs Basalt Member"	No change other than inclusion of undifferentiated Mount McGrath Formation	No change
"Nummana Member"	Not used by Daniels (1970)....	Included with unnamed quartzite unit 3 on Figure 40.
"Beasley River Quartzite"	Part unchanged; part now unnamed quartzite unit 3	Part unchanged; part now unnamed quartzite unit 3
"Turee Creek Formation"	Part now Beasley River Quartzite; part now Turee Creek Group	Turee Creek Group

A CONTRIBUTION TO THE STRATIGRAPHY OF THE MARRA MAMBA IRON FORMATION

by J. G. Blockley

ABSTRACT

Inspection of company gamma-ray logs and eight artificial and natural exposures indicates that there are six identifiable 'shale' horizons in the upper banded iron-formation member of the Marra Mamba Iron Formation which can be traced for at least 300 km along the length of the Hamersley Basin.

Some 'shale' horizons within the middle shaly member may also have a similar lateral persistence.

INTRODUCTION

During inspections of a number of iron-ore exploration projects within the Lower Proterozoic Marra Mamba Iron Formation in 1977, it became apparent that there is a remarkable similarity between sections of the upper banded iron-formation (BIF) member in widely separate parts of the Hamersley Basin. This similarity indicates that within this member, 'shale' bands have the same basin-wide lateral persistence as was previously found in the stratigraphically higher Dales Gorge Member of the Brockman Iron Formation (Trendall and Blockley, 1970). There is also a suggestion that a similar lateral continuity may be found for 'shales' within the middle shaly member of the Marra Mamba Iron Formation, but there is as yet insufficient information to confirm this possibility.

The results presented in this report are based on sections of mineralized Marra Mamba Iron Formation measured at the Newman, West Angelas, Marandoo and Nammuldi deposits, and on a well-exposed natural section in Kungarra Gorge. Additional information was obtained from gamma-ray logs of holes drilled in these deposits and in others at Tom Price and Paraburdoo. In fact, for some deposits, the 'shales' show rather better on the logs than in the available exposures.

The various locations mentioned in the text are shown in Figure 44, which also indicates the area containing the main outcrops of the Marra Mamba Iron Formation.

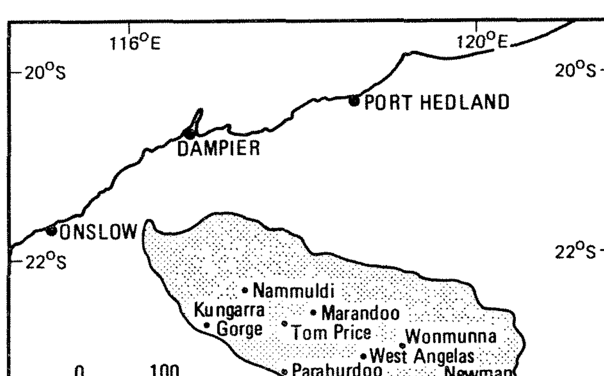

Figure 44 Locality map showing positions of sections examined, and area containing main outcrops of the Marra Mamba Iron Formation.

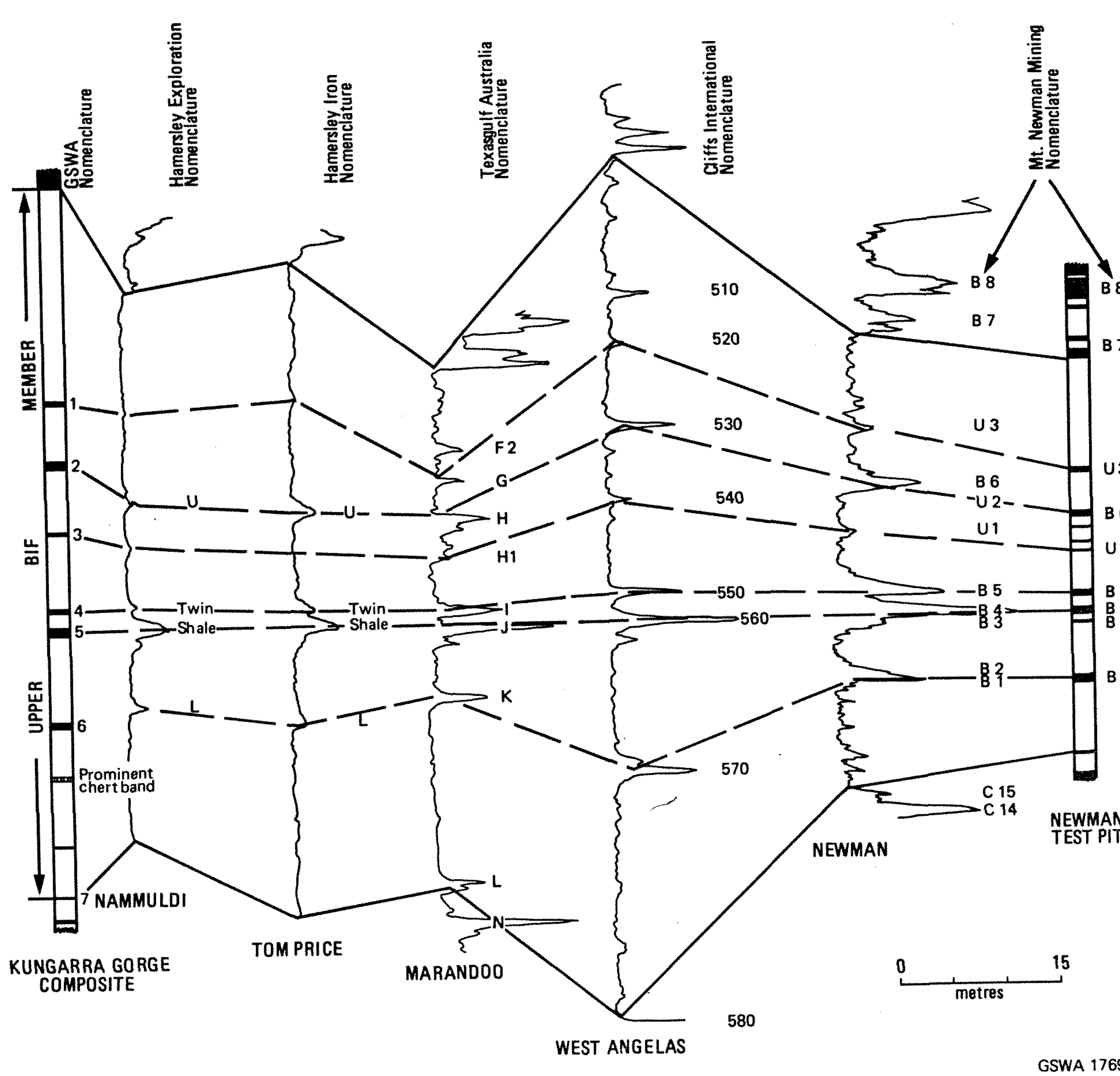

Figure 45 Comparison of gamma-ray logs and measured sections, upper BIF member, Marra Mamba Iron Formation, showing company nomenclature and correlations. Thickness variations are thought to be mainly due to thinning during mineralization of iron formation to iron ore.

Previous descriptions of the stratigraphy of the Marra Mamba Iron Formation can be found in MacLeod and others (1963), Ryan and Blockley (1965), Blockley (1967) and Trendall and Blockley (1970).

Thanks are due to the geological staffs of Mt Newman Mining Co Pty Ltd, Texasgulf Australia Ltd, Cliffs International Inc, Goldsworthy Mining Co Ltd, Hamersley Iron Pty Ltd and Hamersley Exploration Pty Ltd for facilitating access to drill cores and exposures, and permitting publication of drill-hole gamma-ray logs.

UPPER BIF MEMBER

Figure 45 compares gamma-ray logs of the upper BIF member obtained from Nammuldi, Tom Price, Marandoo, West Angelas, and Newman with one another and with lithological sections measured at Newman and Kungarra Gorge. The various nomenclatures in use are indicated alongside each column, that adopted in this paper being shown beside the Kungarra Gorge section. Figure 46A shows the typical appearance of the 'shales' in man-made exposures. It should be noted that the 'shale horizons' contain not only true shale, but also closely associated massive stilpnomelane and, in some fresher sections, thin beds of dolomite. In some cases true shale is the subordinate lithology. These 'shale horizons' are equivalent to the S macrobands of Trendall and Blockley (1970), but the term 'shale' is used here because of its wide acceptance by the iron-ore industry.

Correlations between the sections on Figure 45 are indicated by the dashed lines. Although based in the first instance on similarities of spacing and gamma-ray log traces, they are confirmed by certain lithological features described below.

'Shale 1' generally gives a poor response on gamma-ray logs. Its thickness is typically about 30 cm, with a range of 10 to 60 cm. Apart from 2 or 3 cm of yellow to pink bedded material at its top, the 'shale' consists entirely of massive stilpnomelane which locally weathers to massive goethite. Exposures in Kungarra Gorge have a distinctive 'limestone weathering' appearance.

'Shales 2 and 6' are very similar bands each ranging from about 20 to 60 cm thick. Typically the lower two thirds of the units consist of massive, unctuous, khaki-weathering stilpnomelane (or goethite) and the upper one third comprises well-bedded pink, red and yellow shale. Each gives a prominent peak on most gamma-ray logs.

'Shale 3' is of similar composition to 'shale 1', but is normally thinner, averaging about 20 to 25 cm in thickness. Like 'shale 1' it has a poor gamma-ray log response.

'Shales 4 and 5' are typically 1.5 to 2 m apart and give a distinctive double peak on gamma-ray log traces. They are widely used as stratigraphic markers by the iron-ore explorers, being represented by a 3- or 4-m wide exposure gap in most natural outcrops. 'Shale 4' is 30 to 50 cm thick and 'shale 5' is typically 50 cm to 1 m thick. Both consist of finely laminated, yellow, pink and red shale interbedded with thin bands of massive stilpnomelane. Near

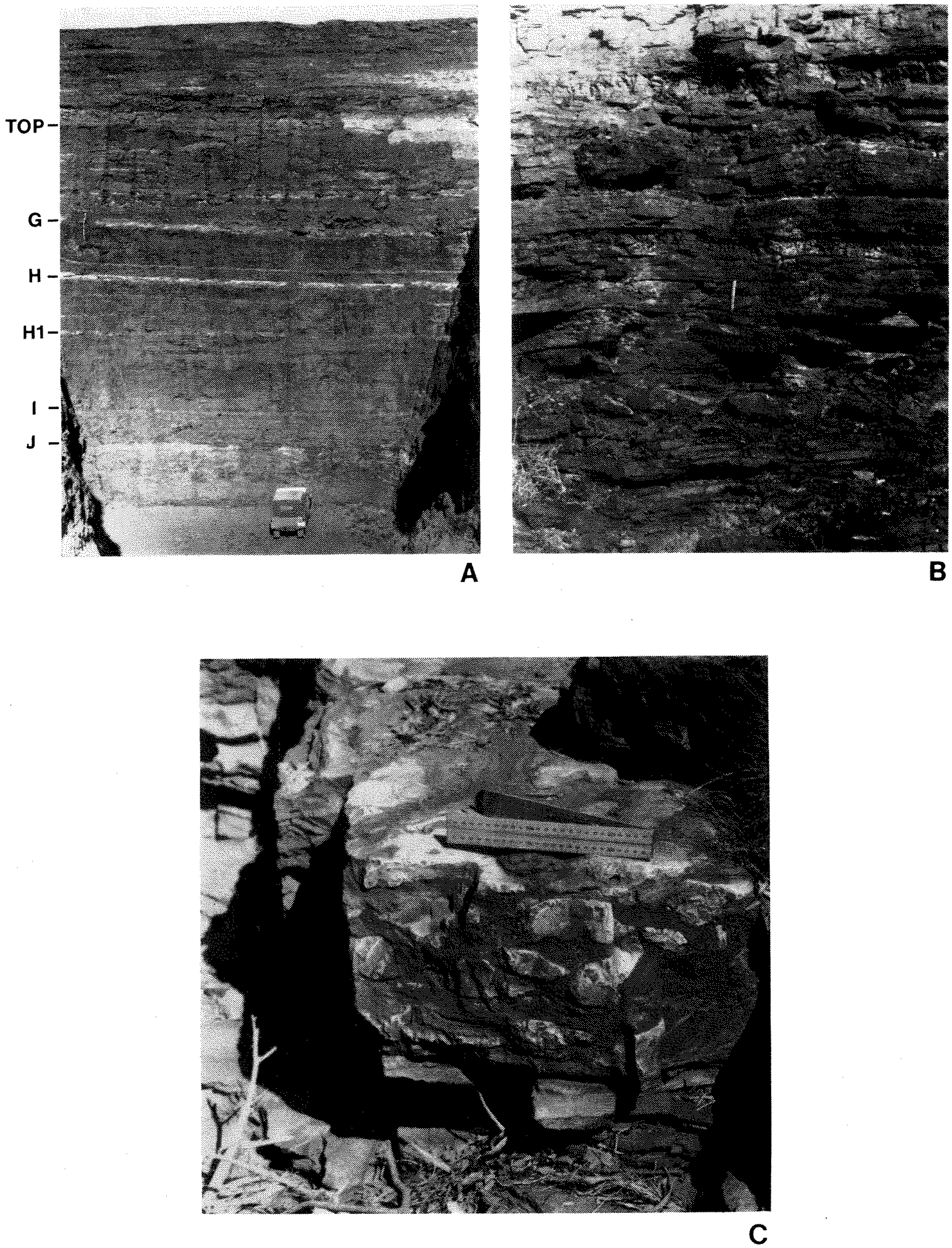

Figure 46 Photographs of the upper and middle members of the Marra Mamba Iron Formation.
A. Section of mineralized upper BIF member exposed in the test pit at Marandoo. The 'shale' horizons are numbered according to the scheme used by Texasgulf Australia Ltd. White appearance of 'shales' is due to efflorescence.
B. Distinctive podded chert horizon 4·5 m below 'shale 6' in Kungarra Gorge.
C. Interbedded stilpnomelane (blocky appearance) and cherty iron formation (well-bedded appearance) typical of the middle shaly member in Kungarra Gorge.

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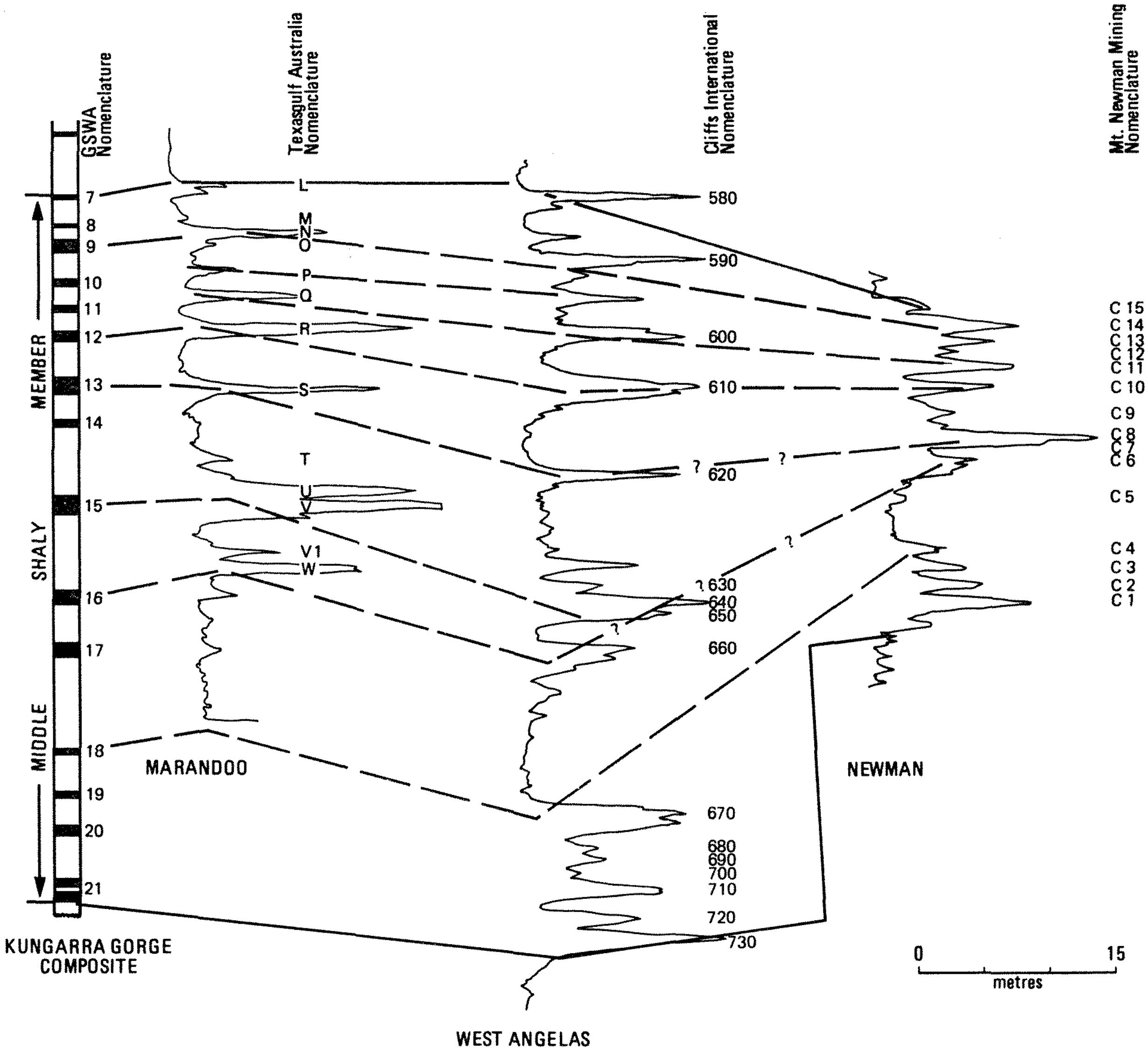

Figure 47 Comparison of gamma-ray logs and a measured section of the middle shaly member of the Marra Mamba Iron Formation, showing company nomenclature and some tentative correlations. As all sections are stated to be unmineralized, the thickness variations may be primary.

the centre of 'shale 5' is a band about 5 cm thick containing hematite nodules 3 to 5 mm in diameter. This band, first observed at West Angelas, was later recorded at Newman, Marandoo, Nammuldi and Kungarra Gorge.

An important feature of the 'shale' bands is that they retain their distinctive lithologies even where the surrounding iron formation has been converted to iron ore, although locally there may be difficulty in recognizing them due to slumping or squeezing of the units.

Another marker horizon of potential use in less weathered sections is a 40-cm band of distinctively podded chert occurring about 4.5 m below 'shale 6' in Kungarra Gorge (Fig. 46B). A smiliar band was noted about 6 m below 'shale 6' in a section measured in the Wonmunna area.

MIDDLE SHALY MEMBER

Figure 47 compares three gamma-ray logs of the middle shaly member with a well-exposed section in Kungarra Gorge. A suggested correlation, based on spacing and estimated thicknesses of the 'shales', is indicated by the dashed lines. Further information, particularly the matching of lithogolical sections and gamma-ray logs from several localities, is needed to confirm or modify the suggested correlations. An exposure of the member in Kungarra Gorge is shown in Figure 46C.

CONCLUSIONS

Although the stratigraphic subdivision of the upper BIF member of the Marra Mamba Iron Formation has been recognized independently by several operators, its basin-wide application may not have been appreciated by all of them.

The presence of indentifiable 'shale' bands within mineralized Marra Mamba Iron Formation has already been used in structural interpretations and ore-reserve calculations. In the future the 'shale' markers will almost certainly prove useful for grade control during mining operations. The knowledge that these 'shale' units extend for at least 300 km should add to the confidence with which they are employed as stratigraphic markers.

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THE BLUE SPEC GOLD–ANTIMONY MINE

by R. J. Morrison

ABSTRACT

The Blue Spec gold-antimony mine is located east of Nullagine, Western Australia, on a major shear zone which lies parallel to the regional strike of the Archaean Mosquito Creek Formation. During renewed operations from 1976 to 1978 a total of over 723 kg of gold and 690 t of antimony in concentrates were recovered from 47 422 t of ore with an average head grade of 30.9 g/t gold and 2.9 per cent antimony. Tailings assays indicate that the ore may average 0.1 per cent tungstic oxide.

The mineralization occurs in a complex, narrow, steeply plunging lode system which has a strike length of 70 to 100 m and is known to a depth of 350 m. The dominant ore minerals are stibnite, aurostibite and gold, which occur associated with quartz with or without carbonate veins. Sediments adjacent to the mine workings contain 10 to 20 per cent carbonate.

The lodes have proved to be unpredictable. Variograms of lode-width measurements indicate that the lodes maintain a measure of continuity to about 12 m along strike. Assays show no correlation at the mine sample scale, gold values having a log-normal distribution and antimony values having an anomalous log-normal distribution above a threshold of 5 per cent antimony.

INTRODUCTION

The Blue Spec mine is located on GML 46/404, 19 km north-northeast of Nullagine (230 km southeast of Port Hedland) at approximately lat. 21°49'S., long. 120°16'E. In October, 1978, the lease was registered jointly in the names of Mulga Mines Pty. Ltd. (50 per cent) and Metramar Minerals Ltd. (50 per cent).

The mine was visited from February 21st to 25th, 1978, to obtain representative samples of drill core and other material, and to collect data available at the termination of mining to assist any future evaluations. Unfortunately, the underground workings proved to be inaccessible at the time of the inspection.

The mineralization was discovered in 1905 and named after the winner of the 1905 Melbourne Cup. Because of difficulties in recovering gold from the antimony-rich ore, commercial production did not begin until 1935. After initial gold production, wartime demand for antimony led to the Wiluna Gold Corporation producing stibnite concentrates from the ore from 1945 to 1956. During 1956-57 the leases were held by the Western Australian Development Syndicate N.L., and the Golden Spec mine and the area east of Blue Spec mine were drilled with Government assistance (Ellis, 1957). North West Mining N.L. began operations in 1960 with the hope of increasing gold recoveries; however, metallurgical problems were not overcome. In 1962, after selective mining of high-grade areas, the mine closed with a substantial debt remaining to the Government, which then took over the property (Fitch, 1970).

The Metal Traders group acquired the mine in July, 1968, passing it to their subsidiary, Western Alluvials Pty. Ltd., in February, 1969. Investigations, commencing in 1970 after Metramar Minerals Ltd. was floated, initially concentrated on the antimony mineralization. When antimony prices returned to more normal levels after the 1970 boom the mineralization was re-examined for its gold potential. After considerable work had been carried out, Metramar was joined in 1972 by the Australian Anglo American subsidiary Mulga Mines Pty. Ltd. A minor interest in Mulga Mines Pty. Ltd's interest was purchased by Australian Consolidated Minerals Ltd. in December, 1975.

Up to November, 1972, $2 million had been spent on the mine and on feasibility studies. Capital expenditure after that date included $1 million on risk exploration and about $6.7 million on fixed capital items.

Just prior to the end of operations at Blue Spec mine, a proposal was made to extend the mine life by producing from the Golden Spec mine, 1 km west of Blue Spec mine. This proposal was found to be economically unattractive and consequently the mine closed on January 10th, 1978. An auction of all plant and equipment at the mine was held in March, 1978.

The total production reported to the Mines Department from the leases is summarized in Table 17.

TABLE 17. BLUE SPEC MINE PRODUCTION FIGURES

Period	Ore (t)	Gold (Au)		Antimony (Sb)
		Production (kg)	Recovery (g/t)	Production (t Sb in concentrate)
1935–1975	64 200	1 187·748	18·5	798·85
1975–1978	47 422	723·973	15·3	690·8
Total	111 622	1 911·721	17·1	1 489·65

GEOLOGY

Blue Spec mine lies within the thick Archaean Mosquito Creek Formation. Hickman (1975) has described the geology of the formation which consists of metamorphosed greywacke and siltstone. The geology of the upper sections of the mine has previously been described by McKeown (1953).

LITHOLOGY

Inspection of rock types on the mullock dumps show that the country rocks are dominantly coarse- to fine-grained metasediments. The finer sediments tend to have a strong fabric giving rise to slaty cleavage which locally has been crenulated by later deformation. In places a phyllitic sheen has developed. The coarser sediments vary from sandy siltstone to coarse greywacke and have a more poorly developed fabric but a greater tendency to contain irregular carbonate, quartz-carbonate, or quartz veins.

An unexpected feature of the geology is the widespread presence of carbonate, both associated with quartz in the veins, and in the matrix of the country rocks. On the mullock dumps the carbonate in the quartz-carbonate veins weathers to a characteristic cream colour. On the surface, approximately 100 m west of the old main shaft, coarse-grained carbonate was found outcropping at the western end of the mineralized shear zone.

All sediments examined in thin section (Blight, 1978) contain significant quantities of carbonate in the groundmass, typically 10 to 15 per cent. The clastic fragments are mainly quartz or quartzite with some coarse detrital muscovite flakes and cherty fragments. Pyrite occurs locally both as disseminated grains and in quartz veins and veinlets. Despite their appearance in hand specimen, the shales are not particularly graphitic or chloritic, the dark colouring being due to minute specks of rutile and pyrite together with fine flaky opaque material interleaved with mica (unpublished Mulga Mines petrographic report).

MINERALIZATION

The mineralization which has been defined to date is associated with veins of quartz with or without carbonate, and sheared metasediments. Carbonate minerals are not normally abundant in the main orebody, but petrographic examination has demonstrated that they do occur in close association with the ore in some samples (Blight, 1978). Typically, quartz and quartz-carbonate veins are intruded by veinlets of stibnite in fine microstockworks adjacent to patches of massive stibnite. The characteristic mottled grey colour of the Blue Spec stibnite-quartz mineralization is caused by the variable intensity of these microfractures. Individual stibnite-bearing fractures usually cut across both the grain boundaries and the carbonate cleavage. The massive stibnite is commonly partially recrystallized from typical fine- to medium-grained material into coarse tabular crystals over 30 mm long.

Normally economic mineralization is confined within the veins, assays having a sharp cutoff at vein contacts (A. C. Gifford, pers. comm.). Gold is not always intimately associated with stibnite, and high gold assays have been recorded in some pyritic quartz lodes. There is currently no evidence of vertical mineralization zoning.

