GEOLOGICAL SURVEY
of
WESTERN AUSTRALIA

ANNUAL REPORT 1976

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REPORT

FOR THE YEAR

1976

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

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Annual Report of the Geological Survey Branch of the Mines Department for the Year 1976

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REPORTS

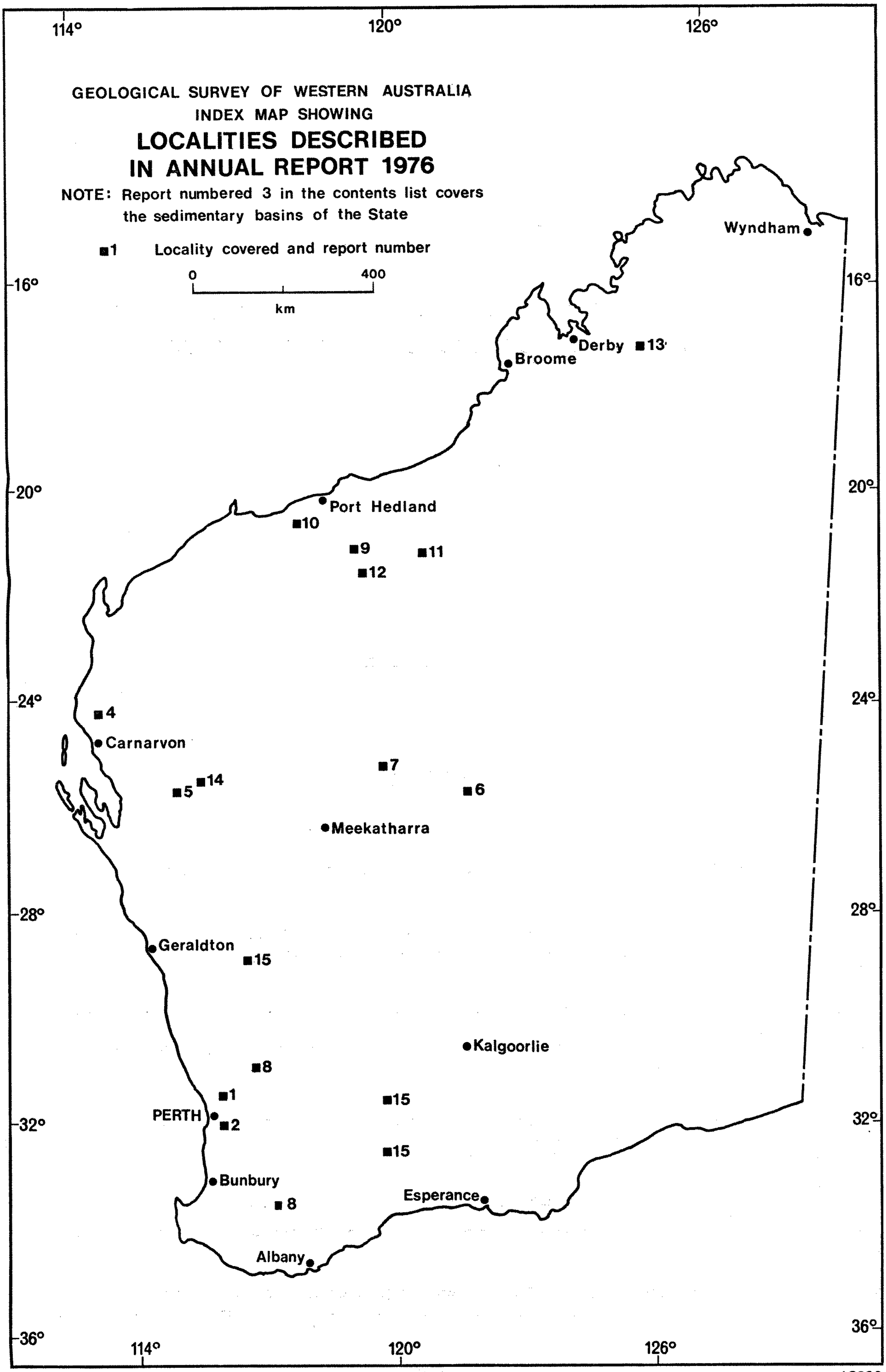

Figure 1. Index map showing areas and localities described in the Annual Report for 1976.

LIST OF FIGURES

DIVISION IV

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Annual Report of the Geological Survey Branch of the Mines Department for the Year 1976

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Under Secretary for Mines:

For the information of the Honourable Minister for Mines I submit my report for 1976 on the activities of the Geological Survey of Western Australia together with selected reports on investigations and studies made for Departmental purposes.