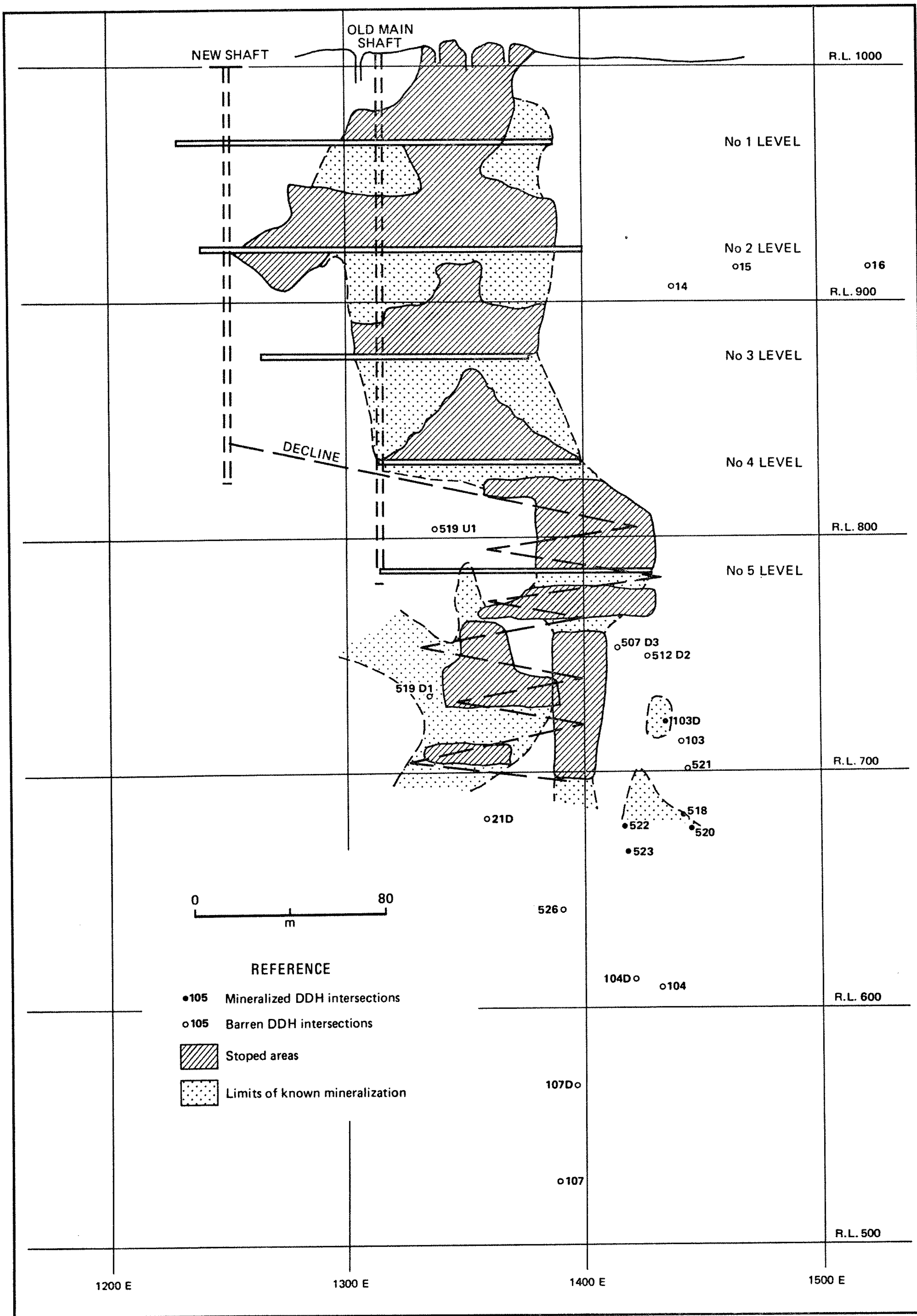

Figure 48 Generalized longitudinal projection, Blue Spec mine (many stope outlines are not precisely known).

Although in many parts of the mine scheelite mineralization is negligible, it is locally abundant in the lode channel where it is said to correlate closely with gold. For example, samples taken by the company from a crosscut in the vicinity of 1370E at RL810 assayed up to 2.29 per cent tungstic oxide (WO_3), averaging 0.33 per cent WO_3, 23.3 g/t gold (Au), and 2.4 per cent antimony (Sb). However, analyses of samples from the upper sections of the tailings dams (Table 18) encountered only low tungsten values and it is concluded that the scheelite mineralization is very sporadic and may average about 0.1 per cent WO_3.

STRUCTURE

The Blue Spec mine lies near the western end of an easterly trending strike-fault zone which has gold and antimony mineralization intermittently associated with it over 17 km. In the immediate vicinity of the mine the Mosquito Creek Formation is dominantly south dipping, with a number of drag structures developed at intervals. A complex system of shears cuts across the area. Company mapping in 1971 showed that the mine is located near the junction of the main east-northeasterly trending Blue Spec shear with a more northeasterly trending fault system.

The mineralization occurs in a complex shear zone which strikes 080° and has a near-vertical dip. This lode system plunges at approximately 80°E and typically has a strike length of 70 to 100 m (Fig. 48). Within the shear zone irregular mineralized veins range up to 5 m in width but average about 1 m.

Individual lodes (referred to by the operators as "elements") usually dip vertically and are typically bounded on one side by a strong shear (A. C. Gifford, pers. comm.). Two or more lodes are usually present on any given level and are found in various positions, end to end, overlapping, and sometimes branching or folded (Fig. 49). The lodes tend to vary through the mine and may show local reductions in strike length and locally increased variation in grade.

Structure contours were constructed from company mapping of the lower levels in an attempt to define the lode structure and to predict any extensions to, or repetitions of, the mineralization (Morrison, 1978). No significant correlation appears to exist between "element 3" and the structure contours, although the axis of greatest thickness is subvertical, parallel to the trend of the structure. The "element 1" and "2" lodes have a complex structure, being separate units above RL 780, below which they join and reduce in strike length to become the vertically plunging "element 1-2".

Despite negative results in several deep drill holes, the mineralization is still open at depth. Drill holes 518, 520, and 523 intersected mineralization to a maximum depth of 350 m below the mine workings, close to reference plane 1400N. This suggests that the "element 1-2" shear zone either continues or is repeated down plunge. Work carried out by the company showed that mineralization indicated by these drill holes was of insufficient tonnage and grade to warrant further development and mining (Douglas, 1978).

STATISTICAL TREATMENT OF SAMPLING DATA.

McKeown (1953) noted that crossfolding gave rise to dispersed and erratic mineralization and to the formation of relatively small bodies of high-grade stibnite. Because the orebody has proved to be relatively unpredictable the available sampling data were examined in some detail to assist in any future evaluation of the mineralization.

SAMPLING

Examination of the diamond drill core showed that most shear zones produced very broken core and that some friable sections were present. In general the quartz reefs and massive stibnite cored well. Reliable sampling of faces underground proved to be difficult because of the different hardnesses of various mineralized and unmineralized rock types.

Figure 50A compares cumulative frequency plots for three groups of gold and antimony samples, that is, No. 5 level horizontal DDH assays, No. 5 level crosscut assays, and channel samples from drives below No. 5 level. The smaller diamond drill core samples have a greater spread of values, 90 per cent lying between 2 g/t and 380 g/t about a median of 17 g/t Au. In comparison 90

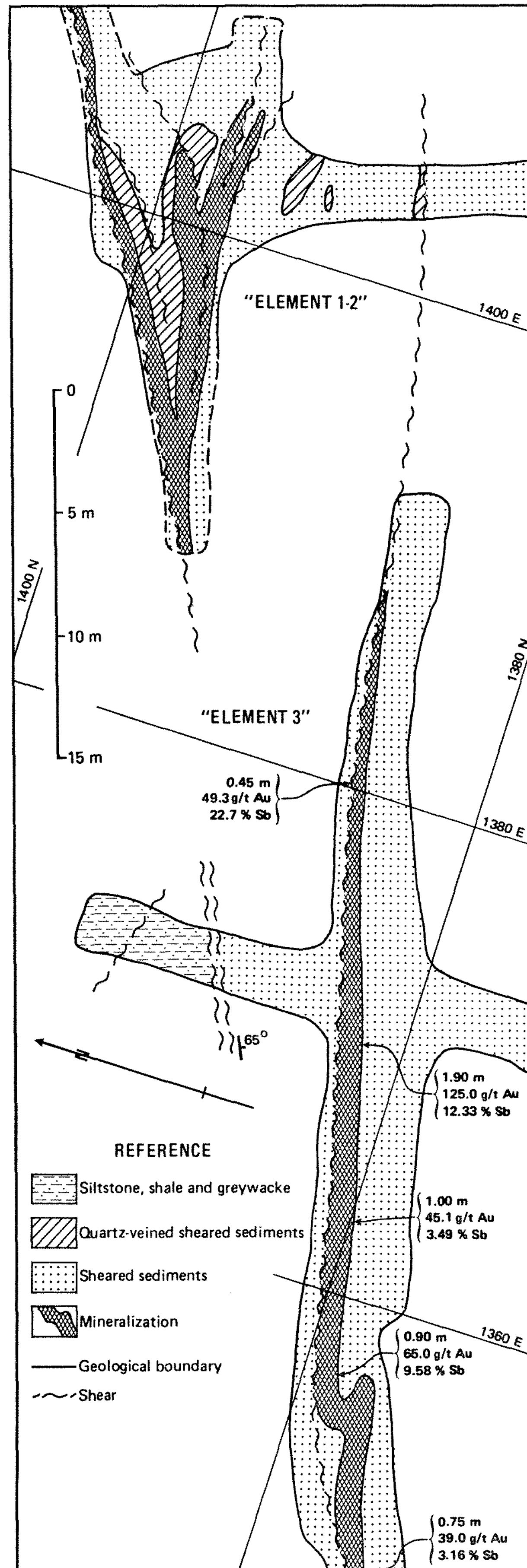

Figure 49 Generalized geology of the RL 722m level, Blue Spec mine (after mapping by A.C. Gifford for Mulga Mines Pty Ltd).

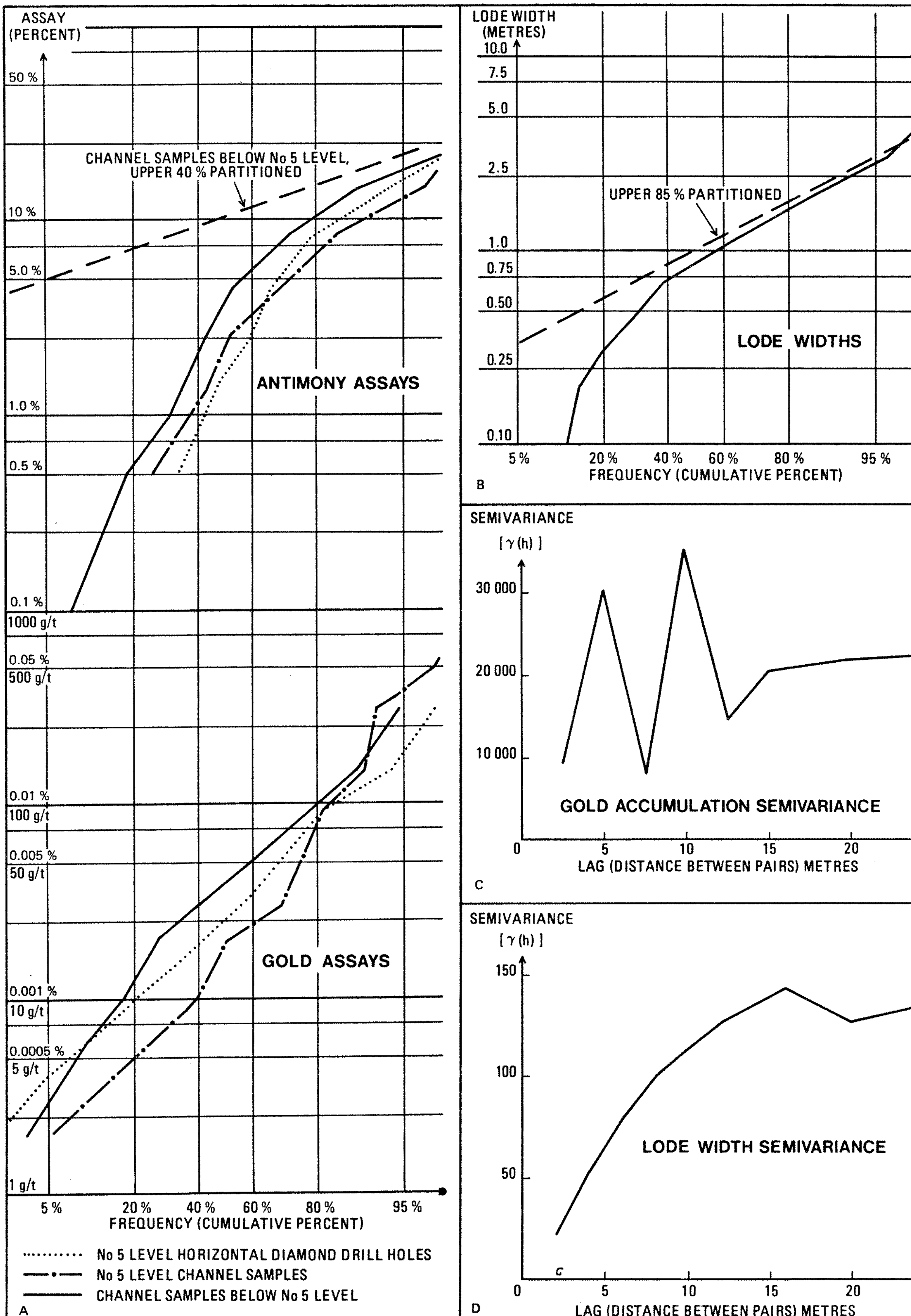

Figure 50 Cumulative frequency plots and variograms of sampling data, Blue Spec mine.
A. Cumulative frequency plots of gold and antimony assays on logarithmic probability paper.
B. Cumulative frequency plots of mapped lode widths below No.5 level on logarithmic probability paper.
C. Variogram of gold accumulations (metres width of samples x average assay in g/t) in channel samples below No.5 level. (A variogram is plot of the semivariance between pairs of samples against the distance (lag) between the pairs).
D. Variogram of mapped lode widths RL 697-702, RL 722, RL 754-757.

per cent of the No. 5 level channel samples, which tested the same area, lie between 4 and 174 g/t about a median of 25 g/t Au. Channel samples below the No. 5 level taken by different personnel tend to be higher grade, having a median of 39 g/t, with a 90 per cent spread from 3 g/t to over 300 g/t Au. The smaller drill core samples also tend to have a greater variance than the channel samples. When using a particular cut-off grade the smaller samples indicate a higher average assay than is suggested by larger volume samples (Krige, 1977).

GRADE DISTRIBUTION

The approximately linear plot of gold on log probability paper suggests that the distribution is log normal (Fig. 50A). This is best demonstrated by the No. 5 level channel samples. Antimony values on the other hand show a negative skew and obviously do not represent a single log normal distribution. Partitioning (Sinclair, 1974) of the upper 40 per cent of the antimony values suggests that a log normal distribution with a median value of 10 per cent Sb is present, having a threshold at about 5 per cent Sb.

With one exception (RL 757) the mean Au:Sb ratios in drive samples below No. 5 level showed little variation with depth and remained consistently close to the 1:900 Au:Sb ratio encountered during the 1976-78 mine production. Correlograms of individual sample ratios of Au:Sb, however, show extreme variation.

A variogram (David, 1977) of gold accumulations of mine channel samples was constructed to determine the dimensions of the zone of influence of the samples (Fig. 50C). In this case the variogram, which is a plot of semivariance ($\gamma(h)$) against lag (h), was constructed from pairs of samples of lag (i.e. distance) h apart, along the strike of the lode. The semivariance, $\gamma(h)$, was calculated from the formula:

$$\gamma(h) = \frac{1}{2N} \sum_{i=1}^{n-h} \{g(x_i) - g(x_{i+h})\}^2,$$

where N is the number of samples, h is the distance between pairs of samples, $g(x_i)$ is the gold accumulation (m.g/t) at position x_i, and $g(x_{i+h})$ is the gold accumulation at distance $_h$ beyond x_i. Figure 50C shows that the semivariances of the gold accumulations are high and that there is little evidence of continuity within the mineralization, even over short distances.

The semivariances of gold assays between adjacent and next but adjacent samples (i.e. lag of 1 and 2) for both diamond drill hole (DDH) and channel samples on No. 5 level were also calculated to determine whether any correlation could be found over shorter distances. These indicated that there is no correlation between adjacent samples and thus classical satistics rather than geostatistics should be applied to the gold assays. Antimony assays in No. 5 level diamond drill holes were also examined and there is only a slight possibility of a weak correlation between adjacent samples.

LODE WIDTH

A cumulative frequency plot of the width of lodes below No. 5 level (Fig. 50B) was based on measurements taken from company mapping. Partitioning of the dominant log normal distribution, represented by a straight line between 40 per cent and 96 per cent cumulative frequency, suggests that about 85 per cent of the measured points lie within this distribution which has a median of 1 m width.

A variogram of lode widths (Fig. 50D) was constructed from mapping on RL 697-702, 722, and 754-757. This has characteristics of the spherical model (David, 1977) and shows decreasing continuity up to its range of approximately 12 m after which the lode widths are independent of distance. Thus in the area studied, the maximum distance which a lode width measurement can be projected and still retain any degree of correlation with the sampling point is about 12 m along strike. (Variograms for individual levels showed some variation about this figure.) No data are available to construct a vertical variogram and thus to test for anisotropy within the deposit.

MINING

The main shaft used in the first phase of mining down to No. 4 level proved to be unsuited to further production. After drilling in 1970-71 had indicated additional reserves at depth, General Mining and Finance sank a new shaft to the northwest of the main shaft. The old main shaft was later deepened to No. 5 level and an exploratory drive was cut to provide a bulk sample of the mineralization and to give access for underground drilling.

The mining method was mechanized cut-and-fill, with stope access off a 1 in 7 decline. The decline was chosen because of considerations of both mining efficiency and the extra capital cost and delay involved in shaft sinking. It was extended for a length of approximately 1 km from near the base of the new shaft.

The final stoping procedure adopted was a flat back resue method, the mineralized vein being mined first and walls stripped later where necessary. The minimum stoping width was 1 m. Attempts to fill stopes with wet tailings were not successful because the very sheared wall rock became unstable when wet. Dry river gravel was used as fill in the latter stages of mining.

Typical production figures for the mine are illustrated by the period from April to November 1977 when the median weekly tonnage extracted was 660 t, 90 per cent of the weekly production being between 470 t and 770 t. The median head grades for this period were 29.5 g/t Au and 3.25 per cent Sb, 90 per cent being between 20 and 40 g/t Au, and 1.7 and 4.6 per cent Sb.

A. C. Gifford (pers. comm.) indicated that at the cessation of mining operations in January 1978 little mineralization remained readily accessible for underground inspection. Virtually all the blocked out ore reserves had been extracted from the workings, which persist to 310 m below the original surface. The mined ore bodies have averaged 360 t per vertical metre.

METALLURGY

The concentrating process was based on gravity tabling followed by cyanidation and carbon absorption of gold, and flotation of antimony concentrates.

Recoveries of both gold and antimony were low, the average recovered grade from all operations at the mine being about 17 g/t Au and 1.5 per cent Sb. A number of factors appear to have contributed to the problem. Ores containing aurostibite ($AuSb_2$) are notoriously difficult to treat commercially, being virtually unattacked by mercury or cyanide solutions (Henley, 1975). In addition, arsenic and antimony sulphides cause difficulties in cyanidation, reducing gold extraction, and themselves being dissolved while at the same time increasing reagent consumption. Other factors may have been important such as the low head grades caused by the unavoidabily high dilution. Typical analyses of grab samples of stibnite concentrates (unpublished Mulga Mines Pty Ltd data) were:

- antimony >60%
- sulphur 24.0%
- iron 1.24%
- lead 0.10%
- arsenic 0.0255%
- gold 0.0044% (44 g/t)
- mercury 0.00015% (1.5 ppm)

Because of the known high losses of gold and antimony from the mill, and the presence of significant WO_3 within the ore, shallow samples were taken from each of the five main tailings dams (Table 18).

TABLE 18. ASSAY RESULTS OF TAILINGS SAMPLES, BLUE SPEC MINE

Sample No.	Locality	Au g/t	Sb %	W %
55022	SE tailings composite	4·7	0·24	0·054
55023	E tailings composite	6·9	0·48	0·090
55024	S tailings composite	8·9	0·34	0·091
55025	N tailings composite....	12·4	0·31	0·062
55026	W tailings composite	4·7	0·18	0·094

It should be emphasized that the samples were designed only to provide an indication of tailings values. Any future economic evaluation of this material should be based on a comprehensive sampling programme.

The Government Chemical Laboratories used x-ray powder photographs, scanning-electron microscopy and other means in an attempt to identify the gold, antimony and tungsten minerals present in the tailings. The minerals could not be definitely identified, but the evidence suggested that tungsten may be present as scheelite, and antimony as stibiconite.

ACKNOWLEDGEMENTS

The assistance of Mulga Mines Pty Ltd, Metramar Minerals Ltd and Australian Anglo American Ltd is gratefully acknowledged. Particular thanks are also due to Dr Tony Gifford, and Messrs Bruce Mellor and Bruce Jannson who provided much useful information on the mine geology and recent operations.

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BIOTITE DATES AND COOLING HISTORY AT THE WESTERN MARGIN OF THE YILGARN BLOCK

by W. G. Libby and J. R. de Laeter*

ABSTRACT

Twenty-eight rubidium-strontium whole-rock-biotite two-point isochrons give dates which regularly decline from typical Yilgarn Block ages of about 2 500 m.y. near Meckering, to about 500 m.y. at the western limit of the Yilgarn Block, 70 km to the west. In contrast, four whole-rock isochrons supported by additional model dates suggest that whole-rock dates maintain the typical Yilgarn Block level (2 500-2 700 m.y.) to the western limit of the block.

The only whole-rock date younger than Archaean is from Bald Hill quarry in the Avon Gorge, where an isochron from six samples gives a date of 1 566 ± 302 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio (R_i) of 0.722 6 ± 0.005 3. Whole-rock dates somewhat older than 2 700 m.y. seem typical of the Avon Valley between Toodyay and York, in keeping with the earlier determinations of Arriens (1971).

INTRODUCTION

Mapping of biotite Rb-Sr dates throughout Western Australia was suggested by W. Compston (written communication) in 1969, apparently as an outgrowth of discussions he had in the field with A. F. Trendall, P. A. Arriens and J. L. Daniels. By 1971 plans for mapping biotite Rb-Sr dates were formalized within the Geological Survey. For convenience and significance the Perth 1:250 000 Sheet was chosen as a pilot area to be studied in conjunction with the biotite isotope data from the Gascoyne Province (de Laeter, 1976). Accordingly, samples were collected by W. G. Libby and S. A. Wilde, beginning in March, 1972. The location of the study area within the tectonic framework of the Yilgarn Block is shown in Figure 51 and the locations of samples within the study area are shown in Figure 52.

The samples were prepared mechanically in the laboratory of the Geological Survey for chemical and isotopic analysis in the Department of Physics, Western Australian Institute of Technology. Samples are briefly described in Petrology Report no. 945 on file with the Geological Survey.

The petrographic conventions of Streckeisen (1973) are followed, with the addition of fields for adamellite, quartz monzonite, and monzonite. In an attempt to follow

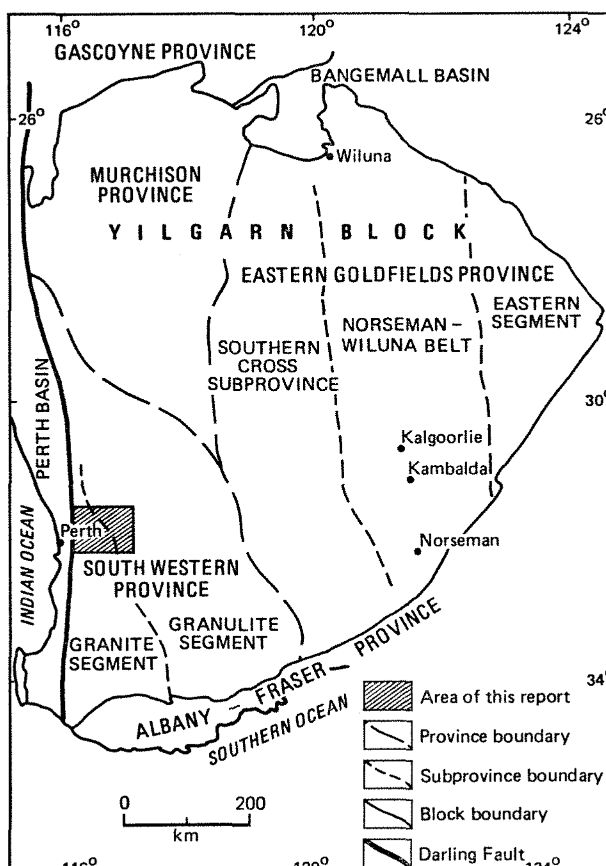

Figure 51 Index map and tectonic subdivisions of the Yilgarn Block.

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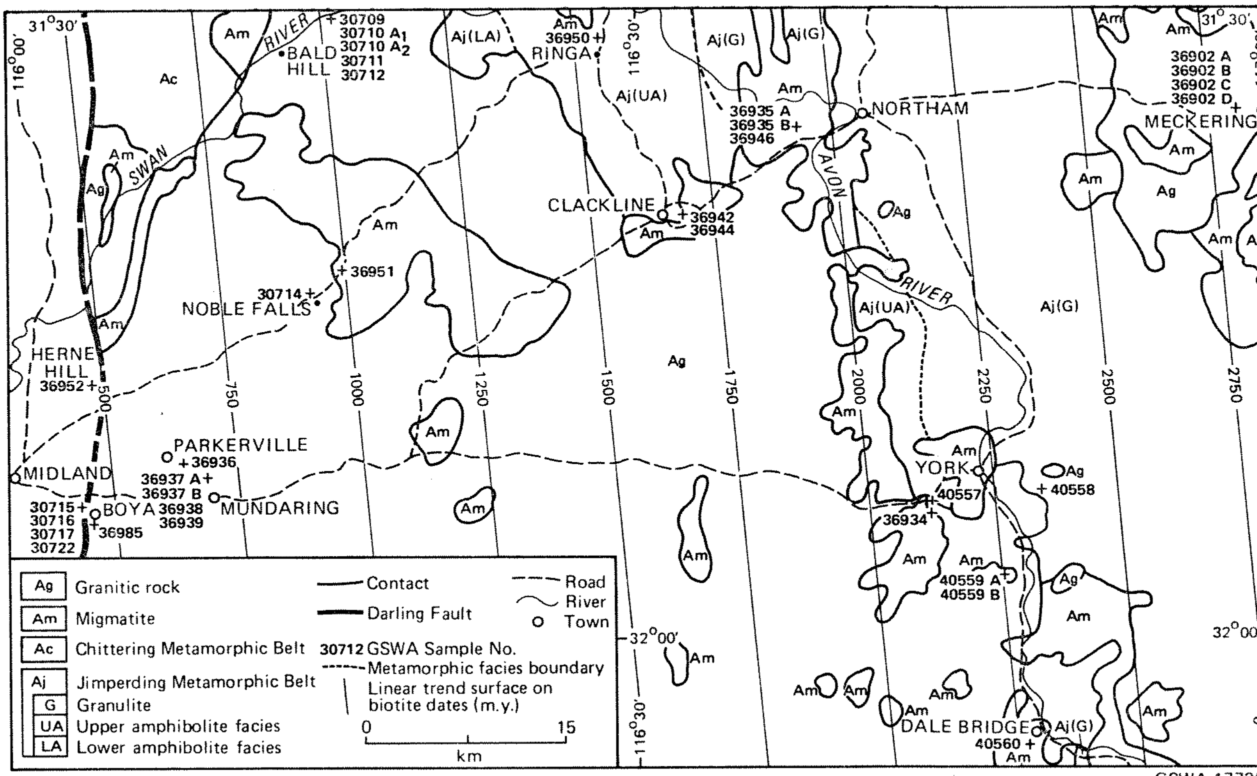

Figure 52 Locality index, linear trend surface on biotite Rb-Sr dates, and bedrock geology.

the convention of Faure and Powell (1972), 'age' is applied to the time that a real event occurred whereas 'date' is applied to the result of a calculation based on analytical data expressed in years before present, which may or may not correspond with a geological event.

This pilot study of biotite Rb-Sr dates is limited to a portion of the western margin of the Yilgarn Block, extending from the Darling Fault, where the Archaean Yilgarn Block terminates against the Phanerozoic Perth Basin, eastward for about 100 km into the Yilgarn Block. All localities except Dale Bridge lie within the Perth 1:250 000 map sheet. Dale Bridge is on the adjacent Pinjarra Sheet.

The project has shown that whole-rock Rb-Sr dates of about 2 500 m.y. tend to persist to the western edge of the Yilgarn Block whereas biotite Rb-Sr dates decline regularly westward in the western 70 km of the block from about 2 500 m.y. at Meckering to about 500 m.y. at the Darling Scarp near Perth. A single anomalous whole-rock date of 1 600 m.y. at Bald Hill suggests that at least one local high-grade Proterozoic event affected the area in addition to the pervasive low-grade effects recorded by biotite.

REGIONAL GEOLOGY

The Yilgarn Block, about 350 000 km² of almost exclusively Archaean rock, has been divided into three sections: the Eastern Goldfields Province in the east, the Murchison Province in the northwest, and the Southwestern Province. Outside the Southwestern Province most of the Yilgarn Block is granite-greenstone terrain. Within the Southwestern Province metamorphic grade is higher, rocks are more coarsely crystalline, and distinct greenstone belts are more difficult to define (Trendall, 1975; Williams, 1975). The Southwestern Province has been subdivided (Gee, 1975) into a granulite segment in the east and a granite segment in the west. The line separating the two segments passes from northwest to southeast across the middle of the area chosen for the pilot study of biotite ages. Gneisses of the Toodyay, Northam, York and Dale Bridge areas belong to the granulite segment whereas gneisses and granitoids of Bald Hill, Noble Falls, Boya, Parkerville, Mundaring and Clackline belong to the granite segment.

Most of the Precambrian rocks from the Perth and Pinjarra Sheets described by Wilde (1974, 1976) can be classified in one of four associations, the Chittering Metamorphic Belt, the Jimperding Metamorphic Belt, plutonic rocks of the granite segment between these belts, and migmatite and granitoid northeast of the Jimperding Metamorphic Belt. The geology of the study area is outlined in Figure 52.

Apart from weakly metamorphosed Proterozoic rocks of the Cardup Group along the Darling Scarp, metamorphosed supracrustal Precambrian rocks in the vicinity of Perth belong to one of two suites, the Jimperding metamorphics in the northeast and the Chittering metamorphics in the west. The Jimperding Metamorphic Belt consists of pelitic to arenaceous schists and gneisses up to granulite facies. The belt trends south-southeasterly along the Avon River valley in the vicinity of Toodyay, Northam, York and Dale Bridge. The Chittering Metamorphic Belt to the west consists of gneiss with intercalated amphibolite and pelitic schist. The schists contain kyanite, staurolite and sillimanite but, unlike the Jimperding Metamorphic Belt, are limited to grades below granulite facies. The Chittering Metamorphic Belt trends southward along the Darling Fault eventually pinching out against the fault in the southern third of the Perth Sheet.

The two belts of metamorphosed supracrustal rocks are separated by a wedge of complex granitic and gneissic rock which widens southward to form the granitic segment of the Southwestern Province described by Gee (1975).

Within the area of study metamorphic grade tends to decrease from east to west, reversing the more general westerly increase in grade across most of the Yilgarn Block (Wilde, 1974, 1976).

EARLIER ISOTOPIC STUDIES NEAR PERTH

Several earlier geochronological studies in the Perth area have been published (Compston and Jeffery, 1959; Compston and others, 1960; Wilson and others, 1960; Compston and Arriens, 1968; and Arriens, 1971). Unfortunately, much of the earlier data are not directly comparable with the whole-rock isochrons used in this work. Analytical data for three whole-rock samples published by Compston and others (1960) would, if combined with our data from Mundaring (Fig. 53C), slightly raise the date and lower the $^{87}Sr/^{86}Sr$ initial ratio (R_i). A whole-rock isochron date from York (Compston and Arriens, 1968) of 2 690 ± 210 m.y. ($\lambda = 1.39 \times 10^{-11}\ yr^{-1}$) is consistent with our dates in the area. Seven dates determined by Arriens (1971) are plotted in the time-distance graph, Figure 56.

Additional biotite data, mostly east of the area of specific interest, are provided by Wilson and others (1960) and Aldrich and others (1959). These data also are plotted on the time-distance graph (Fig. 56). A mildly disturbing biotite date by Mullumby is quoted by Compston and Arriens (1968). Mullumby determined a date of 1 070 m.y. (probably $\lambda = 1.39 \times 10^{-11}$ yr^{-1}) from biotite at South Chittering, well west of biotites of this age found in the present study, but direct comparison is not possible as the present study did not reach north to the Chittering area.

Total rock, mineral dates between 560 and 590 m.y. ($\lambda = 1.39 \times 10^{-11}$ yr^{-1}) were measured on metasomatized and sheared edges of basic dykes near Mundaring (Compston and Arriens, 1968). When adjusted for a decay constant equal to 1.42×10^{-11} yr^{-1} (548 m.y. and 577 m.y., respectively), these dates are close to the biotite ages we determined in the same area.

Modern whole-rock data are provided by Arriens (1971) including eight dates from localities within our area of interest. Five localities are on the Perth Sheet, and three

TABLE 19. ANALYTICAL DATA FOR WHOLE-ROCK SAMPLES AND BIOTITE CONCENTRATES FROM *LOCALITIES MENTIONED IN THE TEXT*

Locality	Sample Number	Rock Type	Material Analysed	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Bald Hill Quarry	30709	bgd	wr	123	294	0·417±0·005‡	1·21±0·02	0·750 09±0·000 31
			btt			33·6±0·7	113±2	2·352 4±0·002 4
	30710 A*	bgd	wr	142	290	0·489±0·005	1·42±0·02	0·753 87±0·000 28
			btt			26·2±0·5	82±1·5	1·609 8±0·001 3
	30710 A†	bgd	wr	136	250	0·545±0·006	1·58±0·02	0·757 10±0·000 41
			btt			16·8±0·4	51±1	1·266 6±0·001 5
	30711	bgd	wr	135	262	0·514±0·006	1·49±0·02	0·754 62±0·000 37
			btt			42·6±0·8	143±2	2·348 1±0·002 7
	30711†	bgd	wr	115	252	0·453±0·005‡	1·31±0·02	0·750 60±0·000 42
			btt			26·9±0·5	85±1·5	1·641 5±0·002 0
	30712	msgd	wr	115	364	0·316±0·004	0·92±0·01	0·742 52±0·000 31
			btt			60±1·2	230±5	4·088 7±0·003 9
Noble Falls	30714	adgn	wr	159	205	0·775±0·008	2·25±0·03	0·782 75±0·000 43
			btt			116±2	547±10	7·182 7±0·007 3
	36951		wr	145	184	0·789±0·009	2·30±0·04	0·786 88±0·000 42
			btt			26·2±0·5	81±1·5	1·424 9±0·001 1
Boya Quarry	30715	bgd	wr	114	168	0·678±0·007	1·97±0·03	0·768 64±0·000 39
			btt			63±1·2	211±4	2·401 3±0·002 8
	30716	bgd	wr	106	107	0·99±0·01	2·88±0·04	0·795 09±0·000 28
			btt			31·9±0·7	99±2	1·495 8±0·001 9
	30717	bgd	wr	148	114	1·30±0·02	3·79±0·05	0·824 08±0·000 53
			btt			39·4±0·8	124±3	1·598 0±0·001 8
	30722		wr	167	134	1·25±0·02‡	3·64±0·05	0·832 69±0·000 55
Meckering Quarry	36902 A	bad	wr	244	376	0·665±0·007	1·93±0·03	0·774 76±0·000 33
			btt			45±0·9	247±5	9·673 4±0·008 4
	36902 B	bgt	wr	327	270	1·21±0·02	3·54±0·05	0·831 29±0·000 50
	36902 C	bgt	wr	225	278	0·808±0·009	2·35±0·03	0·791 05±0·000 62
			btt			68±1·3	614±12	22·482±0·020
	36902 D	bad	wr	180	318	0·565±0·006	1·64±0·03	0·764 31±0·000 37
			btt			30·6±0.6	126±3	5·060 8±0·005 1
York area	36934	adgn	wr	177	74	2·40±0·03	7·1±0·1	0·990 77±0·000 71
			btt			59±1	376±7	13·039 9±0·010 3
	40557	bgn	wr	200	101	1·99±0·02	5·88±0·08	0·938 78±0·000 85
			btt			36±0·6	163±4	6·554 2±0·005 4
	40558	mig	wr	121	269	0·451±0·005	1·31±0·02	0·754 04±0·000 38
			btt			28·1±0·6	114±2	4·837 0±0·003 8
	40559 A		wr	71	695	0·102±0·002‡	0·296±0·005	0·714 10±0·000 35
	40559 C		wr	68	686	0·010±0·001‡	0·288±0·004	0·713 78±0·000 39
Northam Quarry	36946	adgn	wr	148	155	0·95±0·01	2·78±0·04	0·813 79±0·000 47
	36935 A	htgn	wr	151	168	0·91±0·01	2·64±0·04	0·788 70±0·000 46
			btt			69±1·4	600±10	21·251±0·019
	36935 B	bsch	wr	612	16·6	36·7±0·5‡	169±3	6·820 0±0·003 4
			btt			94±2	1 710±30	54·900±0·044
Parkerville Quarry	36936	bgd	wr	197	130	1·52±0·02	4·45±0·06	0·878 10±0·000 55
			btt			143±3	599±10	5·267 6±0·004 3
Mundaring Quarry	36937 A	bgd	wr	230	130	1·76±0·02‡	5·18±0·07	0·896 23±0·000 61
			btt			90±2	325±6	3·284 0±0·002 1
	36937 B	bgd	wr	233	134	1·74±0·02	5·11±0·07	0·896 13±0·000 57
			btt			193±4	955±20	8·008 6±0·007 4
	36938	bgd	wr	218	129	1·69±0·02	4·96±0·07	0·890 96±0·000 53
			btt			82±1·5	290±5	3·005 0±0·001 9
	36939	bgd	wr	190	133	1·43±0·02	4·19±0·06	0·860 41±0·000 71
			btt			76±1	266±5	2·895 1±0·002 2
Clackline	36942	gdgn	wr	132	369	0·357±0·004	1·04±0·02	0·746 98±0·000 28
			btt			32·2±0·6	123±2	3·978 4±0·002 5
	36944	gdgn	wr	259	343	0·754±0·008	2·19±0·05	0·788 65±0·000 53
			btt			62±1·2	322±6	9·352 6±0·008 5
Ringa	36950	gtgn	wr	270	144	1·88±0·02	5·53±0·08	0·929 05±0·000 61
			btt			36±0·6	144±3	5·065 7±0·003 7
Herne Hill Quarry	36952 A	bgd	wr	151	94	1·61±0·02	4·70±0·07	0·832 86±0·000 49
						148±3	633±12	5·587 6±0·004 2
Helena Valley Quarry	36982		wr	208	104	1·99±0·02	5·85±0·08	0·907 20±0·000 82
Dale Bridge Quarry	40560 B	bgn	wr	104	267	0·389±0·004	1·13±0·02	0·748 04±0·000 41
	40560 B†	bgn	wr			0·204	0·590	0·725 54
	40560 C(L)	btgn	wr			0·142	0·410	0·719 577
	40560 C(D)	htgn	wr			0·506	1·46	0·756 18

Rock type codes:

bgd biotite granodiorite
msgd mafic schlieren in granodiorite
adgn adamellite gneiss
bad biotite adamellite
bgt biotite granite
bgn biotite gneiss
mig migmatite

htgn hornblende tonalite gneiss
bsch biotite schist
gdgn granodiorite gneiss
gtgn granite gneiss
btgn biotite tonalite gneiss
wr whole rock
btt biotite

* first subsample
† second subsample
‡ average of two analyses
(L) Light phase
(D) dark phase

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on the Pinjarra Sheet. Using a decay constant of 1.39 x 10^{-11} yr^{-1}, dates range from about 2 200 to about 3 600 m.y. though the extreme dates are poorly controlled. A pooled date on 23 gneiss samples from the Avon River valley and near the Darling Scarp is about 3 100 m.y. A date on 7 samples of microgranite dykes near Northam is about 2 300 m.y. The gneisses, principally in the Avon River valley (Dale Bridge, York, Northam and Toodyay) give dates of about 3 100 m.y., systematically older than granitic rocks of the Yilgarn Block as a whole. Most dates from Yilgarn Block granitic rocks lie between 2 600 and 2 700 m.y. (Arriens, 1971).

SUMMARY OF GEOPHYSICAL DATA ON CRUSTAL STRUCTURE NEAR PERTH

Bouguer gravity anomalies are higher in the Darling Range than across most of the Yilgarn Block (Everingham, 1965, plates 8 and 9; Mathur, 1974, Figure 7). Everingham suggested that the general rise in Bouguer anomalies takes place across the Yandanooka-Cape Riche lineament (west of Meckering), as illustrated by his plate 9. Mathur (1974), on the other hand, suggests that the observed increase in Bouguer anomalies across the Yandanooka-Cape Riche lineament is part of the regional increase from the Eastern Goldfields to the Southwestern Provinces.

Everingham attributed the high Bouguer anomaly of the Darling Range to shallowing of intermediate crustal layers, despite deepening of the Mohorovicic discontinuity, and to an increase in mafic dykes near the Darling Scarp. A change in crustal structure along the Yandanooka-Cape Riche lineament is appealing as the lineament coincides with changes in surface rock types, topography, and metamorphic grade, and is defined as an active seismic zone.

Gravity, reflection and refraction data were interpreted by Mathur to show three crustal layers, a top layer at a density of 2.78 g/cm^3, a middle layer of 2.91 to 2.94 g/cm^3, and a lower layer of 3.04 to 3.10 g/cm^3. The two upper layers become shallower and thinner to the west whereas the lower layer thickens to the west, resulting in an overall westward thickening of the crust. The crustal thickness near Kalgoorlie is about 34 km, and under the Yilgarn Block near Perth it is about 44 km.

Thus the Southwestern Province has an anomalous crustal structure but it is not clear whether the anomaly is limited by the Yandanooka-Cape Riche lineament or whether it is the culmination of a regional trend.

EXPERIMENTAL PROCEDURE

About 500 grams of each sample was crushed to pea size and split. The split for whole-rock analysis was reduced to -200 mesh in a Tema-style mill. Three to five grams of biotite were separated from the remaining split, mainly with a Frantz magnetic separator, and reduced to -200 mesh in an automatic agate mortar. The procedure for Rb-Sr analysis was essentially as described by Lewis and others (1975), de Laeter and Abercrombie (1970) and de Laeter (1976).

Measured Rb and Sr values and measured Rb/Sr ratios, determined by X-ray fluorescence spectrometry, are listed with mass spectrometric determinations of $^{87}Sr/^{86}Sr$ in Table 19. We believe the measured values of Rb and Sr are accurate to ±7 per cent; however, the measured Rb/Sr ratios should not be expected to correspond precisely with ratios which would be derived from the separate Rb and Sr values listed. Errors are reported at the 95 per cent confidence level. The value 1.42 x $10^{-11}yr^{-1}$ was used for the decay constant of ^{87}Rb (Steiger and Jäger, 1977).

ANALYTICAL RESULTS AND REGIONAL PATTERNS

WHOLE-ROCK RESULTS

The results of whole-rock analyses are listed in Table 19. Although whole-rock data are used primarily to support one end of the whole-rock-biotite isochron for each sample, at four localities sufficient samples were collected to form whole-rock isochrons independent of biotite data. These isochrons are plotted at a single scale in Figures 53 A to D. The isochron from Bald Hill is also plotted at an expanded scale in Figure 54. The data for these samples have been regressed using the least-squares program of McIntyre and others (1966). Results are listed in Table 20. Whole-rock model ages are mapped on Figure 55.

The results from Bald Hill are of particular interest as they imply a Proterozoic age in an area conventionally considered Archaean.

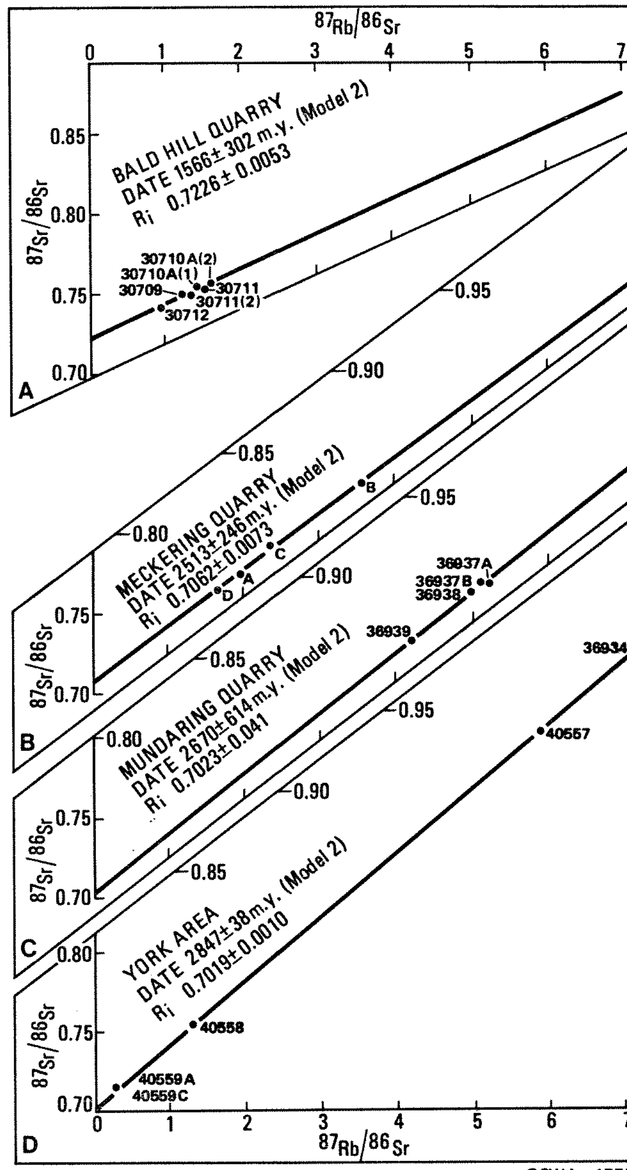

Figure 53 Biotite – whole-rock isochrons.
A. York area
B. Meckering quarry
C. Bald Hill quarry
D. Mundaring quarry

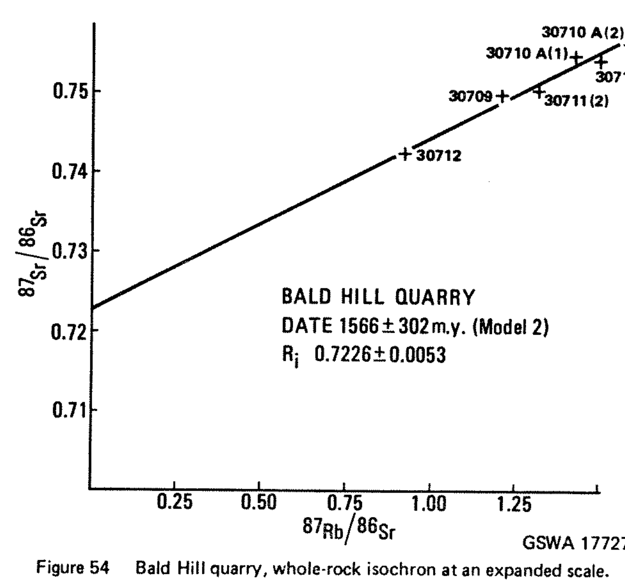

Figure 54 Bald Hill quarry, whole-rock isochron at an expanded scale.

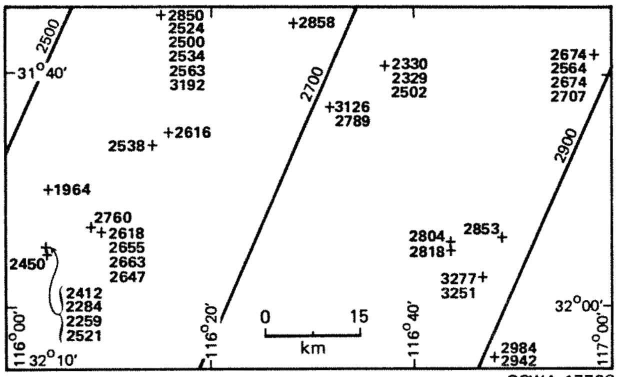

Figure 55 Map of whole-rock model ages with an assumed initial ratio of 0.700.

BIOTITE RESULTS

Biotite analytical results are listed with the whole-rock results in Table 19. Ages for each biotite, formed by joining the analysis at each separated biotite with that of a whole-rock split from the same sample, appear in Table 21 and are plotted in Figure 56. Biotite ages decrease regularly from Meckering (about 2 500 m.y.) westward for 70 km to the edge of the Yilgarn Block at the Darling Scarp (about 500 m.y.). This strong age gradient contrasts with whole-rock ages which, apart from the Bald Hill site, are consistent across the entire area.

Apart, possibly, from the Bald Hill site, there is no clear relation between either biotite or whole-rock dates and geology. Samples from the most westerly and most easterly localities are from granitoid rocks; intermediate samples are from migmatite and, possibly, Jimperding metamorphics (Fig. 52). However, the oldest whole-rock dates are from the Avon River valley area from which old dates have been previously recorded (Arriens, 1971).

TABLE 20. DATES FROM WHOLE-ROCK SAMPLES

Locality	No. of samples	MSWD*	Date (m.y.)	Ri	Model
Bald Hill Quarry	6	6·9	1 555±130 1 566±302	0·722 8±0·002 4 0·722 6±0·005 3	1 2†
Meckering Quarry	4	3·3	2 508±131 2 513±246	0·706 4±0·004 0 0·706 2±0·007 3	1 2†
Mundaring Quarry	4	3·0	2 678±362 2 670±614	0·701 7±0·024 2 0·702 3±0·041	1 2†
York area	5	1·4	2 844±35 2 847±38	0·702 0±0·000 7 0·701 9±0·001 0	1 2†

* Mean square of weighted deviates. † Preferred model.

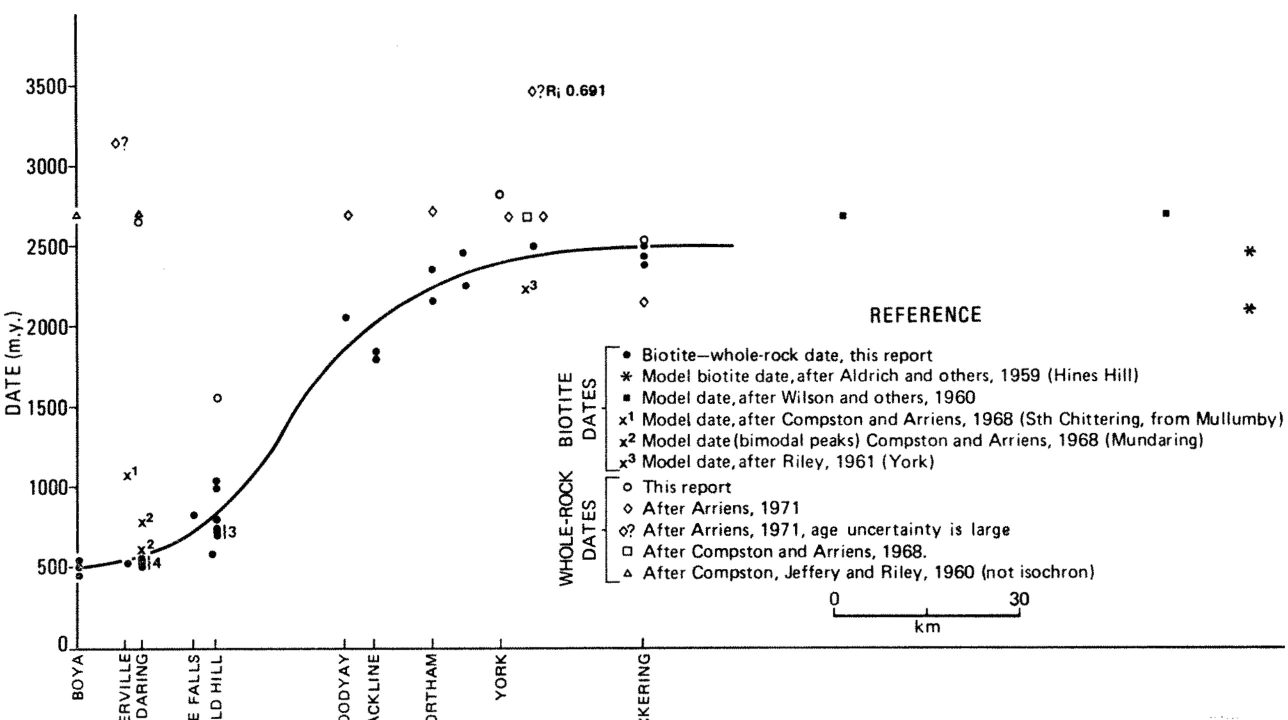

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Figure 56 Plot of dates against distance east of the Darling Scarp, measured normal to isopleths on the linear trend surface of biotite Rb-Sr dates.

TABLE 21. DATES FROM BIOTITE SAMPLES

Locality	Sample	Date (m.y.)	Locality	Sample	Date (m.y.)
Bald Hill Quarry	30709	1002	York	36934	2264
	30710A*	744		40557	2473
	30710A†	722		40558	2506
	30711	789			
	30711†	746	Northam Quarry	36935A	2372
	30712	1021		36935B	2164
Noble Falls	30714	823	Parkerville Quarry	36936	518
	36951	569	Mundaring Quarry	36937A	524
Boya Quarry	30715	548		36937B	525
	30716	512		36938	520
	30717	452		36939	545
Meckering Quarry	36902A	2512	Clackline	36942	1842
	36902C	2454		36944	1805
	36902D	2392			
			Ringa	36950	2073
			Herne Hill	36952	531

* First subsample. † Second subsample.

REGIONAL BIOTITE DATES

Biotite dates from the current study plus 33 Yilgarn Block biotite dates from other sources (Aldrich and others, 1959; Wilson and others, 1960; Turek, 1966; Compston and Arriens, 1968; and Roddick and others, 1976) along with dates from adjacent areas are plotted on Figure 57. All of the dates in the southwestern part of the Yilgarn Block are less than 2 000 m.y.; all those elsewhere in the Yilgarn exceed 2 000 m.y. In the western part of the Perth Sheet the transition from dates above 2 000 m.y. to dates below this figure approximates the boundary between the granulite and granite segments of the Southwestern Province.

Biotite data are not available for the south-central part of the Yilgarn Block or from a very large area in the northwestern part; however, biotite dates are available from the adjacent Gascoyne Province where they have a westward-decreasing trend similar to the pattern on the Perth Sheet, though less steep. Data from the east Gascoyne are from Williams and others (1978); those from the west Gascoyne have been drawn from de Laeter (1976) but recalculated to $\lambda = 1.42 \times 10^{-11}yr^{-1}$, the decay constant which we have used. Both data sets are plotted on the map, Figure 57. Three dates in the southwestern part of the Yilgarn Block similarly define a westward-sloping trend surface: (a) Wellington Dam (Compston and Arriens, 1968), 675 m.y. at $\lambda = 1.39 \times 10^{-11}yr^{-1}$; (b) Donnybrook (Compston and Arriens, 1968), 500 m.y. at $\lambda = 1.39 \times 10^{-11}yr^{-1}$; and (c) Hester (Wilson and others, 1960), 760 m.y. at $\lambda = 1.386 \times 10^{-11}yr^{-1}$. Adjusted for $\lambda = 1.42 \times 10^{-11}yr^{-1}$, these dates become, respectively, 661 m.y., 489 m.y., and 742 m.y. Although the three points are insufficient in themselves to provide confidence in a trend, it may be significant that the trend is consistent with the data from the Perth Sheet and the Gascoyne Province.

Although broad areas are devoid of Rb-Sr data on biotite, the reasonably continuous set of data between Perth and Kalgoorlie provides some constraint on proposed models for the Yilgarn Block. A model consistent with current data shows random variations in dates above 2 000 m.y. over most of the Yilgarn Block, decreasing rapidly but regularly in a westerly direction to about 500 m.y. along the western margin of the block. The decrease in dates may be reflected in the Gascoyne Province as well as in the adjacent Yilgarn Block.

Material is now being collected for a similar study of biotite dates along the western margin of the Yilgarn Block between Perth and the Gascoyne Province.

INTERPRETATION

DATING OF UPLIFT

Rubidium-strontium dates from biotite commonly are younger than whole-rock Rb-Sr isochron dates from the same rocks. The relatively late biotite date is commonly attributed to a metamorphic event which expelled Sr from biotite but failed to homogenize strontium among the whole-rock samples. However, an alternative interpretation was suggested by Hurley and other (1962). In their view biotite K-Ar and Rb-Sr dates may reflect time of uplift rather than time of thermal climax. This interpretation is particularly attractive if the rocks can be shown to have been at such a depth that a reasonably normal geothermal gradient would have brought them to a temperature above the blocking temperature of Sr for biotite.