INTRODUCTION

There is definite evidence that the downward trend in exploration levelled off in the first half of 1976 and in the second half an upward trend developed which is expected to continue in 1977. This opinion is based on the amount of work commitments associated with the increased applications for tenements rather than on financial commitments which are subject to inflationary trends.

This upward trend is illustrated best in the number of new temporary reserves approved during 1976 for minerals other than gold and iron. This showed a marked increase as compared with 1975, and, as 34 per cent of the applications were applied for and approved during the last quarter of 1976, intention of increased activity in 1977 is indicated.

Year	*Temporary Reserves Approved* (excluding gold, iron and coal)
1973	182
1974	47
1975	20
1976	117

The applicants in 1976 are committed to a minimum work expenditure of over $3.7 million on exploration during the first 12 months for which the reserves are held.

Oil and gas exploration stabilized and the amount of work done during 1976 was similar to 1975, both on and offshore. There was promise at the end of the year that there would be an upturn of activity during 1977.

Year	Total wells drilled	Total metrage	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

The only significant discovery during the year was gas in Parentie No. 1 on Barrow Island, which was a follow-up to two previous deep test wells, Biggada No. 1 and Barrow Deep No. 1.

A number of areas, both onshore and offshore, were offered for public tender. Although there was considerable interest shown in the areas concerned, the number of tenders actually received was disappointing.

In the early part of the year, interest in mineral exploration was directed mainly towards uranium throughout the State, but with the announcement of the good copper-zinc-silver values located in drilling near Teutonic Bore, 60 km north of Leonora, much attention was concentrated on this area and this type of mineralization. This discovery of copper-zinc mineralization in a volcanogenic environment produces a new sphere for prospecting. It is probably as important to copper exploration in this State as the discovery of Kambalda was to the nickel exploration.

Iron ore exploration has continued in the Hamersley Range on a limited scale without any major new discoveries. Exploration for iron should expand again as 85 new temporary reserves were approved late in 1976. Several companies are involved and a minimum of $1.7 million should be expended on exploration. No new large iron ore sales contracts eventuated to warrant the development of new mines, although the two major production companies each expanded their capacity to 40 million tonnes per year.

Following decisions to develop the Alwest area in conjunction with Alcoa and to build a new alumina refinery near Wagerup, bauxite investigations were recommenced near the end of the year. Also the Mitchell Plateau deposit is being reconsidered to decide if it is possible to plan production on a limited scale.

Probably due to the economic situation, prospecting and exploration for nickel was sluggish. Work continued in the Forrestania area, and an announcement was made to proceed with the development of the Perseverance nickel occurrence near Agnew.

Despite difficulties in marketing its products, the heavy mineral sands industry continued to develop, with three plants now in operation near Eneabba and one at Jurien Bay. A new deposit at Cataby, West Dandaragan, has been proved and awaits development.

Uranium has been the most sought after mineral throughout the State. Exploration has been directed mainly towards calcrete drainages of the inland. However, the search has also extended to the sedimentary basins and hardrock areas. Although further uranium mineralization has been located, particularly in the calcrete and inland lakes areas, no economic deposits, such as that at Yeelirrie, have been confirmed.

Exploration for copper-zinc deposits developed rapidly in the eastern goldfields after the discovery of the Teutonic Bore deposit in acid volcanic rocks. Exploration continues at Golden Grove for copper and near Kundip for copper-gold ores.

In the Kimberley region exploration has been active, particularly for diamond, following the announcement of the location of 160 microdiamonds totalling seven carats, with the biggest stone being 0.42 carat. Elsewhere in the Kimberley region, exploration for lead at Sorby Hills, nickel at Sally Malay near Turkey Creek, and copper near Halls Creek continues.

Gold prospecting declined during the year but the price improvement during the latter part of the year prevented closure of the last mine at Kalgoorlie. Further increase in the price of gold is required to stimulate prospecting for this metal.

The International Geological Congress was held in Australia for the first time during August and this Survey made a major contribution by arranging and providing leaders for three Congress Excursions, namely: Denovian Reef Complexes of the Canning Basis (P. E. Playford), Archaean Geology and Mineral Deposits of the Eastern Goldfields (R. D. Gee), and Geology of the Hamersley Basin (A. F. Trendall). Co-leaders were provided for two Congress Excursions, namely: Archaean Geology of the Yilgarn Block (I. R. Williams), and the Mining Centres of Southern and Western Australia (J. H. Lord).