Armstrong (1966) suggested the contouring of mapped biotite dates. Each contour would represent the intersection of the surface of the earth with a surface bearing a particular biotite age. The surface was formed at the depth of the regional blocking temperature for biotite. The biotite in deeper rocks lost the radiogenic Sr daughter product, those above retained it. On cooling associated with uplift and erosion the radiogenic isotope was frozen into the lattice and the date of uplift recorded. A succession of such surfaces, each younger than the previous, would be formed as long as uplift and erosion continued to bring new rock through the level in the crust at which Sr was frozen in biotite. On exposure these surfaces can be contoured. The conturs may outline the original shape of the isothermal surface if uplift has been uniform over the region or may reflect relative amounts of uplift if the original surface was flat. Armstrong called contours on biotite dates 'chrontours', Harper (1967) preferred 'thermochrons'.

Dates of uplift have been inferred from biotites using both K-Ar data (Armstrong and Hansen, 1966; Harper, 1967; and Krummenacher and others, 1975) and Rb-Sr data (Jäger, 1965; and Armstrong and others, 1966).

BIOTITE ^{87}Sr BLOCKING TEMPERATURE

A low ^{87}Sr diffusion blocking temperature in biotite is necessary for the interpretation of biotite dates as age of uplift. The blocking temperature should be equivalent to ambient temperatures well within the crust under a normal geothermal gradient.

Hanson and Gast (1967) calculated that biotite lost radiogenic Sr at temperatures down to 350°C near the Duluth Gabbro and down to 450°C at a quartz dolerite dyke, 50 m thick, near Christmas Lake Wyoming. They concluded that temperatures in excess of 300°C are necessary to effect complete radiogenic Sr daughter loss in biotite. Jäger and Zwart (1968) assume a 300°C blocking temperature for Rb-Sr in biotite from the Pyrenees. Dodson (1973) calculated that the 300°C estimate for Sr biotite closure derived by Jäger and others (1967) from mineralogical data in the Alps is reasonable. Williams and others (1975) accept the temperature of about 300°C; and Roddick and others (1976) accept a blocking temperature near 250°C on the basis of the work of Hart (1964) and Hanson and Gast (1967). Thus the consensus of observation and acceptance places the biotite blocking temperature near 300°C for an environment of regional heating. This is equivalent to a depth of 15 km at the modest rate of 20° C/km. The data of Hanson and Gast from Christmas Lake, suggesting somewhat higher temperatures, may be influenced by kinetic effects associated with the contact environment which they studied.

MODELS OF CRUSTAL DEVELOPMENT

The results of the botite analysis probably cannot now be given a unique interpretation. Various assumptions are necessary to arrive at any model. Apart from the fundamental assumption that the pattern of westward-decreasing biotite dates reflects a real, simple cause rather than fortuitous sampling one may assume:

(model 1), that each reported date closely approximates the age of a short-lived thermal event in the area;

(model 2), that the dates closely approximate the age of closure of the biotite system after an extended period above closure temperatures; or

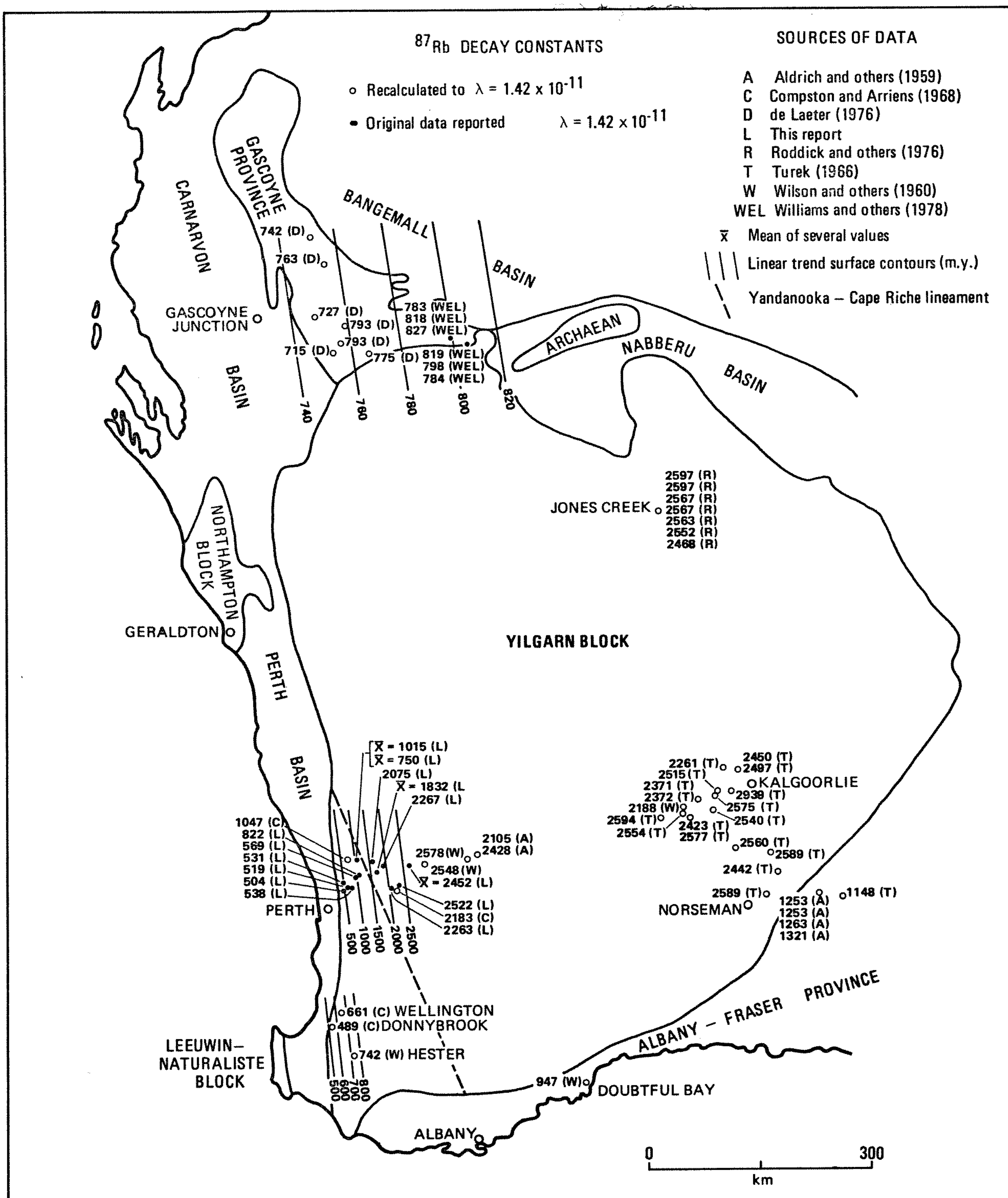

Figure 57 Regional biotite Rb-Sr dates, Yilgarn Block, with local linear trend surfaces.

(model 3), that the range in dates is due to variable expulsion of radiogenic ^{87}Sr from the biotite lattice near the closure temperature of ^{87}Sr in biotite.

Model 1 would require a wave, continuous or in discrete steps, of thermal activity passing from the Meckering area to the Darling Fault, or progressively contracting in that direction, over a period of 2 000 m.y., from 2 500 m.y. to 500 m.y. In the absence of precedent for this type of process elsewhere or necessity to invoke it here, model 1 seems less attractive than models 2 and 3. Nevertheless, the possibility of discrete thermal events draws some support from whole-rock Rb-Sr data. There are whole-rock dates which span much of the time interval involved. A date of 548-577 m.y. on basaltic dyke margins in the Mundaring area (Compston and Arriens, 1968) has already been mentioned. Assuming that this is an igneous date, an igneous event is provided to account for the western, young, biotite dates. Various dates on dykes from the Perth area, from 750 m.y. to 1 500 m.y., are quoted by Giddings (1976) from unpublished work by Compston and Crawford. The six-point whole-rock isochron from Bald Hill (Fig. 54) indicates a substantial mid-Proterozoic igneous or metamorphic event near the centre of the zone of transition of biotite dates. A high $^{87}Sr/^{86}Sr$ initial ratio (R_i), large mean square of weighted deviates, and large error limits favour a metamorphic origin for the Bald Hill whole-rock date although the rock appears no more metamorphosed than others which give an Archaean date. However, regardless of igneous or metamorphic origin of the date, a very substantial mid-Proterozoic event is indicated.

Thus there is plentiful evidence for discrete events capable of resetting biotite throughout the range of dates observed.

Apart from evidence from whole-rock data, a few biotite results seem to support multiple discrete events. Inspection of biotite results from Bald Hill suggests two ages. Figure 58 is a plot of biotite-whole-rock isochrons from Bald Hill, translated in the manner of van Schmus (1965) for more ready comparison of slopes. The clustering of slopes about 1 000 m.y. and 750 m.y. confirms the bimodal distribution of dates, though their statistical significance is not established.

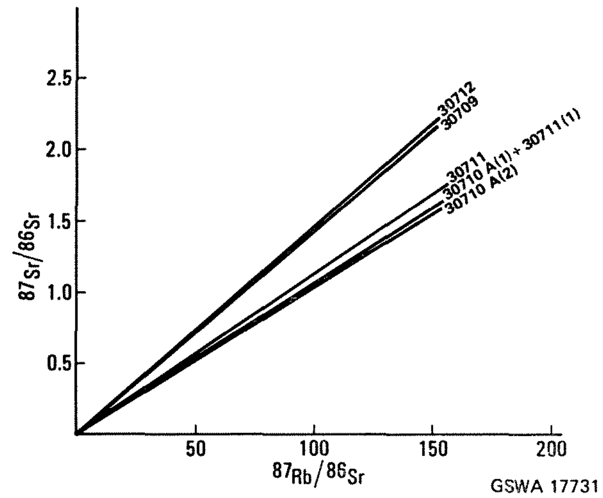

Figure 58 Bald Hill quarry, isochrons from biotite to associated whole-rock points, translated to pass through a common origin (O,O).

Despite suggestions of multiple discrete events the most direct interpretation of the data is a smooth progression of dates from 2 500 m.y. to 500 m.y. A mechanism for triggering discrete events sequentially to give the observed gradient in biotite dates remains difficult to find. Thus until better correlation between biotite dates and igneous or metamorphic events is established, or the regular progression of dates is shown to be spurious, models 2 and 3 are preferred.

Model 2 has substantial appeal as the steady march of events for 2 000 m.y. can be attributed to erosion and isostasy, processes which conceivably could have acted uniformly over the required period. In this model, slow and steady uplift of crustal material through the 300°C isotherm, accompanied by erosion, sets the sequence of dates. The truncated edges of surfaces of equal date are exposed successively either by uniform uplift and erosion of originally sloping paleo-isothermal surfaces or by erosion after continuous or episodic tilting of these surfaces. In any of these cases, erosion truncates the surfaces of equal date, giving the observed geographic spread of dates. This model would seem to be consistent with the geophysical pattern of westward-shallowing of the intermediate crustal layer. However, to explain the westward thickening of the total crust as well as to account for continued uplift of the magnitude assumed, crustal underplating would seem to be required.

In model 3, the disequilibrium model, only the oldest and youngest dates have age significance. The intermediate dates reflect incomplete expulsion of strontium from the biotite lattice. The appeal of this system is that a uniform succession of events spanning 2 000 m.y. is not required. A principal objection is that the entire 70 km from the Darling Scarp to Meckering would need to have been poised in the presumably small temperature range of partial discharge of ^{87}Sr from biotite. It seems unrealistic to propose vertical isotherms with the required temperature range spread from Meckering to the Darling Scarp, but gently eastward-dipping isotherms might be acceptable. Here, however, model 3 begins to converge on model 2. Truth may lie in this area.

The critical area for testing model 1 against models 2 and 3 seems to be the zone of steep gradients in dates between Toodyay and Bald Hill. Further samples have been collected in this area and are being analysed.

In summary, whole-rock Rb-Sr dates appear to average about 2 700 m.y. throughout the Southwestern Province whereas biotite Rb-Sr dates fall regularly westward from about 1 500 m.y. at Meckering to about 500 m.y. at the Darling Scarp, 70 km to the west. The succession of dates may be attributed either to a series of discrete events, the gradual elevation of the rock mass through the 300°C isotherm, or the increased completion of expulsion of radiogenic ^{87}Sr from the biotite lattice upon westward approach to a source of heat less than 500 m.y. ago. No choice is made among the 3 models, but the last two are favoured over the first.

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INTRACOENOSTEAL VARIATION IN A SPECIMEN OF *ACTINOSTROMA*

by A. E. Cockbain

ABSTRACT

Six variables have been measured in 6 thin sections cut from one coenosteum of *Actinostroma papillosum*. Ten measurements were made of each variable in each thin section and the results statistically analysed. The median test suggests that lamina thickness, number of laminae in 5 mm and distance in which 15 pillars occur, show significant intracoenosteal variation at the 0.05 level while the other 3 variables—pillar thickness, number of pillars in 5 mm and distance in which 15 laminae occur—show no variation. The Kruskal-Wallis test suggests that only pillar thickness shows *no* variation at this level. Fagerstrom and Saxena's (1973) data on intracoenosteal variation in *Syringostroma sherzeri* were re-examined and significant variations were found to occur in 2 of their 4 variates. It is concluded that intracoenosteal variation is higher than previously believed. The treatment of tied median values in the median test is discussed in an appendix.

INTRODUCTION

Measurement of variables, for example the spacing of laminae and pillars, is an important aspect of the description of stromatoporoid specimens. Such measurements are usually few in number and are often made on only one thin section from a coenosteum. The assumption that such measurements are representative of the variation throughout the coenosteum has been tested by Fagerstrom and Saxena (1973). They showed that in a specimen of *Syringostroma sherzeri* from the Devonian of Ontario, 3 out of 4 variables showed no significant variation within the coenosteum.

In the course of a study of Devonian stromatoporoids from the reef complexes of the Canning Basin, numerous specimens of *Actinostroma* were observed. In the form of the 'Art-Diagram' (Flügel, 1959), measurements have been considered especially critical in differentiating species of *Actinostroma* and it was decided to extend Fagerstrom and Saxena's work to see how much intracoenosteal variation there is in this genus.

MATERIAL AND METHODS

Actinostroma is one of the commonest stromatoproids in the Pillara Limestone (Playford and Lowry, 1966; Playford and Cockbain, 1976). Several species are present and the most abundant one is identified as *A. papillosum* Bargatzsky. Specimen F9861 from sample no. 18660 is a large, well-preserved example of *A. papillosum* and was collected from reef facies of the Pillara Limestone at the southern end of McWhae Ridge (Fossil locality MRM 2; Mount Ramsay 1:250 000 map sheet, grid reference (yards) E 408 900; N 649 610). It is hemispherical in shape with a diameter of 350 mm and a height of 250 mm. The coenosteum was cut vertically through the middle and 6 thin sections were made from different parts of cut surface (Fig. 59). The cut surface has an area of about 600 cm^2 and the thin sections ranged in area from 14.5 to 30 cm^2.

Ten measurements of 6 variables were measured on each thin section. The variables are:

1. Numbr of laminae in 5 mm (L5)
2. Number of pillars in 5 mm (P5)
3. Lamina thickness (in mm) (Lt)
4. Pillar thickness (in mm) (Pt)
5. Distance (in mm) occupied by 15 laminae (15L)
6. Distance (in mm) occupied by 15 pillars (15P)

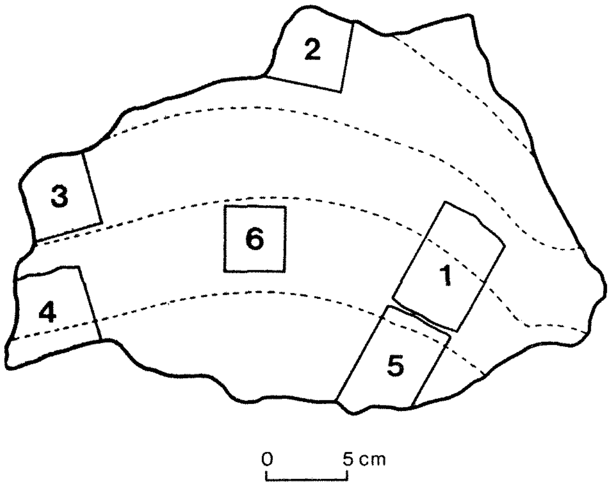

Figure 59 Sketch of vertical section through coenosteum F9861 showing position of slides (1-6) and course of selected laminae (------).

GSWA 17713

Variables 5 and 6 are equivalent to variables 1 and 2. However, measuring the distance in which a number of laminae and pillars occurs, rather than the number of laminae and pillars in a particular distance, gives a more continuous variate and (incidentally) simplifies the calculation of the gallery index. By way of emphasising the small sample size that these thin sections represent, it was calculated that the coenosteum had a volume of 12.3 x 10^3 cm^3 and possessed about 100 laminae and around half a million pillars.

The original data are on file at the Geological Survey of Western Australia.

STATISTICAL ANALYSIS

The amount of intracoenosteal variation may be analysed stastistically by determining the probability that, for any variable, the measurements in each of the 6 samples (thin sections) are drawn from the same population (coenosteum). This may be re-phrased: taking a probability of 0.05 as the rejection level, do the samples come from the same population?

Three tests were carried out on the data, the F test, extension of the median test, and the Kruskal-Wallis one-way-anova test. Fagerstrom and Saxena (1973) argued that the F test was inappropriate because the data are (a) discontinuous variates and (b) are not necessarily normally distributed. They preferred to use the distribution-free median test. Their reasoning is accepted here and the F test is included purely for comparative purposes and will not be discussed further.

The results of the tests are tabulated below:

Variate	F test	Median test *	Kruskal-Wallis test †
L5	3·55	13·04	14·71
P5	4·61	9·57	16·77
Lt	2·42	11·20	11·07
Pt	1·02	1·94	3·91
15L	2·75	9·60	12·46
15P	3·83	12·00	14·07
Significance level:			
0·05	2·37	11·07	11·07
0·01	3·34	15·09	15·09

* See Appendix for tied median values
† Corrected for ties.

INTERPRETATION

Two features stand out from the above table. Firstly the difference between the two distribution-free tests and secondly the high values of the test statistics. At the 0.05 probability level the median test shows that for only 3 of the variates are the samples drawn from the same population (P5, Pt and 15L). The Kruskal-Wallis test indicates that this is true for only one variate (Pt). Hence there is considerable intracoenosteal variation in L5, Lt and 15P, much less in P5 and 15L and least (negligible) in Pt.

Intracoenosteal variation in the lamina characters (L5, Lt) could be explained by the presence of latilaminae, which do occur in this specimen; however, it is strange that latilamination does not affect 15L to the same extent. The great variation in pillar spacing (15P) is hard to account for and is not reflected in the P5 variate.

Which of the two distribution-free tests to prefer is a difficult problem. The Kruskal-Wallis test uses more information than the median test and has a higher asymptotic relative efficiency (0.955 as compared with 0.637 for the median test; see Gibbons, 1971, p. 202). Conover (1971, p. 256) states that the median test is preferable to the Kruskal-Wallis test if there are too many tied observations. Here the most favourable test outcome is accepted, that is that the samples are drawn from the same population and hence the results of the median test are preferred. At the same time a note of caution should be sounded and perhaps variable Pt is the only one that has an acceptably small amount of variation.

RE-EXAMINATION OF FAGERSTROM AND SAXENA'S DATA

The conclusion that half of the variables studied showed considerable intracoenosteal variation is quite different from Fagerstrom and Saxena's results. In *Syringostroma sherzeri* they found that only 1 of the 4 variables studied showed appreciable intracoenosteal variation.

Through the courtesy of J. A. Fagerstrom I have been able to re-examine their data. The variables measured in *S. sherzeri* were:

1. Number of microlaminae in 2 mm (L2)
2. Megapillar diameter (MPd)
3. Megapillar spacing (MPsp)
4. Number of galleries encircling each megapillar (EG)

The data were tested in the same way as for *Actinostroma* with the following results:

Variate	F test	Median test*	Kruskal-Wallis test†
L2	2·85	9·91	16·97
MPd	3·21	10·88	16·75
MPsp	6·65	14·63	27·94
EG	4·45	20·00	22·21
Significance level:			
0·05	2·17	14·07	14·07
0·01	2·95	18·48	18·48

* See Appendix for tied median values.
† Corrected for ties.

The values for the results of the median test differ from those published by Fagerstrom and Saxena (1973) because of the different way of resolving tied median values (see Appendix for discussion of this problem). Again the two distribution-free tests give different results. Accepting the more favourable results of the median test, the thin sections do not come from the same population with respect to variables MPsp and EG. Hence there is considerable intracoenosteal variation in these two variables. Fagerstrom and Saxena recognised considerable variation only in EG.

CONCLUSIONS

Of the 6 variables examined in *A. papillosum* and the 4 in *S. sherzeri*, only half show no intracoenosteal variation at the 0.05 probability level using the median test. The Kruskal-Wallis test would reduce to one the variables showing no such variation at the same level of acceptance. The variates showing no intracoenosteal variation are, in *A. papillosum:* P5, Pt and 15L; in *S. sherzeri:* L2 and MPd.

Three things emerge from this analysis: (a) variation in one thin section may not reflect the variation throughout the coenosteum; (b) more measurements of coenosteal variables should be made, preferably on more than one thin section; (c) caution should be exercised in differentiating species solely on the basis of small differences in coenosteal variables.

ACKNOWLEDGEMENTS

I thank J. A. Fagerstrom for supplying the data from his measurement on *S. sherzeri* and I thank both him and K. M. L. Saxena for their helpful comments on the whole question of the analysis of intracoenosteal variation.

APPENDIX

THE TREATMENT OF TIED MEDIAN VALUES IN THE MEDIAN TEST

Tied observations do not affect the median test except where the median value is tied. Gibbons (1971, p. 137) suggests that such ties should be broken in all possible ways, and the minimum computed test value accepted.

The *Actinostroma clathratum* P5 data will be taken as an example.

No. of pillars	Frequency	Cumulative frequency
14	1	1
15	4	5
16	8	13
17	15	28
18	16	44
19	10	54
20	5	59
21	1	60

Here the median is 18 and the number of tied median values is 16.

The median test may be calculated as follows:

χ^2 with m–1 df = $N^2/R(N-R)\ (\Sigma(Om^2/n)-R^2/N)$

where N is the grand total of measurement (here 60)

n is the number of measurements in each sample (10)

m is the number of samples (6)

Om is the number of measurements below the median in each sample

R is the grand total of measurements below the median (=ΣOm)

The χ^2 values for R=28 and R=44 (i.e. for values <Md class and for values ⩽Md class) are calculated. Then χ^2 for R between 28 and 44 is calculated by breaking the ties. The following will show the method:

R	Sample No. 1	2	3	4	5	6	χ^2
28	7·0	2·0	2·0	4·0	7·0	6·0	10·98
30	7·38	2·25	2·75	4·13	7·0	6·5	10·16
32	7·75	2·5	3·5	4·25	7·0	7·0	9·63
34	8·13	2·75	4·25	4·38	7·0	7·5	9·57
36	8·5	3·0	5·0	4·5	7·0	8·0	9·79
38	8·88	3·25	5·75	4·63	7·0	8·5	10·55
40	9·25	3·5	6·5	4·75	7·0	9·0	11·68
42	9·63	3·75	7·25	4·88	7·0	9·5	13·54
44	10·0	4·0	8·0	5·0	7·0	10·0	16·02
(Ties 16	3·0	2·0	6·0	1·0	0	4·0)	

In this example χ^2min lies at R=34. Note that two obvious choices of R, namely R=30 (the mid point or median) and R=36 (allocating half the tied median values to <Md class) do not give minimum values of χ^2 in this case, although either may do so in other examples.

When χ^2 is plotted against R values for the median class, a smooth 2nd degree polynomial curve is obtained and this is true for all cases where the median values are tied. This suggests that χ^2min can be calculated from the polynomial equation and that the minimum need not lie at an integer value of R.

If $\chi^2 = aR^2 + bR + c$

then χ^2min = c-(b^2/4a)

and occurs where R = -b/2a

It is relatively easy to fit a 2nd degree polynomial to the calculated χ^2 values using a programmable calculator (although the R values may have to be restored from O to n, where n = number of ties, in order to avoid rounding errors in the calculation). A good approximation to χ^2min can be obtained by finding χ^2 for R<Md class and R⩽Md class and for the mid-point between these R values, and then determining the polynomial equation for these three pairs of values.

The following table compares χ^2min calculated by three different methods.

	by iteration (breaking ties)	by polynomial	by polynomial approximation
L5	13·04	13·00	12·98
P5	9·57	9·41	9·36
Pd	1·94	1·93	1·89
MPd	10·88	10·88	10·90
L2	9·91	9·91	9·91
MPsp	14·63	14·59	14·59

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PALAEOECOLOGICAL AND PALAEOGEOGRAPHIC IMPLICATIONS OF *RHIPIDOMELLA MICHELINI?* (LEVEILLE) IN THE CARBONIFEROUS OF THE CARNARVON BASIN

by I. H. Lavaring

ABSTRACT

Shelly coquinoid deposits in the middle and upper parts of the Lower Carboniferous Moogooree Limestone are dominated by shells of *Rhipidomella michelini?* (Leveille). Tho separate biofacies are identified within the coquinas: (1) *Syringopora* biofacies consisting of coral, bryozoan and brachiopod debris, and (2) *Rhipidomella michelini?* biofacies consisting of brachiopod shells and crinoid ossicles. Taphonomic evidence suggests they are postmortem, transported assemblages and not *in situ* benthic communities. The morphology of *Rhipidomella michelini?* reflects adaptation to turbulent, shallow marine conditions similar to those experienced by its Visean homoeomorph from eastern Australia, *Rhipidomella fortimuscula* Cvancara. A westerly deepening palaeobathymetry, evident from the coquinas, differs from the Early Carboniferous palaeogeography of the Carnarvon Basin proposed by Condon (1965, 1968), and provides further evidence of shoreline positions during this time.

INTRODUCTION

The major Carboniferous marine invertebrate fauna of the Carnarvon Basin is preserved in the middle and upper parts of the Moogooree Limestone. Glenister (1955), Veevers (1959), and Thomas (1971) described brachiopod species from the fauna, and Thomas (1971) considered it to be Tournaisian in age. Roberts (1971) and Thomas (1971) compared the fauna to others of the same age and similar faunal composition in the Canning and Bonaparte Gulf Basins.

Detailed mapping of outcrop of the Moogooree Limestone carried out during 1978 has shown that shelly faunas are limited to several stratigraphic horizons, and are dominated by shells of *Rhipidomella michelini?*. Condon (1965) considered the unit to be a shallow-marine sequence and noted that fossils were restricted in occurrence. Examination of the fossiliferous horizons has revealed that the faunal content of each horizon is facies dependent. Further, the distribution, orientation, and preservation of *Rhipidomella michelini?* provides an indication of sedimentary conditions prevalent during deposition of the sequence.

The Tournaisian age given to the fauna of the Moogooree Limestone by Thomas (1971) provides the only definite age determination for the Carboniferous sequence in the Carnarvon Basin; the Visean age for the Yindagindy Formation is less certain. *Rhipidomella* is one of the few genera represented by different species in the Carboniferous faunal successions of eastern and western Australia. The stratigraphic range of species such as *Rhipidomella michelini?* provides the basis for the biostratigraphic zonations proposed for the Carboniferous system of Western Australia by Roberts (1971) and Thomas (1971). The present study provides the first evidence of palaeoecological factors influencing the geographic and stratigraphic distribution of brachiopod species within the faunal succession. The shallow-marine environment postulated for the Moogooree Limestone by Condon (1965) is supported, and the palaeobathymetry established from the position and environment of deposition of the coquinas. These show a westward-deepening trend during deposition of the upper part of the Moogooree Limestone.

STRATIGRAPHIC SETTING

The Moogooree Limestone is the basal unit of the Carboniferous sequence in the Carnarvon Basin; it crops out as a series of north-trending strike ridges near the eastern edge of the basin on Williambury and Moogooree Stations (Fig. 60). Teichert (1949) originally named the unit, but Condon (1954, 1965) redefined and described it, and proposed a type section southeast of Williambury Homestead.

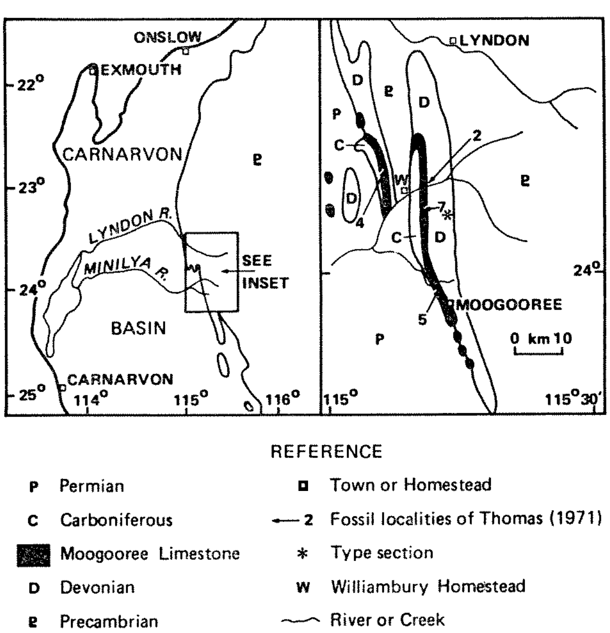

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Figure 60 Location of Moogooree Limestone outcrop and fossiliferous horizons.

The sequence within the type section is calcarenite, quartz sandstone, calcilutite, dolomite and oolite. Shelly coquinoid deposits are limited to calcarenite beds in the middle and upper part of the sequence, and extend along strike north and south of the line of section.

The Moogooree Limestone lies disconformably on the Willaraddie Formation, or unconformably on the Munabia Sandstone. Where the complete Lower Carboniferous sequence is present, the Moogooree Limestone is conformably overlain by the Williambury Formation; elsewhere it is unconformably overlain by the Lower Permian Lyons Formation. The Tournaisian age assigned to the Moogooree Limestone is the basis for ages Condon (1965) assigned to the other unfossiliferous units in the sequence: the Willaraddie Formation, Munabia Sandstone, and Williambury Formation.

Condon (1965) suggested that the Moogooree Limestone is a shallow-marine shelf sequence. The presence of corals and other shallow-marine invertebrates supports this interpretation. Low-angle planar cross-stratification is evident within the coarse-grained calcarenite which contains shell-rich coquinas. Fine-grained, well-sorted calcarenite contains some sets of trough cross-stratification and a fauna of corals, brachiopods, and bryozoans. The calcilutite is planar bedded, and generally devoid of macrofossils. Few of the macrofossils, except colonies of *Syringopora* sp., are preserved *in situ*. Abrasion and transportation of the fossiliferous debris has resulted in damage to specimens, which are scattered along bedding planes in dense layers. Marine conditions appear to have prevailed during deposition of the sequence, and a turbulent shallow-marine environment is envisaged.

Dolomite comprises a significant proportion of the unfossiliferous part of the Moogooree Limestone, but is not as common in other marine units of the Devonian or Carboniferous sequence.

BIOFACIES

Two biofacies are distinguished within fossiliferous horizons of the sequence: (1) the *Syringopora* biofacies which consists of *in situ* colonies of *Syringopora* sp., small pedunculate brachiopods, and bryozoan fragments; and (2) the *Rhipidomella michelini?* biofacies which consists of whole shells and disarticulated valves of *Rhipidomella michelini?*, *Unispirifer fluctuosus* (Glenister), *Syringothyris spissus* Glenister, other brachiopod species, crinoid ossicles, and occasionally, coral debris, all of which are significantly damaged and abraded.

Each biofacies is characterized by its distribution as well as its faunal content: the *Syringopora* biofacies occurs northwest of Williambury Homestead, in beds of fine-grained well-sorted calcarenite (Thomas, 1971, Fig. 1, locality 4). The *Rhipidomella michelini?* biofacies is present at the same stratigraphic level in coarse-grained, well-sorted calcarenite that is exposed on the northern and southern banks of the Minilya River (Veevers, 1959, Fig. 1, CC120; Thomas, 1971, locality 2) and the upper part of the sequence within the type section (Thomas, 1971, locality 7).

TAPHONOMY

Shells comprising coquinas of the *Rhipidomella michelini?* biofacies are oriented parallel to bedding planes and exhibit evidence of abrasion, such as wear on the umbo and rounding of shell edges, features typical of movement and winnowing in nearshore areas. Many complete valves of *Rhipidomella michelini?* exhibit fracture patterns consisting of three linear or curvilinear fractures which intersect at or near the centre of each valve at angles of approximately 120°. Crushing after burial is interpreted to be the cause.

The absence of juvenile shells indicates either a continued winnowing and removal prior to burial, or a low juvenile mortality rate in the living population. The first alternative is favoured because of the damaged and abraded nature of the shells, and because present-day marine invertebrates inhabiting turbulent environments generally possess high juvenile mortality rates (Valentine, 1973).

Specimens of *Syringopora* sp, exhibit few signs of turbulent conditions such as damaged colonies or broken corallites and are present northwest of Williambury Homestead in fine-grained, well-sorted calcarenite. Coarse-grained calcarenite is lacking and this occurrence which is interpreted as a sublittoral assemblage of both *in situ* and transported remains, formed below wave base.

The *Rhipidomella michelini?* biofacies was formed as a littoral accumulation of shelly debris, built up in near-shore areas by progressive deposition of live and dead shells by wave action. Living shells detached from the substrate by rupture of the pedicle, were then transported shorewards with dead shells, many being disarticulated or otherwise damaged during the process.

FUNCTIONAL MORPHOLOGY OF *RHIPIDOMELLA MICHELINI?*

Shells of the species were anchored to the substrate, or other hard objects, by means of a muscular pedicle (Fig. 61). A low lateral profile was thus attained, minimizing the possibility of detachment.

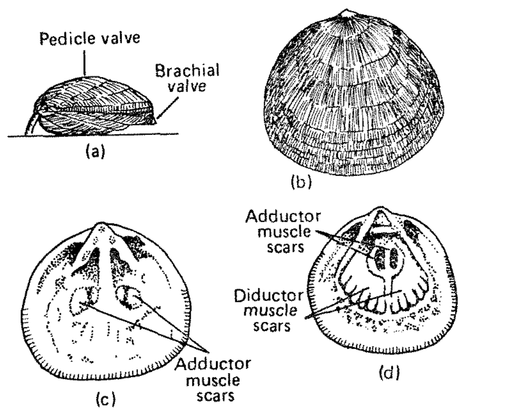

Figure 61 A. Living orientation of Rhipidomella michelini? (Leveille).
B. Pedicle valve exterior, F10288 (x 1).
C. Brachial valve exterior, F10281 (x 1).
D. Pedicle valve interior, F10287 (x 1).

The external surface of some valves contain elliptical borings, up to 5 mm long and 2 mm wide, which are similar to acrothoracic barnacle borings described by Rodriguez and Gutschick (1970). As no indication of host response is evident, boring may have taken place after death. Present-day populations of encrusting barnacles are known to be limited to the intertidal zone (Valentine, 1973), but it is not known if Carboniferous forms were distributed in this manner.

Distinctive features of the internal surface of the pedicle valve of *Rhipidomella michelini?* are the large muscle scars which served as a base for the attachment of the diductor muscle system. Confined space within the shell and the anterior position of the hinge line necessitated development of a large muscle system with a wide base of attachment, to ensure fast and efficient opening and closure of valves. Fine rounded costae on the external surface of both valves served as structural reinforcement, strengthening the shell without significantly increasing weight.

Of the three described species from eastern Australia *Rhipidomella australis* (M'Coy) (Mid-Tournaisian to Mid-Visean), *Rhipidomella myosa* Campbell (Mid-Visean), and *Rhipidomella fortimuscula* Cvancara (Late Visean), the latter species is most similar to *Rhipidomella michelini?*

Considerable variability is apparent in the specimens of *Rhipidomella michelini?* figured by Thomas (1971), particularly in the size and shape of the diductor muscle scars (Thomas, 1971, pl. 21, fig. 46, 6). They are larger in *Rhipidomella fortimuscula*, and may be an adaptation for living in turbulent shallow-marine conditions as Lavaring (1974) indicated.

PALAEOGEOGRAPHIC SIGNIFICANCE

Devonian sedimentation along the eastern margin of the Carnarvon Basin commenced with a marine invasion which penetrated well to the east of the present basin margin and formed a shallow sea which received little terrigenous material. Sediments deposited include a basal transgressive unit, the Nanyarra Greywacke, and the carbonate-rich shelf sequence of the Gneudna Formation. Regression occurred during the Late Devonian, with deposition of the shallow-marine Munabia Sandstone, which infilled the marine basin. Uplift along the eastern margin of the basin and deposition of the non-marine Willaraddie Formation followed.

Marine transgression during the Early Carboniferous (Tournaisian) initially penetrated beyond the present basin margin, but was restricted during deposition of the upper part of the Moogooree Limestone (Fig. 62). The presence of littoral shell deposits, *in situ* coral colonies, and the absence of tidally influenced sedimentation is the basis of the palaeogeography shown in Figure 62. The sharp lateral transition between the biofacies indicates a well-defined but gentle bathymetric slope and a shoreline adjacent and parallel to the *Rhipidomella michelini?* biofacies (Fig. 62). A north-south shoreline is evident from the biofacies; this conflicts with the indented coastline postulated by Condon (1965) and provides further evidence that the "abutment" unconformities he postulated to account for the discrepancy, are faults as Playford and others (1975) suggested. The limit of wave agitation is the boundary between the two biofacies, and is placed mid-way between them, parallel to the shoreline.

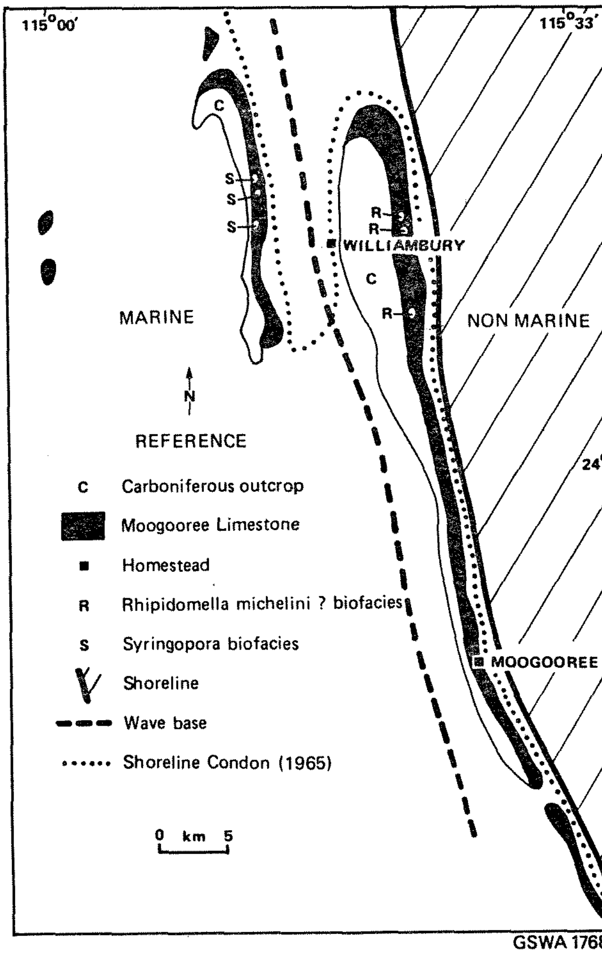

Figure 62 Early Carboniferous palaeogeography of the eastern margin of the Carnarvon Basin during deposition of the upper part of the Moogooree Limestone.

CONCLUSION

Shelly coquinoid layers in the Moogooree Limestone are dominated by *Rhipidomella michelini?*, and were formed by deposition of shelly material between wave base and the strand line. Less disturbed fossiliferous remains and *in situ* colonies of *Syringopora* sp. were preserved below wave base. Compared to the three known species from the Carboniferous of eastern Australia *Rhipidomella fortimuscula* is most similar to *Rhipidomella michelini?* and populated similar sedimentary environments. Palaeobathymetric trends evident from the distribution of biofacies show a straight north-south oriented shoreline during deposition of the fossiliferous upper parts of the Moogooree Limestone, whereas the shoreline was further east during deposition of the lower part of the unit.

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EXPLORATION GEOCHEMISTRY AT THE MOUNT PALGRAVE AND MOUNT VERNON Cu–Zn LOCATIONS, BANGEMALL BASIN

by R. E. Smith* and R. Davy

ABSTRACT

Geochemical exploration surveys carried out by Westfield Minerals (W.A.) N.L. and Union Minière Mining and Development Corporation Limited show that both the Mount Palgrave and Mount Vernon locations have strong surface geochemical expression.

Regional stream-sediment surveys which included the region about Mount Palgrave show Cu and Zn anomalies relatable to outcrops of shale in the Jillawarra Formation. A multi-element investigation of leached shale outcrops and microgossans shows a Cu-Mo-Ag association at Westfield Minerals' Cu-shale location. A similar investigation of thin, Zn-sulphide intersections from their diamond-drill core showed only a weak Mo-Ag pathfinder signature. The copper-rich shale outcrops appear to be unrelated to the weak Zn-sulphide mineralization.

In the region of the Mount Vernon Syncline, a stream-sediment geochemical survey by Westfield Minerals defined Zn-Cu anomalies, most of which were related to outcrops of shale in the Kiangi Creek Formation, which in turn carry Cu and Zn anomalies. Systematic chip sampling of stratigraphic sections by UNIMIN closely defined the anomalies. Multi-element analyses of the mineralization, a low-grade Zn-Cu-sulphide zone in black shale, showed a Cd-Mo-Ag pathfinder signature. Investigation showed the same association to be recognizable as a surface anomaly in the leached shale outcrops of the mineralized zone. Hydromorphic dispersion has enlarged the anomaly size in the down-hill direction, particularly for Zn, less so for Cu, and intermittently for Cd, Mo and Ag.

Stream-sediment surveys are confirmed as being valid exploration procedures for regions of the Bangemall Basin with good outcrop. Rock-chip and gossan sampling provide follow-up data. Cd, Mo and Ag are shown to be pathfinder elements for the known types of mineralization in the Bangemall Basin. However, the known mineralization is subeconomic, and it is unlikely that future exploration will be specifically directed at this style of mineralization. It is recommended, therefore, that a comprehensive suite of potential pathfinder elements be determined in future exploration programmes.

INTRODUCTION

Systematic exploration of the Bangemall Basin by Westfield Minerals (W.A.) N.L. (Westfield) in the early 1960s revealed low-grade stratiform Zn-Cu mineralization in the lower part of the Bangemall Group, in stratigraphic units, dominantly shales, which are now called the Jillawarra Formation and the Glen Ross Shale Member of the Kiangi Creek Formation. Subsequent exploration by Union Minière Development and Mining Corporation Limited (UNIMIN) during 1970-72 confirmed the widespread nature of surface indications of Zn and Cu over these two units.

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This paper compares the results of surface geochemical exploration by the two companies with the chemistry of mineralized drill cores obtained by Westfield at two localities (Fig. 63), in the Mount Palgrave area (grid reference

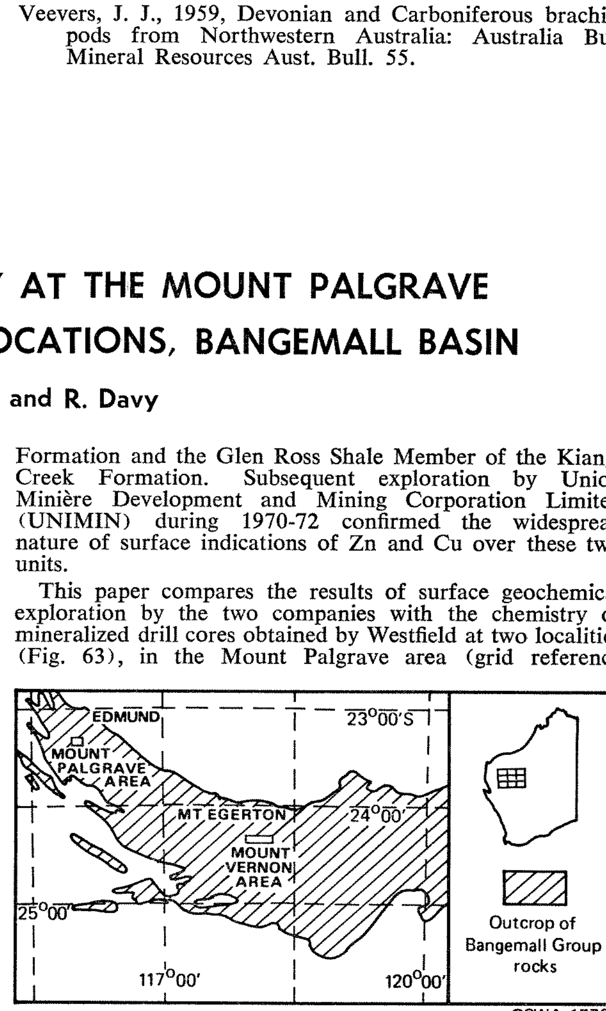

Figure 63 Location diagram.

395088, Edmund 1:250 000 sheet), and the Mount Vernon area (grid reference 644973, Mount Egerton 1:250 000 sheet). Additional multi-element geochemical work on both core and surface material has been carried out by the authors. The purpose of this paper is to review the effectiveness of exploration methods in the Bangemall Basin with particular emphasis on the trial use of multi-element geochemical methods.

In this paper the terms 'pathfinder elements' or 'pathfinders' are used for minor and trace elements that accompany, or have close associations with, base-metal sulphide mineralization. A distinction exists between this usage and that where the term 'pathfinders' is used for relatively more mobile elements than the element(s) being sought.

REGIONAL GEOLOGICAL SETTING

The stratigraphy, sedimentation and structure of the central and western parts of the Bangemall Basin has been presented by Brakel and Muhling (1976). These authors correlate the stratigraphy established on the Edmund 1:250 000 sheet (Daniels, 1969) across the Mount Egerton and Collier 1:250 000 sheets. The rocks of interest are those of the Bangemall Group, which were deposited in shallow-water marine to terrestrial alluvial conditions and which are characterized by lensing, interfingering, and lateral gradations (Brakel and Muhling, 1976).

Throughout the west and central Bangemall Basin, the most widespread rock unit carrying indications of Cu or Zn mineralization is the shale underlying the Discovery Chert, a prominent marker horizon in the western Bangemall Basin. This unit has previously been referred to as the "Prospect Shale" at Mount Palgrave, but it is now formally referred to as part of the Jillawarra Formation (Muhling and others, 1976), and is the host of the drilled mineralization at Mount Palgrave.

At Mount Vernon, shale of the Jillawarra Formation immediately below the Discovery Chert shows weak surface indications of Cu and Zn. However, a lower shale unit, the Glen Ross Shale Member of the Kiangi Creek Formation (Muhling and others, 1976) shows stronger surface indications of the same elements.

Detailed investigation of the mineralization at these two locations has recently been carried out by Davy and Marshall (in prep.).

SURFACE EXPLORATION

Stream-sediment geochemistry has been used by both Westfield and UNIMIN. In both cases samples were collected from the upper 0.1 m of the sediment and sieved at 80 mesh (177 μm). Cu, Pb and Zn were determined by atomic absorption spectrophotometry following digestion in perchloric acid. In addition, UNIMIN determined cold-extractable Cu following digestion with cold, dilute HCl.

UNIMIN's stream-sediment programme was restricted to the Edmund Sheet. Approximately 4 000 sites were sampled covering all the Bangemall Group rocks. The survey was designed to give a linear sample density of 1 sample per 1.6 km (1 mile) down all appropriate stream channels. The Mount Palgrave area was included within this survey (Fig. 64B).

Subsequently UNIMIN changed their emphasis to the collection of weathered shales as a continuous series of chip samples from measured stratigraphic sections. In addition numerous ironstones were sampled separately.

For interpretation, stream sediments derived from each rock unit or formation were considered separately. The 95th and 98th percentile derived from histograms or cumulative-frequency curves were arbitrarily used to define 'threshold' and 'strongly anomalous' levels respectively. Threshold levels used (in ppm) are given in Table 22.

TABLE 22. THRESHOLD VALUES OF UNIMIN STREAM-SEDIMENT SAMPLES (-177 μm) TAKEN ON THE EDMUND SHEET, (HERBERT AND OTHERS, 1972)

Formation	Threshold Values (—177μm fraction)			
	Cold copper (ppm)	Total copper (ppm)	Lead (ppm)	Zinc (ppm)
Irregully Formation	13	70	52	128
Kiangi Creek and Jillawarra Formations	22	73	67	115
Devil Creek Formation and Discovery Chert	10	74	40	125
Ullawarra Formation	13	91	47	99
Fords Creek Shale	10	69	40	96
Curran and Coodardoo Formations	13	80	43	110
Kurabuka Formation	16	101	48	125

Values are the 95th percentile for geological domains (defined as areas based on rock units—mostly formations) mapped on the Edmund Sheet, Daniels (1969).

Other aspects of exploration in the Bangemall Basin are discussed by Smith (in press).

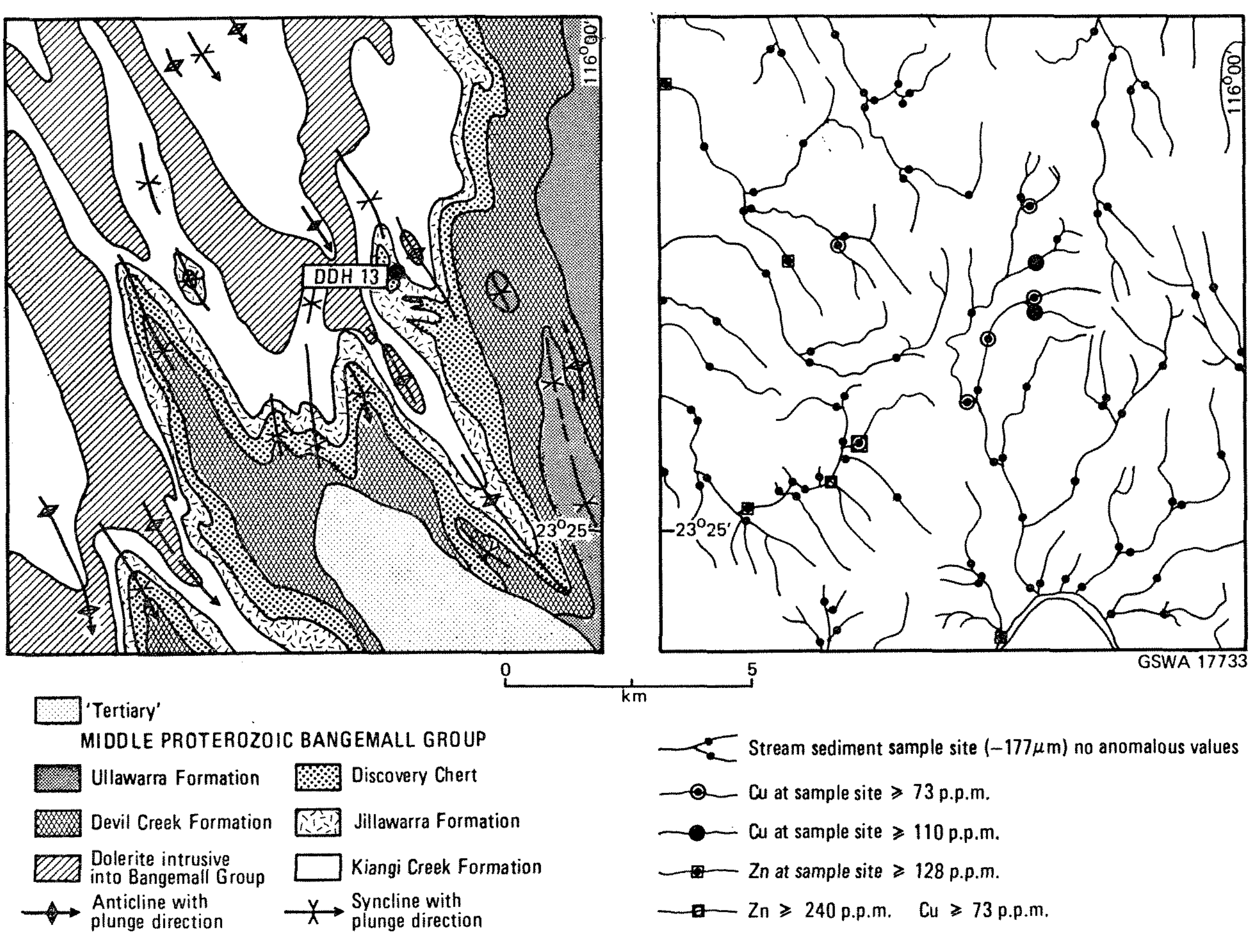

Figure 64 A. Geology of the region about Mount Palgrave from mapping by Herbert and others (1972) following regional mapping of the Edmund Sheet by Daniels (1969).
B. Regional stream-sediment Cu and Zn geochemistry of region shown in (A), part of a regional geochemical survey of the Edmund Sheet by UNIMIN.

MOUNT PALGRAVE AREA

Physical features

Relief is moderate; the softer sedimentary rocks, such as shale, dolomitic shale and siltstone, erode to produce valleys bounded by cliffs, and the area is dissected by gullies which limit vehicular access. Ridges are governed by resistant rocks such as quartzite, dolerite and the Discovery Chert. These resistant rocks control both the position of the major drainages and the sediments contained in them.

Most of the stratigraphic units crop out extensively, although shales are commonly weathered, and form white, buff or chocolate-coloured outcrops, except in cliff faces where they can be black. Mafic igneous rocks are fresh. Soils are poorly developed or absent on most slopes. Skeletal soils predominate, but loamy soils are also present.

The climate is arid to semi-arid. The vegetation consists of sclerophyll shrub-land with scattered tall shrubs and stunted trees *(Eucalyptus, Hakea* and *Grevillia* sp.). Taller eucalypts occur along stream channels.

Erosion is both chemical and mechanical: the depth of weathering is variable, but extends to several tens of metres, and most soils and exposed rocks are leached. Mechanical erosion has taken place mainly as a result of torrential rain and soil creep, and the upper part of the weathering profile has been removed in many places.

Geological setting

The surface geology of the Mount Palgrave area is shown in Figure 64A. Mineralization occurs in shale and siltstone of the Jillawarra Formation, which was deposited on a shallow-marine shelf (Brakel and Muhling, 1976). The shales hosting mineralization are black and pyritic when fresh. The mineralization is stratabound and of probable syngenetic origin (Davy and Marshall, in press).

Following deposition, the sedimentary rocks were folded and intruded by semi-concordant dolorite sills. The metamorphic grade is either low greenschist or just below the greenschist facies, as authigenic actinolite is present in the mafic rocks.

Malachite and, less commonly, azurite were observed at the surface in shale underlying the Discovery Chert (Westfield Minerals, 1967). Goethite pseudomorphs after pyrite occur in many outcrops of shale, but fresh sulphides tend to be present at the surface only where protected by resistant minerals such as quartz.

Mineralization

Drilling by Westfield encountered three sulphide zones containing Zn. All are 3 m thick and appear to be separate lenses (Fig. 65). The grades for Zn are 0.8%, 1.4% and 2.4%. Zn occurs mainly in veinlets of quartz, pyrite and sphalerite, which appear to have been derived from syngenetic, disseminated mineralization by diagenesis or metamorphism (Davy and Marshall, in press). Cu-values in the Zn-rich zones are 110 ppm or less. Elsewhere in the black shale, chalcopyrite and covellite are associated with pyrite and marcasite, but Cu values are low, commonly between 100 and 300 ppm, but isolated values up to 800 ppm are found (Westfield Minerals, 1967).

The profile revealed by Westfield's drilling included a weathered, 'bleached zone' of white or buff-weathered shale containing irregularly distributed Cu-carbonate concentrations. Analyses showed low values (<100 ppm) of Zn Cu-sulphide minerals occur in accessory amounts in the underlying fresh black shale, and the Cu carbonates may represent enrichment as a result of weathering of these minerals. It is just possible, however, that Cu-sulphide mineralization occurs in the top 20 m of the 60 m thick shale, as fresh rock from this zone does not appear to have been tested by drilling.

The multi-element spectrographic scan of the drill-core samples showed only a weak association of other trace elements, namely Mo and Ag, with the Zn mineralization. The maximum value of Mo was 80 ppm and of Ag 0.4 ppm. Cd was not detected (Table 23).

Geochemistry of weathered shale

Ten stratigraphic sections crossing shale of the Jillawarra Formation were chip sampled as part of UNIMIN's exploration programme. Cu anomalies were found in six of these sections. In three traverses, over a length of 1 km along the east side of the syncline at Mount Palgrave, the anomalies were very pronounced. All of the Cu anomalies lie within the top 45 m of the Jillawarra Formation (using the base of the Discovery Chert as a marker), and within this sequence the uppermost 18 m contained Cu values greater than 1 000 ppm. Section ED 17, illustrated in Figure 66, displayed the second strongest anomaly. In section ED68 (not illustrated), 400 m to the south, copper values averaged several per cent (maximum 13.5%) over half the 18 m interval.

A Zn anomaly, revealed in a stratigraphic section 1 km to the east of the known mineralization (section ED73, not illustrated), is present some 67 m stratigraphically below the Discovery Chert. This position corresponds approximately to the position of the highest Zn mineralization encountered in the drill core.

Multi-element analysis of the weathered shale samples taken in section ED17, revealed a Cu-Ag-Mo association with values of Cu, Ag and Mo up to 6 000 ppm, 10 ppm and 30 ppm respectively (Table 23).

A Zn anomaly, also 67 m below the Discovery Chert, is present in a section (ED76, not illustrated) 1 km east of the known Zn mineralization. Its position relative to the Discovery Chert corresponds approximately to the position of the first Zn-rich zone met in the drill core. Multi-element analysis of the samples from ED73 has not been carried out.

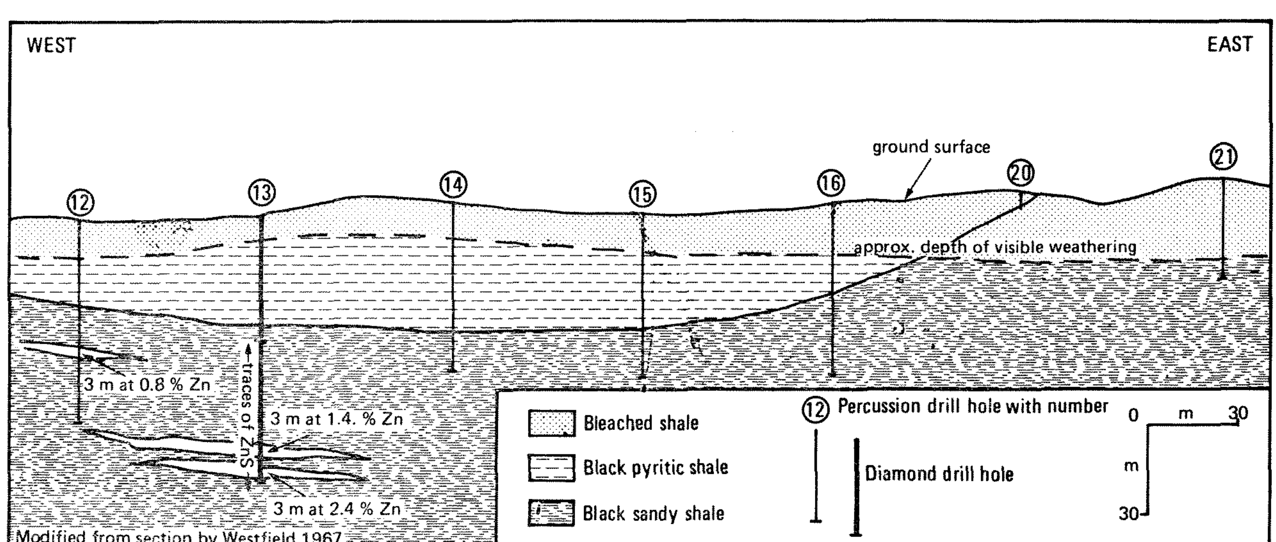

Figure 65 Cross-section showing the relationships at the Mount Palgrave location. The section is taken between chip-sampled stratigraphic locations ED 17 and ED 68 approximately 150 to 250 m to the north and 140 to 200 m to the south respectively.

TABLE 23. RANGES IN VALUES FOR ELEMENTS IN DIAMOND-DRILL CORE, MICROGOSSANS, WEATHERED-SHALE AND ANOMALOUS STREAM-SEDIMENT SAMPLES AT MOUNT PALGRAVE

Element	Diamond-drill core sulphide zone DDH 13	Microgossans ED 17	Weathered shale samples			Anomalous stream sediments
			Cu anomaly ED 17	Cu anomaly ED 68*	Zn anomaly ED 73*	
Cu	<525	0·059%–15·1%	800–6 000	2·5%–13·5%	10–110	73–150
Pb	<30	20–200	20–30	20	30–80	<35
Zn	to 2·4%	<20–300	<20–50	20–200	300–2 600	to 260
Ni	500–1 400	20–200	10–50	....	....	30–50
Co	100–300	<5–300	<5–10	....	....	5
As	to 50	<50–200	<50	....	....	<50
Sb	<30	<30	<30	....	....	<30
Bi	<1	<1	<1	....	....	<1
Cd	<3	<1–3	<1–3	....	....	<3
In	<10	<10	<10	....	....	<10
Mo	to 80	<3–100	<3–30	....	....	10
Ag	to 0·4	0·1–10	0·1–10	....	....	1
Tl	to 10	<1	<1	....	....	<1
Sn	<1	<1–1	<1–3	....	....	1
Ge	to 1	<1	<1–5	....	....	<1–5
Ga	to 7	1–50	3–50	....	....	10–20
W	<50	<50	<50	....	....	<50

Values in ppm unless marked %. * Samples not available for multi-element analyses.

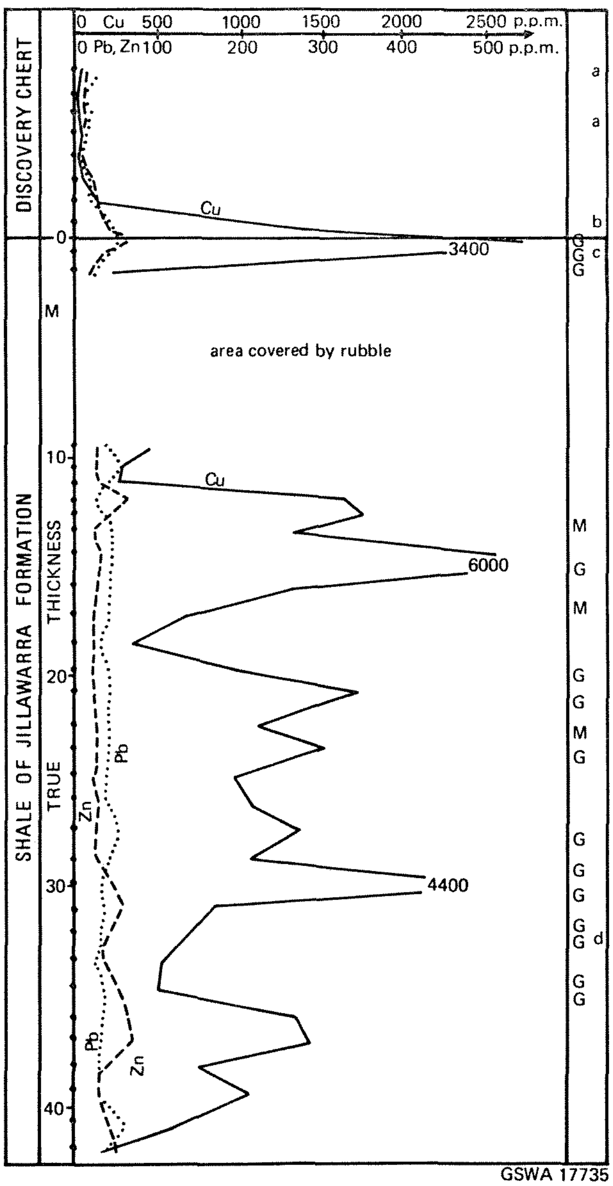

Figure 66 Surface geochemistry along UNIMIN stratigraphic section ED 17 (continuous chip sampling), Mount Palgrave area. All samples were analyzed for a wide range of elements. In last column: G – microgossan grab samples, M – malachite-stained shale, a – surface chips contain 3 ppm Ag, b – surface chips contain 30 ppm Mo and 10 ppm Ag, c – microgossan contained 800 ppm Cu and 10 ppm Ag, d – microgossan contained 8000 ppm Cu, 100 ppm Mo and 10 ppm Ag, e – microgossan contained 2000 ppm Cu, 20 ppm Mo and 3 ppm Cd.

Microgossans

Massive, iron-rich gossans are not present at the Mount Palgrave location. At the surface, the leached shales are impregnated with malachite along bedding and joint planes. However, the shale outcrops do contain thin ferruginous horizons, 2 to 20 mm thick, containing pseudomorphs after sulphides. These are referred to as microgossans, and were sampled separately from the chip sampling of the weathered shales as part of UNIMIN's exploration programme.

In section ED17 many microgossans carried visible malachite. Trace-element values obtained from multi-element analysis are shown in Table 23. They are anomalous in Cu, Mo and Ag. Discussion on the use of microgossans in exploration will be found in Smith (in press).

Stream-sediment geochemistry

Threshold values for Cu, Pb and Zn in stream sediments in the Mount Palgrave area are 73 ppm, 67 ppm and 128 ppm respectively. No Pb anomalies were detected.

Anomalies for both total and cold-extractable Cu clearly relate to outcrops of the Jillawarra Formation, and very strong anomalies occur near the site drilled by Westfield.

Anomalous Zn values, which are also related to outcrops of the Jillawarra Formation, lie to the west of the main Mount Palgrave prospect. Drilling by Westfield of one Zn-anomalous zone showed that the shale contained weak mineralization with up to 1.3% Zn and 0.67% Cu over 2 m intervals. There is no Zn stream-sediment anomaly over the main Mount Palgrave prospect, suggesting that the Zn-rich zones intersected by diamond drilling do not reach the surface. Anomalous stream sediments at Mount Palgrave carry as pathfinders Mo (10 ppm) and Ag (1.0 ppm).

MOUNT VERNON AREA

Physical features

Alternating resistant and softer rock units control the stream-sediment pattern of the Mount Vernon Syncline. Quartzite, chert and dolerite form the ridges; shale, dolomitic shale and siltstone, the valleys. A thick quartzitic sandstone unit marking the top of the Kiangi Creek Formation governs the local drainage around the syncline. Remnants of a colluvial (possibly Tertiary) conglomerate are commonly found flanking the resistant quartzite ridge on both the north and south sides of the syncline. Further remnants of the possibly Tertiary depositional surface are seen in the mesas around Glen Ross Gorge and on the plateaux rising from the flat country around Mount Vernon Station. Some of the mesas are capped by calcrete and represent former valley deposits.

Weathering is intensive, and extends in shales to 30 or 40 m, where determined by drilling. Outcrops of mafic igneous rocks are fresh.

Geological setting

Rocks in the Mount Vernon Syncline consist of shallow-marine, brackish-water and continental sediments of the Kiangi Creek and Jillawarra Formations, the Discovery Chert, and the Devil Creek Formation (Fig. 67A). The Kiangi Creek Formation consists of sandstone, siltstone, shale and quartzite; the Jillawarra Formation (in this area) of shale and the Devil Creek Formation of shale, dolomitic shale, dolomite and siltstone.

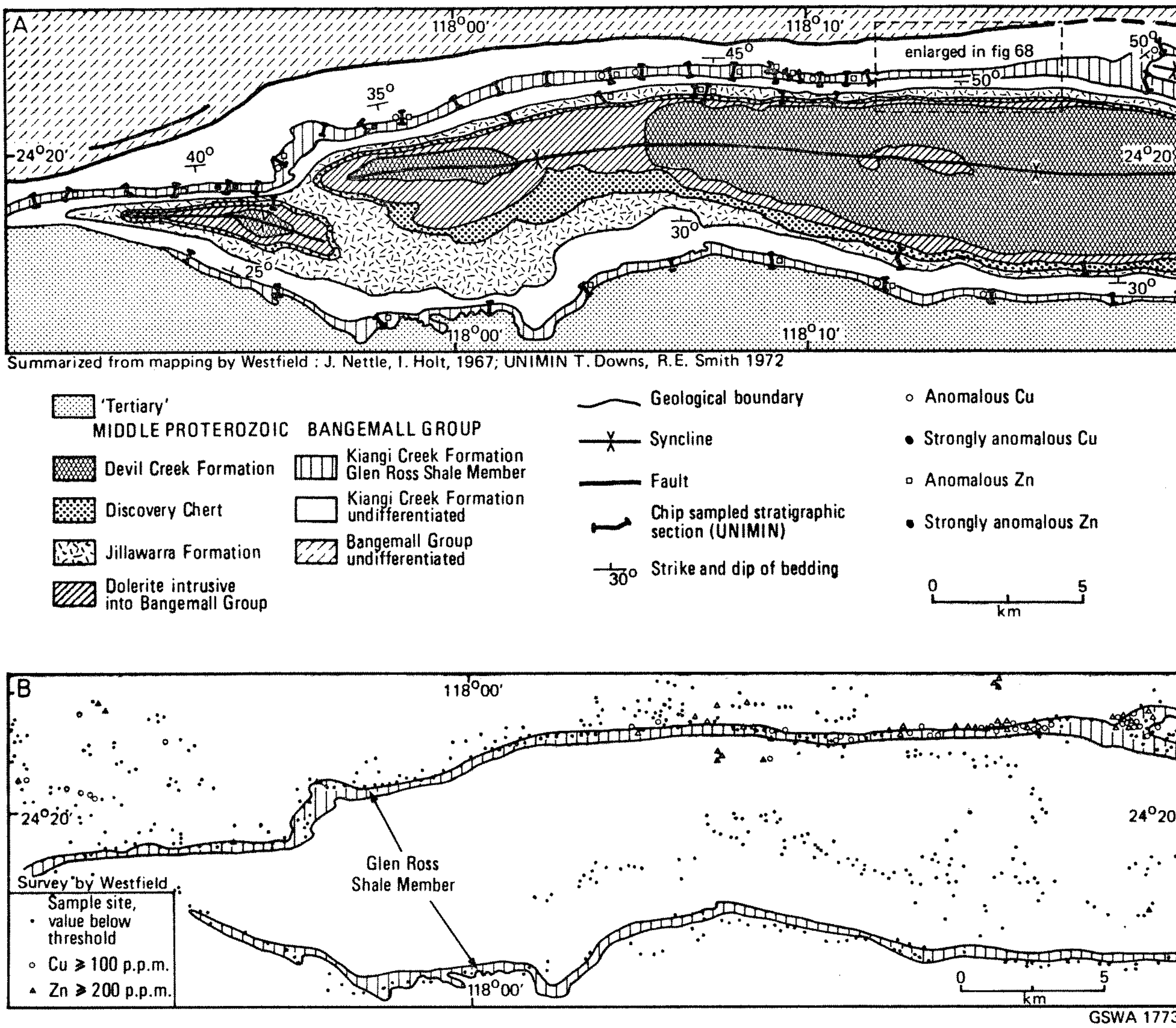

Figure 67 A. Geological map of the Mount Vernon area.
B. Cu and Zn stream-sediment geochemistry of the Mount Vernon area showing locations of anomalies in -177μm fraction.

Dips on each side of the syncline range from 25° to 55°, and the fold axis is subhorizontal. The sequence is truncated to the north by a regional fault which has caused local structural complexity. Metamorphism of the rocks is approximately greenschist facies, based on the occurrence of metamorphic actinolite in the mafic rocks.

Low-grade Zn mineralization occurs in black pyritic shale in the Glen Ross Shale Member of the Kiangi Creek Formation. Anomalous Cu-Zn values have been found in the Jillawarra Formation. These are generally subordinate to those in the Glen Ross Shale Member. Mineralization in the Glen Ross Shale Member is syngenetic; the only alteration since deposition has been local recrystallization, and the mobilization of some of the sphalerite and pyrite into veins (Davy and Marshall, in prep.).

Shales in the weathered zone are bleached, buff or cream in colour and do not contain fresh sulphide.

Stream-sediment geochemistry

The mineralized rocks were identified by Westfield following stream-sediment geochemistry. Sample sites are shown in Figure 67B together with Zn and Cu anomalies. The main shale horizon (the Glen Ross Shale Member) was sampled from gullies separated by 300 m to 1 km. Thresholds for Zn and Cu in the -177μm fraction were 200 ppm and 100 ppm respectively.

Mineralization

Two diamond-drill holes drilled by Westfield tested the main Zn-Cu stream-sediment anomaly, and a third hole tested an anomaly approximately 2.5 km to the west (Fig. 68). All holes were drilled into the Glen Ross Shale Member (Figs. 68 and 69). A 7.3 m intersection of Zn-Cu sulphides, with average values of 1.8% Zn and 0.15% Cu, was found in diamond-drill hole No. 2 (DDH2) under the main anomaly. Weaker base-metal sulphide mineralization was encountered in the third hole, including 2.4 m at 0.8% Zn and 860 ppm Cu. This mineralization appears to occur in a horizon equivalent to that of the main intersection of DDH2.

Multi-element analysis has been carried out on core from DDH2 and 3 (Table 24). Significant traces of Cd (100 ppm), Mo (70 ppm), Sb (150 ppm) and Ag (15 ppm) accompany the main Zn-Cu mineralization.

Most of the black shale contains pyrite, ranging from a trace to 20%, and also contains traces of copper sulphides (mainly covellite). Sphalerite is almost wholly restricted to about 100 m of the black shale (approximately half the total thickness), and the main mineralized zone (40 m in true thickness) lies in the middle.

Geochemistry of weathered shale

Sites for diamond drilling were selected by Westfield on the basis of anomalous Zn-Cu in rock-chip sampling as a follow-up to the stream-sediment investigation. UNIMIN extended exploration by systematic chip sampling of stratigraphic sections in a programme designed to test for a possible extension of the mineralization found by Westfield. All the shale units around the syncline were systematically sampled: sections on the north side were about 1.6 km apart, and, on the south side about 3.2 km apart (Figs. 67A, B).

Detail of several of the chip-sample traverses in the vicinity of the main Zn-Cu anomaly is given in Figure 70. Surface indications of mineralization were shown by thin

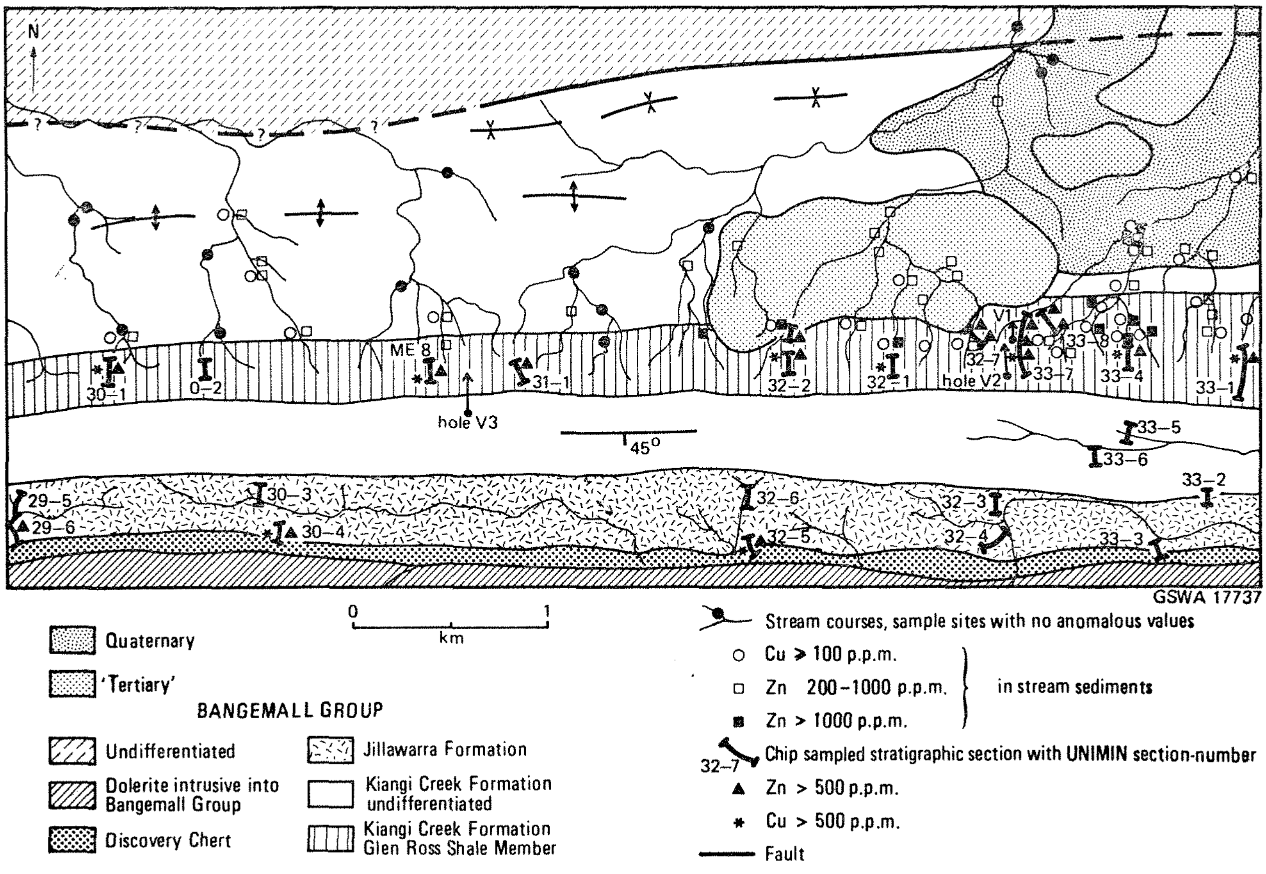

Figure 68 Geological map of the detail of the area indicated in Figure 67A – this zone displays a continuous Cu-Zn anomaly. Detail of Westfield's stream-sediment sampling is superimposed. Strong Cu-Zn anomalies in both stream sediments and weathered shale are shown.

TABLE 24. RANGES IN VALUES FOR ELEMENTS IN DIAMOND-DRILL CORE AND WEATHERED-SHALE OUTCROP AT MOUNT VERNON

Element	Sulphide zone of DDH 2‡	Values in weathered stratigraphic section 33–7			‡Stream-sediment anomaly*
		In situ Zn-Cu anomaly‡	Solution-transported Zn-Cu anomaly‡	Solution-transported Zn anomaly‡	
Cu	1 500	400–850	200–700	50–400	100–1 600
Pb	20	10–40	10–40	10–40	†
Zn	1·8%	500–1 800	600–5 000	0·3%–1%	200–3 000
As	400	50–600	50–100	50–100	....
Sb	150	30–50	<30–50	<30–30	....
Bi	<1	<1	<1	<1	....
Cd	100	<1–10	<1–10	<1–300	....
In	<10	<10	<10	<10	....
Mo	70	10–300	5–300	<5–100	....
Ag	15	2–20	0·5–10	0·1–10	....
Tl	<1	<1–50	<1–50	<1	....
Sn	<1	<1	<1	<1	....
Ge	<10	5–15	5–15	3–8	....
Ga	10	8–10	8	5–15	....
W	<75	<50	<50	<50	....

Values are shown for mineralization, its surface expression as weathered shale, and the anomalous stream sediments derived from the surface expression.
* Sample not available for multi-element analyses. † Pb values not available. ‡ refers to figure 69. Values in ppm unless marked %.

coatings of Cu-carbonates along joint and bedding planes in isolated outcrops. The extent of this 'Cu-staining' is less than that exposed at Mount Palgrave.

Chip sampling showed the main anomaly to extend continuously over 4 km of strike, and discontinuously to a total length of about 8 km. The chip samples indicated a coincident Zn-Cu anomaly starting approximately 100 m stratigraphically below the overlying quartzite. The maximum Zn values were in the range 2 000 ppm to 6 000 ppm and Cu values in the range 1 000 ppm to 2 000 ppm. Zn is anomalous for over 100 m in stratigraphic thickness, the top 50 m being also anomalous in Cu (Fig. 68).

The surface expression of the uppermost mineralized shale met in DDH2 coincides with the top of the Zn-Cu anomaly in the rock-chip sample traverse (Fig. 69). The surface anomaly in addition probably reflects, in part, the 40 m thick zone of weakly disseminated Zn mineralization. However, the northern part of this anomaly represents shale, which in DDH2 has most Zn values less than 500 ppm and most Cu values less than 100 ppm. The northern part of the anomaly lies down-hill from the main mineralization, and it is concluded that the anomalous Zn-Cu values in this area reflect down-hill seepage (in solution) of these elements during weathering.

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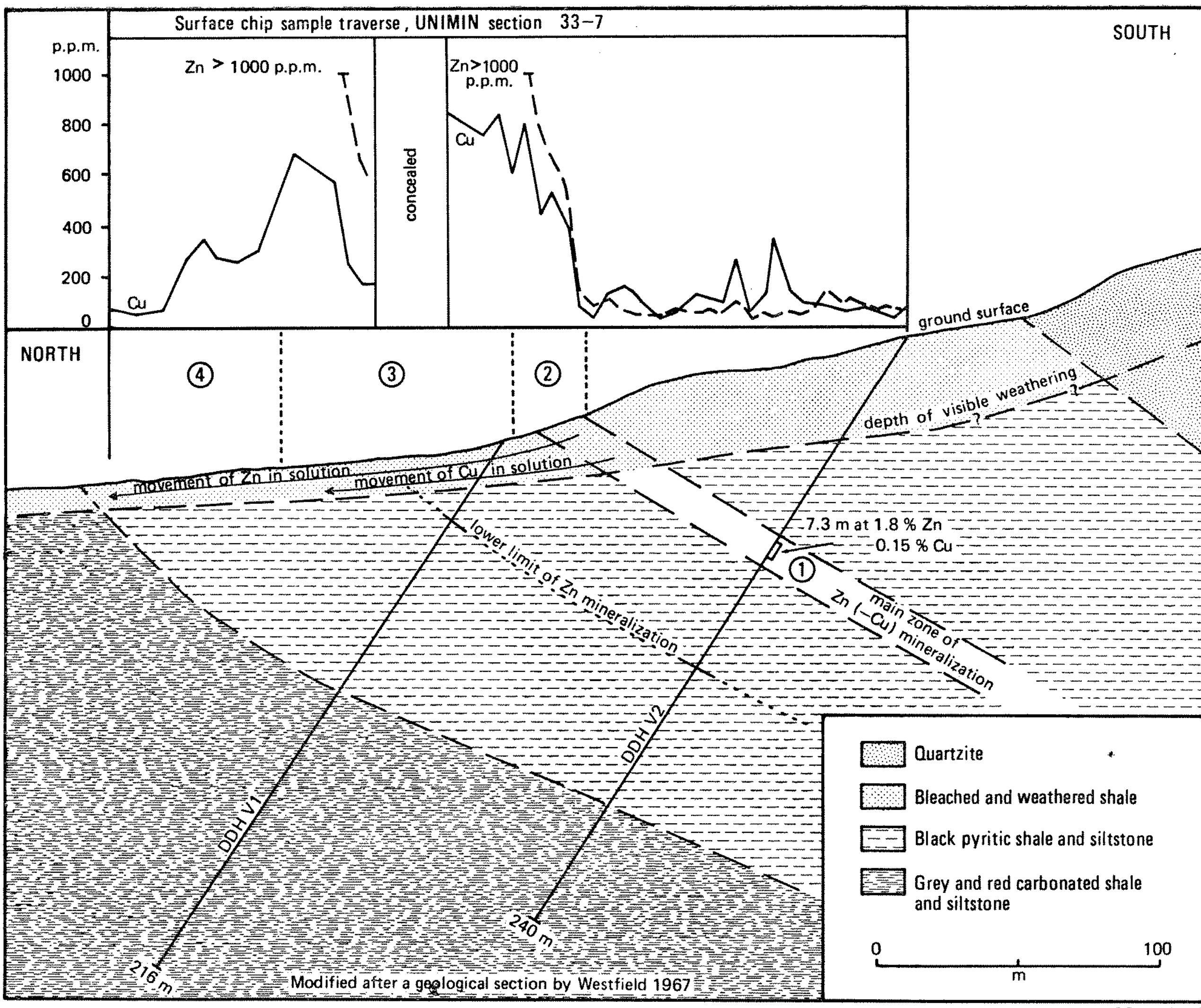

Figure 69 Cross-section along the line of Westfield's diamond-drill holes 1 and 2 at the Mount Vernon location, together with surface geochemistry along UNIMIN's section 33-7 which lies approximately along the cross-section. The numbers 1, 2, 3 and 4 refer to data summarized in the respective columns of Table 24.

Multi-element analyses have been carried out on the weathered shales over selected parts of the main anomaly. Results for Section 33-7 are listed in Table 24, columns 2-4. Mo and Ag are commonly anomalous, and there are isolated high values of Cd and Sb (Fig. 70).

DISCUSSION

Choice of exploration techniques

Both Westfield's and UNIMIN's exploration programmes showed that stream-sediment sampling of appropriate density is a valid exploration procedure that detects even low-grade mineralization. For this type of terrain, outcrop, and degree of weathering, sediment sampling at 1.6 km intervals along streams appears adequate for reconnaissance exploration where the expected mineralization has wide lateral extent. For the two areas studied here, rock-chip sampling is no improvement on stream-sediment sampling as a first reconnaissance exploration tool.

Chip sampling of rock units is a more specialized technique than stream-sediment sampling, and, even though the rocks are weathered, it provides information more directly related to the target mineralization. Chip sampling of both gossans and rock units is also necessary to identify the source rocks of anomalies defined by stream-sediment geochemistry.

Pathfinder elements

The confirmation of a base-metal anomaly in weathered outcrop by pathfinder elements is particularly important because it adds weight to the interpretation that the base metals may be derived from a base-metal sulphide source.

Of the selection of common pathfinder elements that accompany copper, lead or zinc-sulphide mineralization (Table 25), Sb, Cd, Mo and Ag are present in the Mount Vernon mineralization in sufficient quantities to be useful in exploration geochemistry. Bi, In and Sn were undetected in the observed mineralization and their dispersion during weathering was, therefore, precluded. Of the four pathfinder elements present (Sb, Cd, Mo and Ag) all are anomalous in the chip-sample traverse at the mineralized location, though not continuously. By way of contrast, spurious anomalies of Cu, Pb or Zn (false gossans) so far investigated do not contain anomalous pathfinder elements where their metal content is not related to base-metal sulphide sources (Smith, in press).

Microgossans and weathered shale at Mount Palgrave contain, besides their very high Cu values, anomalously high values of Mo and Ag but negligible Sb or Cd. The intersected mineralized zone is characterized by high Zn and anomalous Mo, though Cd and Ag are scarcely anomalous. The microgossans and anomalous copper-shale outcrop do not appear to relate to the mineralization intersected.

For exploration samples of gossans, microgossans and other weathered rock materials, low-cost multi-element analysis of the elements listed in Table 25 is recommended as an integral part of the exploration. Elimination of pathfinder elements from the comprehensive list should only be done after careful thought, because it is unlikely that the character of mineralization can be assumed with certainty, and the mineralization governs the pathfinder elements present.

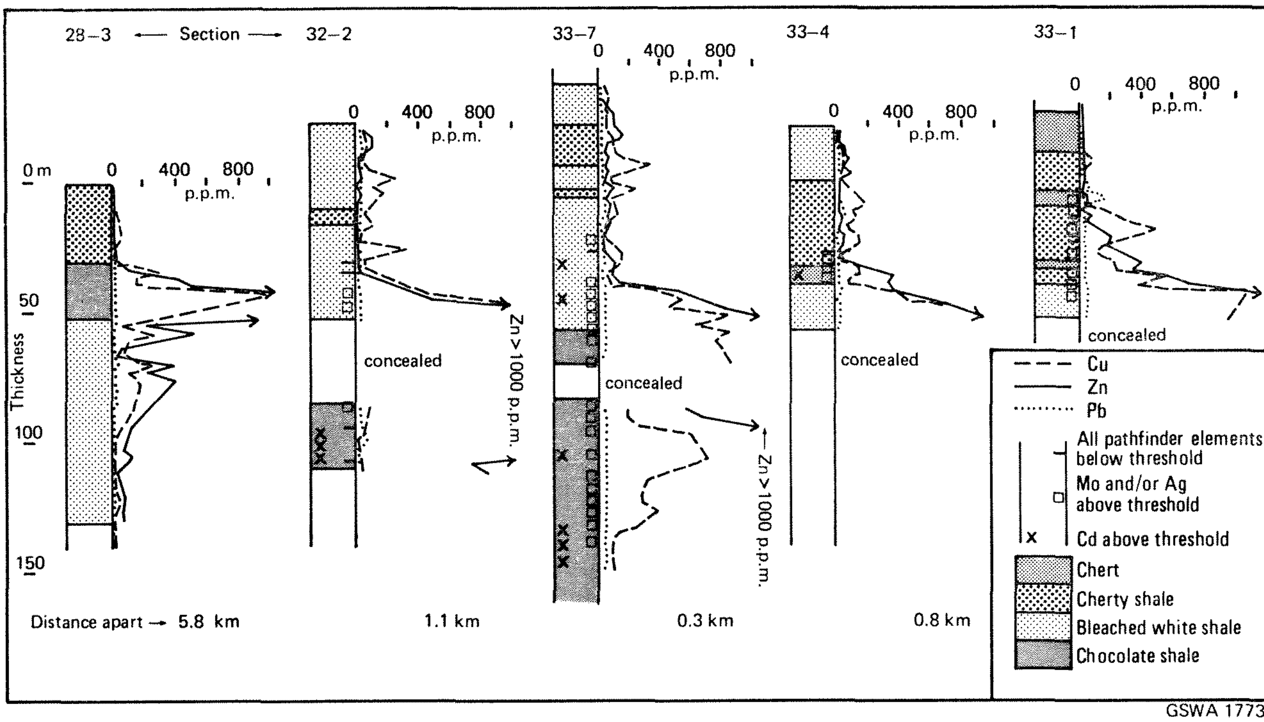

Figure 70 Geochemical information from UNIMIN rock-chip sampled stratigraphic sections along shale outcrops in the main Mount Vernon anomaly. For comparison, the mineralized contact has been placed in an equivalent position for each section. *Some samples were subject to spectrographic multi-element analysis; the position of anomalous samples is shown.*

To the list of elements (Table 25) several others can be added (Hg, Au, Se and Te), but their present comparatively high cost of analysis probably restricts their general use to the follow-up geochemical stage.

SUMMARY AND CONCLUSIONS

1. Anomalous Cu values in exploration stream-sediment surveys in the Mount Palgrave area outline a significant zone of interest in shale of the Jillawarra Formation. Drill sites selected on the basis of follow-up rock chip sampling failed to intersect Cu mineralization, but did encounter three intersections of low-level Zn-sulphide mineralization. The intersections do not appear to have surface expression where drilled. Further west, Zn anomalies were related to additional low-grade Zn mineralization.
2. At Mount Vernon, exploration stream-sediment sampling with sample sites 0.3 km to 1 km along strike outlined a Cu-Zn-anomalous area in the Kiangi Creek Formation which was accurately defined by a chip-sampling programme. Hydromorphic dispersion downhill within the weathered shales extended the surface area of the anomaly to about twice its original size, and perhaps more.
3. The mineralization at both localities is accompanied by anomalous values of other trace elements. These are Mo, Ag, Cd and Sb, at Mount Vernon, and Mo and possibly Ag at Mount Palgrave. These elements are retained at the surface in both leached shales and, at Mount Palgrave, in ferruginous microgossans, though at Mount Palgrave a direct relationship between drilling and the surface Cu anomaly is unclear.

TABLE 25. THRESHOLDS AND LEVELS OF INTEREST FOR MULTI-ELEMENT GEOCHEMISTRY OF GOSSANS, MICROGOSSANS, GENERAL FERRUGINOUS OUTCROPS AND WEATHERED SHALE IN THE BANGEMALL BASIN

Pathfinder elements used and lower limit of detection†	Gossans, microgossans and general ferruginous outcrops		Weathered-shale geochemistry	
	Threshold (ppm)	Moderately anomalous level (ppm)	Threshold (ppm)	Moderately anomalous level (ppm)
Cu (1)	400	900	200	500
Pb (1)	400	1 200	?	?
Zn (20)	2 000	8 000	200	500
Ni (5)	*	*	*	*
Co (5)	300	500	Element levels inadequately known, levels as for gossans etc. tentatively applied	
As (50)	n.k.	300		
Sb (30)	n.k.	50		
Bi (1)	3	10		
Cd (3)	5	10		
In (10)	5	15		
Mo (3)	20	100		
Ag (0·1)	2	5		
Tl (1)	n.k.	?5		
Sn (1)	3	5		
Ge (1)	‡	‡		
Ga (1)	‡	‡		
W (50)	....	100		

† Analysis by semiquantitative optical emission spectrography, AMDEL; high values of interest confirmed by appropriate analytical technique, predominantly by X-ray fluorescence, CSIRO.
* Element may not be applicable to mineralization sought.
‡ Insufficient comparative data available.
n.k. not known.

4. Exploration results showed that stream-sediment surveys with samples taken at 1.6 km intervals along appropriate drainages are valid exploration procedures for reconnaissance exploration in the Bangemall Basin. Rock-chip sampling will be needed to identify those rocks causing metal anomalies in the streams.
5. It is considered that pathfinder elements (Table 25) are invaluable in discriminating between barren and mineralized gossans, ironstones and weathered rocks. For the type of mineralization in the Mount Vernon and Mount Palgrave areas, the pathfinder elements appear to be Cd, Mo and Ag. However, since other types of Cu, Pb, or Zn deposits would be sought in most exploration programmes, the comprehensive list is recommended.

ACKNOWLEDGEMENTS

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BORON-GALLIUM-RUBIDIUM STUDIES IN PHANEROZOIC BASINS ON THE WEST COAST OF WESTERN AUSTRALIA

by R. Davy and J. Backhouse

ABSTRACT

Following apparently successful use of boron-gallium-rubidium ratios (expressed as triangular diagrams) in estimating depositional conditions in the Proterozoic Bangemall Basin (Davy and others, 1978) tests have been carried out to see whether these ratios give equally consistent predictions when used on rocks whose depositional histories are better known.

Ninety core samples of shales and siltstones, and one of halite, taken from the Canning, Carnarvon and Perth Basins have been studied. Conditions of deposition predicted from boron-gallium-rubidium analyses have been compared with those deduced from mineralogical and palynological studies.

The hypothesis proposed for the use of these ratios (Degens and others, 1958) is unacceptable for the Carnarvon Basin since it cannot be demonstrated that boron is located in illite.

In the Canning and Perth Basins boron correlates with illite as expected. However, a possible line of separation between rocks of marine and of freshwater deposition lies close to the gallium-rich part of the diagram in a position far removed from that suggested in the original hypothesis.

It is concluded that boron-gallium-rubidium diagrams cannot by themselves be used to predict the environment of deposition of sediments.

INTRODUCTION

Following apparently successful use of boron-gallium-rubidium (B-Ga-Rb) ratios (expressed as triangular diagrams) in estimating depositional conditions in the Proterozoic Bangemall Basin (Davy and others, 1978), it was decided to see whether these diagrams give equally consistent predictions when drawn for more recent rocks whose depositional histories are better known.

Initially 15 samples of shales from the Perth Basin, 8 of marine origin and 7 of freshwater origin (GSWA, 1975) were analysed and plotted on the ternary diagram (included in Fig. 71). The result indicated that, on the basis of interpretation using the original hypothesis (Degens and others, 1958), 14 of the 15 samples could have been deposited in fresh water.

It was therefore decided to examine the depositional conditions further by adding samples from the Canning and Carnarvon Basins and further samples from the Perth Basin, and by carrying out mineralogical and palaeontological investigations as well as chemical analysis. A total of 90 core samples of shales and siltstones, and one of halite, taken from bores drilled for petroleum exploration have been studied.

THE HYPOTHESIS

The hypothesis behind the use of B-Ga-Rb ratios was postulated by Degens and others (1958). In essence these workers suggest that differential partitioning of the three elements takes place between clay minerals at the time of the formation of the sediments. The main clay minerals of interest are illite and kaolinite. The former is more common in marine sediments, the latter in freshwater (continental) sediments, although the two minerals are not mutually exclusive (Grim, 1968). According to Degens and others (1958) marine sediments commonly contain larger absolute amounts of B and Rb and a higher B/Ga ratio than freshwater sediments. This was inferred to reflect a higher original illite/kaolinite ratio. B and Rb collect preferentially in illite where they replace Al and K respectively. Ga substitutes for Al wherever it occurs and is concentrated in kaolinite compared with illite by virtue of the higher Al content of the kaolinite.

The use of ratios rather than absolute amounts removes the need to separate pure clay fractions, since components such as quartz and carbonates are simply diluents as they do not contain significant amounts of B, Ga or Rb.

This hypothesis has been tested in four ways:

(i) establishment that B and Rb are located in illite and that Ga is located in both kaolinite and illite. These relationships have been tested using correlation coefficients (using K_2O as a measure of the illite content).

(ii) recognition of glauconite and foraminifera as indicators of marine origin.

(iii) palynological examination for marine acritarchs and dinoflagellates.

(iv) by determining the proportions of illite and kaolinite in the samples to see if illite is more common in marine sediments.

Chemical and X-ray diffraction studies were carried out at the WA Government Chemical Laboratories, and grainmount mineralogical and palynological examinations at the Geological Survey. All mineralogical data are semiquantitative.

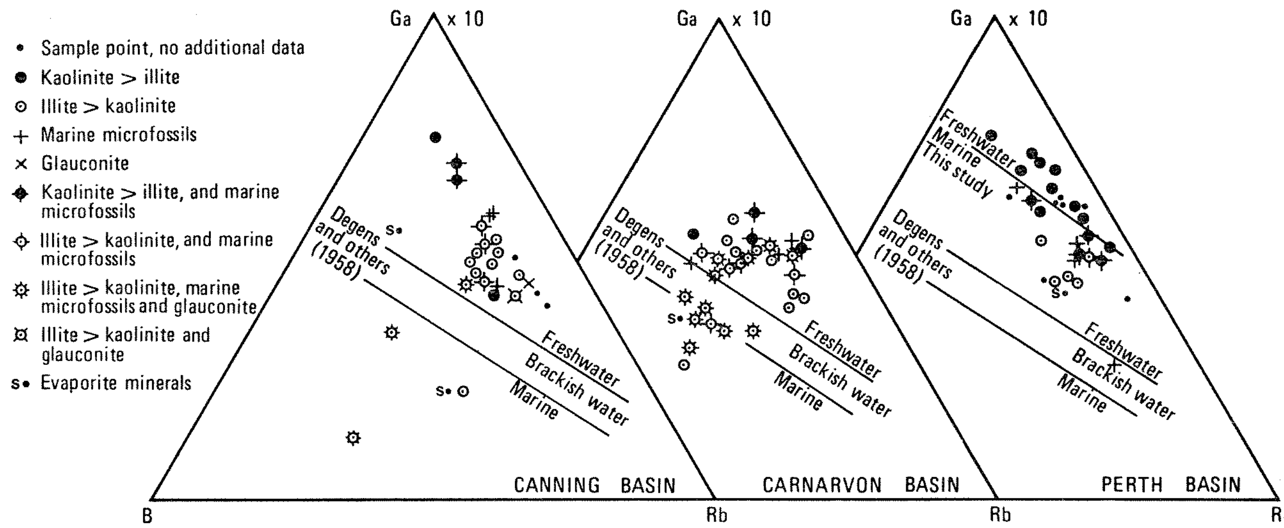

Figure 71 B-Ga-Rb plots for rocks from the various basins.

RESULTS

Results for individual samples are presented in Tables 26-28. The chemical, illite and kaolinite data have been summarized for each basin (Table 29) and appropriate Pearson correlation coefficients calculated (Table 30).

In addition to illite and kaolinite other clay minerals are present. Chlorite is relatively abundant in all basins, montmorillonoids feature in a few samples in each basin and small amounts of glauconite occur in a few samples from the Carnarvon and Canning Basins. Illite is the most common clay mineral in the Carnarvon and Canning Basins, kaolinite in the Perth Basin.

The mean absolute amount of B is higher in the Carnarvon Basin than in the other basins. The absolute amounts and standard deviations of the other chemical constituents are closely similar for all three basins.

TABLE 26. SUMMARY TABLE OF CHEMICAL AND MINERALOGICAL DATA—PERTH BASIN

Sample and Well	Depth (m)	Chemistry				Mineralogy						Fossils	
		B	Ga	Rb	K_2O	KA	IL	CL	MD	GL	TO	P	F
PERMIAN													
Holmwood Shale													
52169 Abbawardoo No. 1	237·7–240·8	15	4	32	0·95	5	1						
52170 Abbawardoo No. 1	225·6–228·6	65	18	150	3·7	1	35	20			*		
52171 Arrowsmith No. 1	3 303·1	65	22	190	4·3	10	35	20			T		
52172 Arrowsmith No. 1	3 301·3	65	22	200	4·4	1	40	20					
42694B Abbawardoo No. 1	225·6–228·6	65	18	150	3·8	20	20	15					
Irwin River Coal Measures													
42691 Arrowsmith No. 1	2 939·2	55	20	115	2·8	1	30	20					
42694A Abbawardoo No. 1	153·3–156·4	25	21	90	2·0	40	10						
42699 Mungarra No. 5	536·4–539·5	20	10	45	0·9	20	5						
TRIASSIC													
Kockatea Shale													
42690A Arrowsmith No. 1	2 265·0	30	6	120	3·3	20	1				T	M	
42690B Arrowsmith No. 1	2 265·9	50	26	200	3·7	40	20					M	
42692A Eneabba No. 1	3 904·5	50	28	220	3·8	20	30	20				M	
42692B Eneabba No. 1	3 904·5	40	20	155	3·2	30	25					M	
42695 Eurangoa No. 1	1 599·6–1 607·2	35	24	200	3·8	50	10					M	
42696 Cadda No. 1	1 700·2	45	27	190	3·6	30	20	20				M	
JURASSIC													
Cockleshell Gully Formation													
42499 Badaminna No. 1	1 546·3	20	20	125	2·8	45	5						
42697 Bookara No. 1	278·6–278·9	30	18	55	1·1	35	5						
42698 Mungarra No. 3	448·0–451·1	5	3	5	0·12	15	1						
52179 Eganu No. 1	597·4–600·5	10	10	30	0·6	15	3		15				
52180 Eganu No. 1	246·9–249·9	10	8	40	0·95	10	10						
Cadda Formation													
52173 Badaminna No. 1	1 036·3–1 039·4	10	10	70	2·1	15	5					M	
52174 Badaminna No. 1	1 543·8	25	30	110	2·1	55	25						
52175 Badaminna No. 1	1 546·3	15	18	100	2·9	35	1						
52176 Bookara No. 2	719·0–721·8	10	8	100	3·1	10	5						
Yarragadee Formation													
42500 Cockburn No. 1	1 190·9	30	31	100	1·5	60	10						
CRETACEOUS													
Yarragadee Formation													
52177 Charlotte No. 1	2 131·4	15	20	160	5·0	20	10	15					
52178 Charlotte No. 1	2 431·2	20	30	170	3·6	40	30						
52183 Roe No. 1	1 360·6	35	25	120	2·6	20	20	15					
52184 Roe No. 1	1 363·3	30	25	120	2·8	20	20	15					
South Perth Shale													
42693 Gage Roads No. 1	1 518·5	45	19	65	1·3	30	25						
52181 Gage Roads No. 1	1 521·3	40	20	70	1·4	20	10		45		T	M	
Leederville Formation													
52182 Quinns Rock No. 1	770·2	50	25	100	2·3	45	15					M	

Mineralogy:—
KA: Kaolinite
IL: illite
CL: Chlorite
MD: montmorillonoid
GL: glauconite
TO: Tourmaline
T: trace

Fossils:—
P: palynology
F: foraminifera
M: marine forms present

* Gypsum present.

TABLE 27. SUMMARY TABLE OF CHEMICAL AND MINERALOGICAL DATA—CARNARVON BASIN

Sample and Well	Depth (m)	Chemistry B	Ga	Rb	K$_2$0	Mineralogy KA	IL	CL	MD	GL	TO	Fossils P	F
PERMIAN													
Lyons Group													
52050 Remarkable Hill No. 1	1 070·8	70	18	160	4·5	5	25	20					
Kennedy Group													
52032 Direction No. 1	522·1	75	18	110	3·8	25	40						
52033 Direction No. 1	671·5	90	20	180	5·4	15	30						
52040 Hope Island No. 1	1 250·0	75	20	130	6·6	15	30	15					
"Unspecified"													
52034 Flinders Shoal No. 1	3 030·9	50	20	130	3·5	10	45	15					
52035 Flinders Shoal No. 1	3 505·5	105	24	140	4·2	5	50	10					
52036 Flinders Shoal No. 1	3 507·9	100	24	120	2·7	1	50	15					
TRIASSIC													
Locker Shale													
52038 Hope Island No. 1	926·6	65	22	150	3·8	40	30					M	
52039 Hope Island No. 1	927·8	60	22	140	3·6	35	30					M	
52046 Mary Anne No. 1	464·2–465·4	70	30	130	3·2	45	20					M	
52047 Mary Anne No. 1	531·3–532·5	80	22	120	3·6	35	20					M	
Mungaroo Formation													
52053 Sandy Point No. 1	3 042·5	120	30	260	7·2	10	80						
JURASSIC													
Dingo Claystone													
52049 Peak No. 1	2 138·8	125	20	85	1·8	25	20	15				M	
Learmonth Formation													
52052 Sandy Point No. 1	1 230·5	110	22	70	1·6	45	15	5					
CRETACEOUS													
"Neocomian"													
52023 Angel No. 3	2 607·0	50	16	110	3·6	25	25	5		T	T	M	
52024 Angel No. 3	2 613·3	70	20	120	3·5	15	25	20		T		M	
52030 Dampier No. 1	2 834·6–2 838·3	85	20	120	5·6	15	35	15		T		M	
52031 Dampier No. 1	2 837·7	90	20	120	3·2	15	20	15		T		M	
Winning Pool Group, Mardie Greensand													
52041 Mardie No. 2	147·5	75	10	110	3·2	5	40	5		5		M	
Muderong Shale													
52037 Glenroy No. 1	493·5	75	6	55	1·4	5	30			5		M	
52045 Marilla No. 1	350·5–353·6	70	20	130	4·0	30	30	10		T		M	
52054 Trimouille No. 1	2 433·5	95	30	120	3·8	10	45	10		T			
52055 Trimouille No. 1	2 432·3	95	20	120	3·8	15	35	15		T		M	
Lower Gearle Siltstone													
52025 Cape Cuvier No. 1	335·3–338·4	50	14	110	3·4	1	25	5	50			M	
52042 Marilla No. 1	84·7–87·8	100	12	85	2·2	1	15		15			M	
52043 Marilla No. 1	126·5–129·6	130	14	100	3·2	1	30		20	5	*	M	
52044 Marilla No. 1	217·9–221·0	110	12	100	2·1	5	20		50			M	
52048 Minderoo No. 1	88·4	120	8	85	2·0	5	20		10				
52051 Rough Range No. 1	1 061·3–1 065·6	90	10	95	2·1	5	55			T		M	
Toolonga Calcilutite													
52026 Dampier No. 1	2 368·3	60	12	65	1·5	1	15	5	45	T		M	M
52027 Dampier No. 1	2 370·4	70	12	65	1·6	1	20	5	45	T		M	M
52028 Dampier No. 1	2 372·6	100	12	65	1·6	1	20	10	45			M	
52029 Dampier No. 1	2 621·3–2 624·6	105	20	90	2·1	35	20	5				M	M

* Gypsum present. Other symbols as in Table 26.

TABLE 28. SUMMARY TABLE OF CHEMICAL AND MINERALOGICAL DATA—CANNING BASIN

Sample and Well	Depth (m)	Chemistry B	Ga	Rb	K$_2$0	Mineralogy KA	IL	CL	MD	GL	TO	Fossils P	F
PRE-PERMIAN UNASSIGNED													
52019 Willara Hill No. 1	759·6–763·5	30	12	110	3·4	10	15	10			T		
52020 Willara Hill No. 1	1 602·3	10	2	6	0·1						△		
PERMIAN													
Grant Formation													
52186 Crossland No. 2	410·3	75	22	230	5·4	1	50	25		T			
Poole Sandstone, Nura Nura Member													
52194 Frome Rocks No. 2	630·9–634·0	40	20	160	3·0	20	25	15			T		
Noonkanbah Formation													
52012 Meda No. 1	592·2–598·4	65	25	160	4·7	15	40	20				M	
52191 Frome Rocks No. 2	513·4–216·5	60	16	140	4·0	20	20					M	
52192 Frome Rocks No. 2	335·0–338·1	85	20	150	3·7	15	25	15					
52193 Frome Rocks No. 2	457·2–460·3	25	6	55	1·5	15	1						
52195 Jurgurra Creek No. 1	57·0	80	20	140	3·7	15	25	15					
52196 Jurgurra Creek No. 1	149·4	80	25	160	3·9	20	40	15					
52197 Jurgurra Creek No. 1	210·0	60	25	160	4·8	20	40	20					
52198 Jurgurra Creek No. 1	246·9	50	16	120	3·4	15	25	15					
52199 Kemp Field No. 1	137·2	35	14	140	4·5	20	20	5		T			
52200 Meda No. 1	429·8–435·9	60	24	170	4·2	15	35	25					
Liveringa Formation													
52013 Myroodah No. 1		65	16	130	3·8	10	30	15			T	M	
Dora Shale													
52022 Willara No. 1	1 742·8	60	4	80	3·6	1	25	5			T*		
52190 Fraser River No. 1	572·4–574·5	15	6	65	1·9	1	5	10					

TABLE 28. SUMMARY TABLE OF CHEMICAL AND MINERALOGICAL DATA—CANNING BASIN—*continued*

Sample and Well	Depth (m)	Chemistry B	Ga	Rb	K_2O	Mineralogy KA	IL	CL	MD	GL	TO	Fossils P	F
JURASSIC													
Jarlemai Siltstone													
52014 Roebuck Bay No. 1	149·4–152·4	70	6	45	1·1	5	15			5		M	
52015 Roebuck Bay No. 1	176·8–179·8	50	24	130	3·5	15	25	20				M	
52016 Roebuck Bay No. 1	179·8–182·9	55	25	140	4·2	15	35	20				M	
52021 Willara No. 1	1 147·6	10	4	50	1·4	1	1						
52185 Chirup No. 1	156·1–156·7	550	12	280	5·6	5	1			80		M	
52187 Dampier Downs No. 1	18·3–21·3	25	16	28	0·6	35	10			T	T		
52188 Dampier Downs No. 1	48·8–50·3	50	24	130	6·6	20	20	20			T	M	
52189 Fraser River No. 1	59·4–62·5	90	18	140	5·3	15	25	5	5	T		M	
"EARLY JURASSIC"													
52017 Ronsard No. 1	2 844·5	55	30	95	1·7	55	15	5				M	
52018 Ronsard No. 1	2 843·8	50	30	85	1·6	55	15					M	

* Gypsum present. △ Rock salt. Other symbols as in Table 26.

TABLE 29. A SUMMARY OF MEAN VALUES AND STANDARD DEVIATIONS FOR EACH BASIN FOR CHEMICAL DATA, KAOLINITE AND ILLITE

(Values of B, Ga, Rb, in ppm, remainder as percentages)

	Boron $\bar{x}$	Boron s	Gallium $\bar{x}$	Gallium s	Rubidium $\bar{x}$	Rubidium s	K_2O $\bar{x}$	K_2O s	Illite $\bar{x}$	Illite s	Kaolinite $\bar{x}$	Kaolinite s
PERTH BASIN 31 samples	33	19	19	8	116	58	2·6	1·3	15	12	25	16
CARNARVON BASIN 33 samples	86	22	18	6	115	38	3·2	1·3	31	14	15	14
CANNING BASIN* 25 samples	53	21	18	8	121	47	3·2	1·3	22	13	16	14

* Halite sample and sample with 550 ppm B omitted.

TABLE 30. PEARSON CORRELATION COEFFICIENTS BETWEEN ELEMENTS, ILLITE AND KAOLINITE FOR EACH SEDIMENTARY BASIN

(Underlined figures are those significant at the 1% probability level)

	Ga	Rb	K_2O	Il	Kaol
PERTH BASIN					
B	0·48	0·62	0·54	0·78	—0·14
Ga	....	0·67	0·47	0·61	0·57
Rb	....	....	0·92	0·66	0·13
K_2O	....	....	....	0·55	—0·05
Il	....	....	....	....	—0·17
CARNARVON BASIN					
B	0·05	—0·01	—0·08	0·13	—0·14
Ga	....	0·64	0·59	0·36	0·52
Rb	....	....	0·91	0·64	0·15
K_2O	....	....	....	0·59	0·11
Il	....	....	....	....	—0·22
CANNING BASIN*					
B	—0·01	0·64	0·46	0·76	—0·13
Ga	....	0·49	0·39	0·40	0·65
Rb	....	....	0·91	0·91	—0·10
K_2O	....	....	....	0·84	—0·24
Il	....	....	....	....	—0·14

* Halite sample and sample with 550 ppm B omitted. Il—illite, Kaol—kaolinite.

RELATIONSHIPS OF B, Ga, AND Rb WITH ILLITE AND KAOLINITE

Correlation coefficients (Table 30) indicate essential similarities of element behaviour in the Perth and Canning Basins. However, B and Ga behave differently in the Carnarvon Basin. In the Perth and Canning Basins, B, Rb and K_2O are closely associated with illite and Ga with both illite and kaolinite. In the Carnarvon Basin B is associated with neither illite nor kaolinite and Ga is dominantly related to kaolinite.

The Carnarvon Basin

The absolute value of B is higher in the Carnarvon Basin than in the other two basins. This is attributed to a different source area for the sediments. Sedimentary rocks of the Bangemall Basin and gneisses and granitoids of the Gascoyne Province are known to be richer in tourmaline than, for example, equivalent rocks in the Yilgarn Block. The highest values of B in the Carnarvon Basin occur, in general, in those samples of undoubted marine origin.

The lack of a relationship between B and illite is unusual and implies that B is concentrated elsewhere. There is no close association of B with kaolinite. Chlorite and montmorillonoids are not present in every sample. There is no correspondence of B with the total proportion of the clay minerals. B is present in tourmaline; this mineral has been identified in grain mounts of the Muderong Shale and other Early Cretaceous rocks, but the samples with the highest B values are marine siltstones and calcilutites with no visible tourmaline. However these samples do contain opal, glauconite, zeolites or montmorillonoids in small (<5 per cent) to moderately large (50 per cent) amounts and it seems likely that B is present in more than one mineral and is partitioned between them.

It is clear that the hypothesis of Degens and others (1958) is inapplicable to sedimentary rocks of the Carnarvon Basin.

Perth and Canning Basins

The highly significant degrees of correlation between B and Rb with illite and Ga with kaolinite in these basins support the original hypothesis of the location of these elements.

There is a clear separation of samples with a low illite: kaolinite ratio (<2:3) from those with a high illite:kaolinite ratio (>3:2) on the triangular diagram (Fig. 71) for the Perth Basin. Although there are fewer samples with the low ratio an almost identical line of separation is possible for samples from the Canning Basin.

In addition to those samples which contain one dominant clay mineral many samples, particularly in the Perth Basin, have approximately equal proportions of illite and kaolinite. These samples fit well into the overall clusters on the triangular plots but occur on both sides of the line of separation noted above. They lessen the possible significance of using simple illite:kaolinite ratios as a separator of samples deposited in marine and freshwater conditions.

The wide range of illite:kaolinite ratios differs from that of Degens and others (1957). These authors found the range of ratios for most samples deposited in fresh water to be 0.8 to 1.9, in brackish water 1.0 to 2.1, and in sea water 1.2 to 2.3. Though mineral results in this study are semiquantitative the range is 0.2 to 11 overall. For sediments recognized as of marine origin the range of the ratios is 0.2 to 1.5 in the Perth Basin, in the Carnarvon Basin 0.4 to 11, and in the Canning Basin 0.3 to 3.

EVIDENCE OF DEPOSITION FROM GLAUCONITE AND FORAMINIFERA

The only identified mineral indicator of depositional conditions is glauconite. This mineral is considered to have formed only in marine sediments (Deer and others, 1962). One sample from the Canning Basin, a greensand, is composed largely of glauconite, and has a very high B content (550 ppm). This value supports Harder (1970) who noted that the B content in glauconite is higher than in illite.

The presence of this mineral may therefore distort the B-illite relationship, though there is no apparent systematic variation due to glauconite.

Glauconite is present in most Cretaceous samples in the Carnarvon Basin and in isolated samples from Permian and Jurassic rocks in the Canning Basin. For the most part it occurs in rocks low in kaolinite. In one sample from Dampier Downs No. 1 the glauconite present may have been reworked from previously deposited marine sediments.

Foraminifera were observed in grain mounts of the Toolonga Calcilutite (Canning Basin) confirming a marine deposition of this rock.

PALYNOLOGY

The presence of dinoflagellates or acritarchs is also considered generally conclusive of open-marine origin. An exception occurs in the Yarragadee Formation (Early Neocomian) of the Perth Basin (Table 26) which contains dinoflagellates regarded as representing a restricted marine environment and probable brackish-water conditions. Species known to occur in open-marine deposits of similar age are not present in this formation. Rare marine forms within the Yarragadee Formation are of apparent Triassic age and are derived from pre-existent sediments.

A number of samples contained no palinomorphs of either marine or non-marine origin.

B-Ga-Rb TRIANGULAR DIAGRAMS

The trace-element chemical data together with observations concerning the illite:kaolinite ratio and inferences of depositional conditions based on mineralogical and palaeontological evidence have all been plotted on triangular diagrams (Fig. 71) showing the lines of separation between freshwater and marine deposition suggested by Degens and others (1958).

The plots show the samples clustering in different positions in the three basins. Those for the Perth and Canning Basins are similar except for ioslated samples in the Canning Basin rich in B. The plot for the Carnarvon Basin reflects the high overall B content relative to the other two basins.

It is immediately apparent that the boundary of depositional conditions suggested by Degens and others (1958) bears no resemblance to the actual depositional conditions in any of the three basins.

The diagrams suggest that if there is a separation between marine and freshwater deposition the line of demarcation lies much closer to the Ga-Rb boundary of the triangular diagram than it did for the samples studied by Degens and others (1958). A possible line of separation is shown in Figure 71 (Perth Basin). The line is close to but not exactly the same as the line of separation of kaolinite-rich from illite-rich samples.

PROBLEM OF IDENTIFICATION OF NON-MARINE SAMPLES

In an exercise of this kind it is easier to positively identify rocks which were deposited in marine conditions. In this study this has been done by the identification of glauconite, foraminifera, marine acritarchs or marine dinoflagellates in the sample. It has proved impossible to identify rocks deposited in fresh water in this way, since no indicator minerals or fossils have been found. The absence of marine fossils is not a certain indication of non-marine origin since some marine sediments are unfossiliferous.

Only those samples demonstrably of marine origin have been plotted as such in Figure 71. Non-marine sediments and those with no clear indication of origin have been plotted without interpretation.

CONCLUSIONS

These studies have shown difficulties in using B-Ga-Rb ratios to determine environments of deposition without other geological, mineralogical or palaeontological controls. They immediately raise doubt as to the validity of the conclusions drawn in Davy and others (1978). It may be fortuitous that there was agreement in the earlier study between the depositional conditions suggested by B-Ga-Rb diagrams (using Degens and others (1958) as a basis for interpretation) and those deduced on geological grounds.

It appears that provenance plays an important part in determining the absolute amounts of the trace elements. Since provenance appears to control B more than Ga or Rb, the provenance indirectly controls the position of the plotted point on the triangular diagram.

The present studies have shown that the hypothesis of Degens and others (1958) is untenable for the Carnarvon Basin since B is not correlated with illite. They have confirmed, however, that illite is in general more abundant than kaolinite in rocks of undoubted marine origin.

A consistent pattern has emerged in the Perth and Canning Basins. There is a reasonably sharp division between kaolinite-rich and illite-rich samples, and the kaolinite-rich samples, as expected, are located in the Ga-rich rather than the B-rich parts of the triangular diagrams. However, palynological studies on Perth Basin samples, whilst not conclusive for all samples, indicate a line of demarcation between marine and brackish water deposition far away from that proposed by Degens and others (1958), close to the Ga-rich part of the diagram (Fig. 71). This suggests that, once adequate parameters are established for a restricted area of deposition, such as one of the basins studied here, the triangular diagrams may be of use for characterizing conditions for samples of unknown origin but from the same general area. The same line of separation may also apply in the Canning Basin; however this basin contains few sedimentary rocks of undoubted freshwater origin.

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ASPECTS OF AMPHIBOLE CHEMISTRY AND METAMORPHIC GRADIENT IN THE WONGAN HILLS, WESTERN AUSTRALIA

by D. F. Blight

ABSTRACT

Ten metamorphic amphiboles from the Wongan Hills area of Western Australia were chemically analysed. A study of their TiO_2 content and the amount of alkalis in relation to silicon suggests a dominantly temperature-controlled metamorphic gradient; rocks formed under higher temperatures occur in the south.

INTRODUCTION

The Wongan Hills, centred at latitude 30°50'S longitude 116° 38'E (Moora 1:250 000 Sheet), are approximately 150 km northeast of Perth. They are approximately 20 km long and 6 km wide. The rocks have been described by Carter, Low and Lipple (in press), and are of metamorphosed and deformed Archaean supracrustal rocks. There are mafic and felsic volcanics, intercalated with sedimentary rocks ranging from banded iron-formation to pelitic schist. Porphyritic and even-grained Archaean granitoids intrude the sequence. The structure of the area is complex, and at least two tectonic events are megascopically visible. Presumed Proterozoic dolerite dykes intrude faults and northeast-trending fractures.

METAMORPHIC GRADE

During the course of service petrology associated with the regional mapping of the Moora 1:250 000 Sheet, the following metamorphic assemblages were recognised within the supracrustal rocks of the Wongan Hills.

Basic rocks

Plagioclase (An >25) + hornblende + opaques ± quartz ± sphene with secondary chlorite, clinozoisite and sericite.

Aluminous rocks

Microcline + andalusite + fibrolite + muscovite + biotite + quartz ±garnet, and
cordierite (altered) + garnet + quartz + biotite + opaques.

Banded iron-formations

Quartz + grunerite + opaques

Ultramafic rocks

Garnet ± grunerite ± hornblende + opaques

The unusual assemblage, cordierite + cummingtonite, was also noted. Rocks of similar composition have been described by many other workers, including Prider (1944), Starmer (1969), Lal and Moorehouse (1969), and Beeson (1976); the consensus favours non-isochemical metamorphism to account for the unusual chemistry. Evidence of metasomatism associated with the copper mineralization in the Wongan Hills supports such a suggestion. All the assemblages mentioned above are characteristic of the amphibolite facies at medium pressures (Turner, 1968).

When the areal distribution of the minerals was examined no definite mineral isograds were found. However, garnet appears to be confined to the south (field observation by S. Lipple during regional mapping), and andalusite was only visible in thin sections collected from the southern regions. This latter observation may well be a function of the composition of the rocks sampled. The assemblage, cordierite + cummingtonite, was noted from all areas of the Wongan Hills. On the basis of subtle colour changes of amphiboles, Blight (1977, unpublished GSWA Petrology Report 783) suggested that a regional metamorphic gradient, increasing to the north, may be evident in the rocks of the Wongan Hills. It was stressed that a detailed chemical study of the amphibole minerals was needed to substantiate such a suggestion. This report deals with such a study.

ELEMENTAL VARIATIONS

Petrographic descriptions of the rocks used in this study are detailed in Appendix I, and analytical techniques are discussed in Appendix II. Analysed amphiboles and structural formulae are listed in Table 31. Sample locations are given in Figure 72. As can be seen from Table 31, all analysed amphiboles, apart from the rim of sample 44045, are hornblendes.

Raase (1974) has demonstrated a good distinction between hornblendes of low-pressure (less than 500 MPa) and high-pressure type of regional metamorphism by using a plot of Al^{VI} against Si. Figure 73 is a similar plot for the hornblendes of the Wongan Hills. All plot in the low-pressure regions, and thus support the estimate of metamorphic grade based on mineral assemblages.

The TiO_2 content of hornblendes and biotites has been considered responsible for colour charges of the minerals which correlate with variations in metamorphic grade (Leake, 1965; Binns, 1969). Furthermore Leake (1965), Binns (1969), and Raase (1974) have demonstrated that, with increasing metamorphic grade, the TiO_2 content of hornblendes also increases. Leake (1965) and Binns (1969) consider that increasing temperature is the important factor in these correlated changes. A visual inspection of location versus the TiO_2 content for the Wongan Hills hornblendes suggests a tendency towards a lower TiO_2 content in the north. The influence of host-rock chemistry may have masked this trend, so a second-order trend-surface analysis was applied to the data. Figure 72 clearly demonstrates that such a trend, of lower TiO_2 values to the north, exists; this suggests that the hornblendes of the southern region were formed at higher temperatures than those in the north.

The charge on silicon ions is different from that on aluminium ions and results in a charge imbalance where aluminium replaces silicon in the anion part of the silicate lattice. Binns (1965) showed that this charge imbalance is rectified differently at high metamorphic grade than at low grade. At low grade, a charge balance is maintained by additional cationic aluminium, whereas at high grade, the charge balance is maintained by additional alkali cations. Thus at

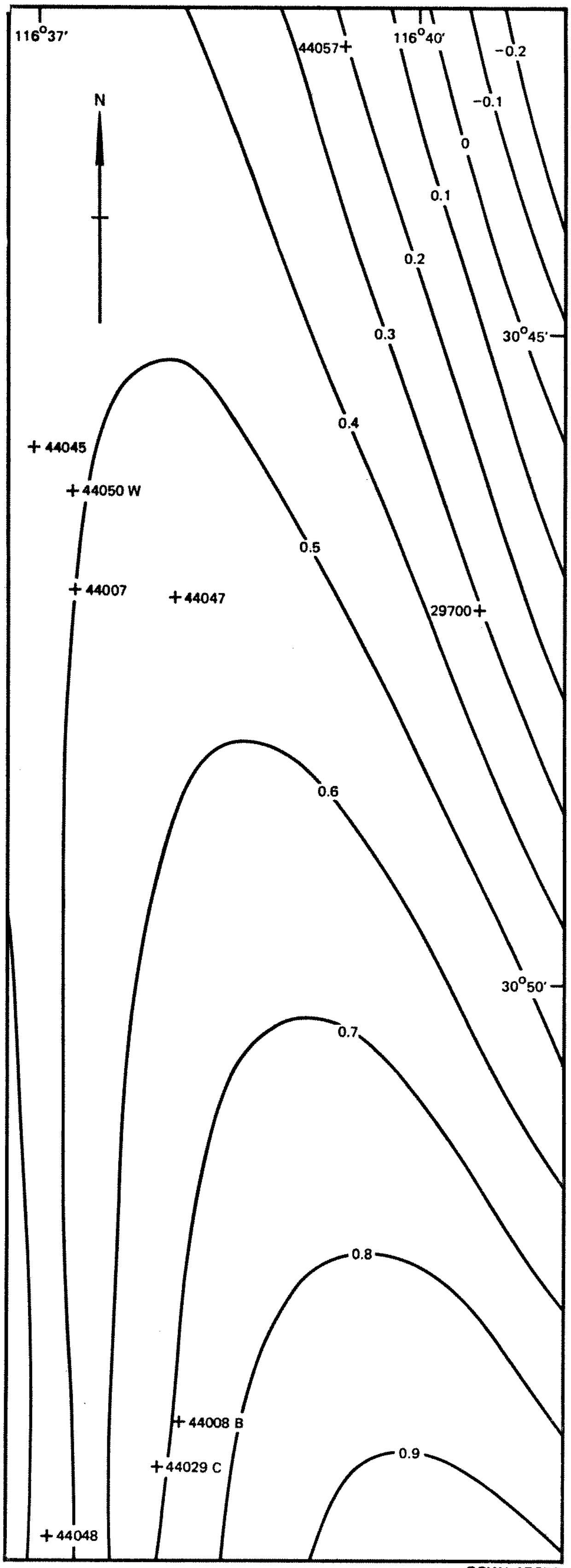

Figure 72 Second order trend surface analysis of TiO_2 content of Wongan Hills amphiboles in relation to location.

higher metamorphic grade, the amphibole contains more "edenitic" alkalis and less Al^{VI}. Binns (1969) further demonstrated this observation with a study of 180 hornblendes from different terrains, and concluded that these types of ". . . changes in amphibole composition appear more highly influenced by temperature than pressure".

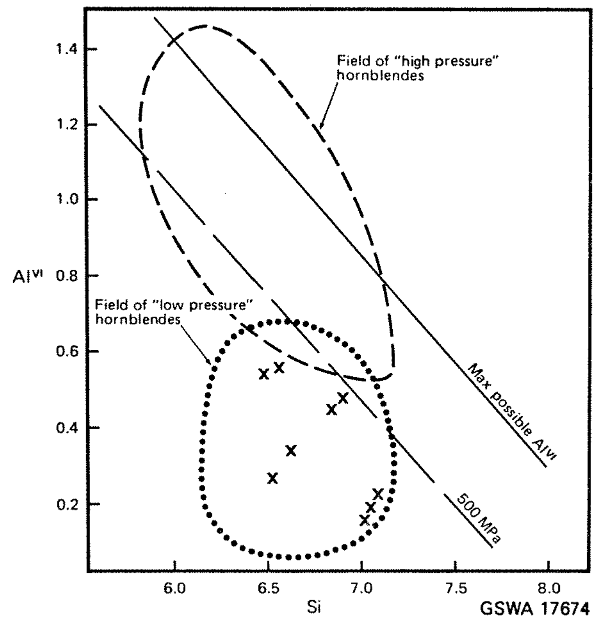

Figure 73 Wongan Hills amphiboles plotted on a Si against Al^{VI} diagram after Raase (1974).

The hornblendes of Wongan Hills have been plotted on Figure 74, Al^{VI} against "edenitic" alkalis (cf. Binns, 1969, page 326). While these amphiboles do not plot within the fields indicated by Binns, they nevertheless show a trend which, in the light of the previous discussion, suggests that those rocks to the south are higher grade, and consequently formed at higher temperature, than those to the north.

CONCLUSIONS

It is apparent from this study of hornblendes that there is a variation of metamorphic grade in the Wongan Hills, from low in the north to higher in the south. Furthermore, it is probable that this variation is a response to temperature and not pressure. This finding is consistent with that of an earlier study (Blight, 1977), which showed, using petrological evidence, that an unusually high geothermal gradient existed in the southern region of the Wongan Hills.

ACKNOWLEDGEMENTS

Assistance with the microprobe analyses, by Dr. J. Graham and Mr. B. Robinson of the CSIRO, Floreat Park, Western Australia, is gratefully acknowledged.

APPENDIX I—PETROGRAPHY OF ANALYSED SAMPLES

29700 Texture: Granoblastic, seriate with a very weak fabric overprinting a faint relict igenous texture.
Mineralogy: Coarse green hornblende (55%) up to 2.0 mm in size with finer grained plagioclase (40%) minor opaques and a trace of apatite.
Name: Meta-Dolerite.

44007 Texture: Fine grained, lepidoblastic, equigranular with a moderate layering and a strong fabric.
Mineralogy: Green hornblende (45%) about 0.1 mm in size, plagioclase (45%) rarely weakly saussuritized, chlorite (10%), and some minor opaques.
Name: Amphibolite.

44008B Texture: Fine grained, granoblastic, equigranular, interlobate.
Mineralogy: Green hornblende (10-15%) scattered throughout a matrix of plagioclase and quartz (?) with minor opaques.
Name: Meta-Dacite.

44029C Texture: Medium to fine grained, moderately lepidoblastic, inequigranular with a moderate fabric. There is a relict but unrecognizable (possibly basaltic) texture.

TABLE 31. ANALYSES OF AMPHIBOLES FROM THE WONGAN HILLS

	29700	44007	44008B	44029C	44045 *core*	44045 *rim*	44047	44048B	44050W	44057
SiO_2	46·42	43·11	47·48	42·40	43·25	52·46	43·72	48·44	47·99	48·64
Al_2O_3	9·28	11·65	6·44	9·69	11·85	·97	9·74	6·26	9·14	6·66
Fe_2O_3	4·98	5·53	5·55	6·61	5·33	2·91	5·68	5·30	3·87	3·86
FeO	13·44	14·93	14·99	17·85	14·39	23·57	15·33	14·32	9·46	10·41
MgO	11·60	8·37	10·40	6·58	9·66	16·00	9·15	11·19	14·10	15·60
CaO	11·62	12·16	12·10	11·76	10·69	·70	11·29	11·84	12·10	10·51
Na_2O	1·01	1·19	·61	1·07	1·51	·24	1·31	·60	1·01	·73
K_2O	·14	·53	·16	·75	·17	....	·32	·42	·14	....
TiO_2	·31	·66	·55	·87	·51	....	·54	·41	·29	·22
MnO	·21	·30	·32	·52	....	·37	·35	·63	·16	·25
H_2O+	1·50	1·57	1·50	1·90	2·00	2·00	2·00	1·50	1·74	2·00
Total	100·51	100·00	100·10	100·00	99·36	99·22	99·43	100·91	100·00	98·88
STRUCTURAL FORMULAE ON THE BASIS OF 24 OXYGENS										
Si	6·853	6·506	7·104	6·509	6·473	7·799	6·604	7·091	6·945	7·138
Al^{IV}	1·147	1·494	·900	1·491	1·527	·170	1·396	·909	1·055	·862
Al^{VI}	·468	·578	·236	·262	·563	....	·338	·171	·504	·283
Fe^{2+}	1·659	1·884	1·876	2·292	1·801	2·930	1·937	1·753	1·145	1·270
Fe^{3+}	·553	·628	·625	·764	·600	·325	·646	·584	·421	·427
Mg	2·553	1·883	2·320	1·506	2·155	3·545	2·060	2·442	3·041	3·391
Ca	1·838	1·966	1·940	1·934	1·714	·112	1·827	1·857	1·876	1·642
Na .... {	·162	·034	·060	·066	·286	·069	·173	·143	·124	·206
	·127	·314	·117	·253	·152	....	·211	·027	·159	....
K	·026	·102	·031	·147	·032	....	·062	·078	·026	....
OH	1·477	1·581	1·497	1·946	1·997	1·983	2·015	1·953	1·680	1·946
Ti	·034	·075	·062	·100	·057	....	·061	·045	·032	·024

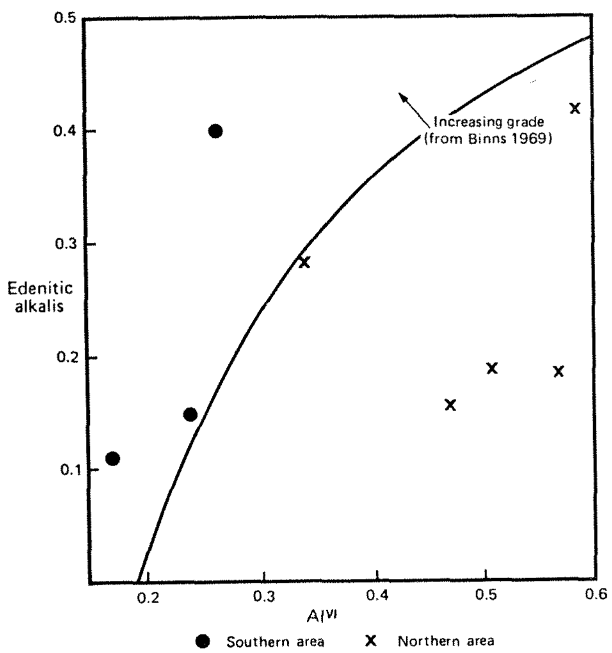

Figure 74 Edenitic alkalis against Al^{VI} for Wongan Hills amphiboles.

Mineralogy: Green hornblende (45%) up to 0.3 mm in size, slightly saussuritized plagioclase (55%) with minor sphene (1%) and a trace of opaques.

Name: Meta-Basalt.

44045 Texture: Fine grained, lepidoblastic, poorly equigranular with a strong fabric.

Mineralogy: Colourless to pale green cummingtonite-grunerite with a green hornblende core (50%) up to 0.6 mm long but averaging about 0.2 mm, plagioclase (50%) and minor opaques.

Name: Amphibolite (Schist).

44047 This rock is similar to 29700 but the fabric is a little more penetrative.

Name: Meta-Dolerite.

44048B Texture: Fine grained, poorly lepidoblastic, equigranular with a weak layering and a moderate fabric—possibly a relict vesicular texture.

Mineralogy: Green hornblende (60%) up to 0.4 mm, totally saussuritized plagioclase producing clinozoisite and muscovite, and minor quartz and opaques.

Name: Amphibolite (Meta-Basalt).

44050W Texture: Medium to fine grained, granoblastic, poorly equigranular.

Mineralogy: Pale green hornblende (99%) averaging about 0.5 mm in size and minor opaques.

Name: Meta-Pyroxenite.

44057 Texture: Barely discernible relict sub-ophitic igneous texture.

Mineralogy: Coarse grained green hornblende (55%) up to 3.0 mm, medium grained calcic plagioclase (45%) up to 1.0 mm in size and minor opaques.

Name: Meta-Dolerite.

APPENDIX II—ANALYTICAL DETAILS

The amphiboles were analysed at the CSIRO, Floreat Park, using a MAC electron microprobe. Determinations were made on a number of grains per sample at different places within the one grain, the results were then averaged. Initially, manually operated wavelength spectrometers were used for detection but later a quantitative energy dispersive multichannel analyser was installed and utilized. The results from both these systems were found to be comparable. The probe analyses did not distinguish between Fe^{2+} and Fe^{3+} so, after examination of other published amphibole analyses, corrections were applied as follows:

$$Fe_2O_3 = \frac{\text{total Fe (as FeO)}}{4} \times 1.1113$$

FeO values were then obtained by difference. H_2O^+ was considered to lie between 1.5 and 2.0, the value assumed gave a total closest to 100.00%. Structural formulae were calculated on the basis of 24 Oxygens.

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INDEX

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