Staff members of the Survey presented the following papers at the Congress:

- The Western Australian Shield .. by R. D. Gee.
- The Pilbara and Yilgarn Archaean Blocks of Western Australia .. by R. D. Gee.
- Geochemistry of Archaean felsic to ultramafic metasediments in relation to crustal evolution, north-eastern Yilgarn Block, Western Australia .. by R. J. Marston.
- Heavy mineral deposits in Western Australia .. by J. L. Baxter.
- Relict early Cainozoic drainages in arid Western Australia .. by W. J. E. van de Graaff *et al.*

A series of four lectures on the geology of the Pinjarra 1:250 000 geological map was given, followed by a two-day excursion to inspect the field occurrences. It proved popular with 70 attending the lectures and 58 participating in the field trip.

In an effort to provide a better water supply for Rottnest Island a detailed sedimentological study was made and test bores recommended. A suitable water supply was located and is being developed by the Department of Public Works. Providing it is managed carefully, the supply should be satisfactory for the island.

Regional geological mapping of the State continues (see Fig. 2) with only 10 sheets remaining in the 175 sheet programme.

STAFF

There were several resignations from the professional staff during the year for several reasons. No difficulty was experienced in recruiting replacements to fill the vacancies.

There continues to be a considerable movement of general and clerical division officers.

PROFESSIONAL

Appointments

Name	Position	Effective Date
Marston, R. J., B.Sc. (Hons.), Ph.D.	Geologist L3	2/2/76
Moncrieff, J. S., B.Sc. (Hons.)	Geologist L1	16/2/76
Wharton, P. H., B.Sc. (Hons.)	Geologist L1	11/5/76
Blight, D. F., B.Sc. (Hons.), Ph.D.	Geologist L1	6/9/76
Cameron, J. F., B.A.	Geologist L1	20/9/76
Furness, L. J., B.Sc. (Hons.), M.App.Sc.	Geologist L1	30/11/76

Promotions

Bunting, J. A.	Geologist L2	22/6/76
Hickman, A. H.	Geologist L2	22/6/76
Wilde, S. A.	Geologist L2	22/6/76

Resignations

Campbell, J. M.	Geologist L1	2/4/76
Drake, J. R.	Geologist L1	15/4/76
Harley, M. M.	Geologist L1	2/9/76

CLERICAL AND GENERAL

Appointments

Horley, J. R.	Geological Assistant	7/1/76
Willis, B. J., B.Sc.	Technical Officer	19/1/76
Miller, I. S.	Clerk	15/3/76
Baggott, S.	Geophysical Assistant	21/4/76
Smith, P. C.	Typist	17/5/76
Domahidy, G.	Core Librarian	5/7/76
Black, A.	Typist	5/10/76
McDonald-Goodall, A.	Technical Assistant	13/12/76

Resignations

Butherway, P.	Geophysical Assistant	27/2/76
Hargrave, D.	Typist	12/5/76
Ridley, J. L.	Typist	5/10/76

Transfer In

Lapthorne, J.	Senior Clerk	12/10/76

Transfer Out

Hewitt, P. A.	Clerk	24/3/76
Wells, R.	Core Librarian	15/4/76
McNamara, T.	Senior Clerk	21/5/76
Green, M.	Technical Assistant	16/9/76

ACCOMMODATION

In August twenty geologists were moved to office accommodation at 196 Adelaide Terrace. This has caused considerable inconvenience because of the need for staff to commute some 800 m to Mineral House for administrative, library and laboratory services.

Although subdivision of the space vacated is not yet complete, it will eventually ease overcrowding of geological staff in Mineral House and increase library space to provide a microfilm viewing and printing room and additional stack area.

OPERATIONS

HYDROGEOLOGY AND ENGINEERING GEOLOGY DIVISION

E. P. O'Driscoll (Chief Hydrogeologist), T. T. Bestow, R. P. Mather (Supervising Geologists), K. Berliat, A. D. Allen (Senior Geologists), J. C. Barnett, W. A. Davidson, A. S. Harley, K.—J. B. Hirschberg, G. W. A. Marcos, E. H. Briese, D. P. Commander, L. J. Furness, G. Klenowski, R. E. J. Leech, I. H. Lewis, J. S. Moncrieff, P. A. Wharton.

Hydrogeology

Exploratory drilling for groundwater resource assessments and water supply investigations was reduced in 1976 compared with the previous year. The aggregate depth of newly completed bores exceeded 7 000 metres.

Three deep exploratory bores have been drilled in Perth Basin west of Moora and another near Bunbury has been comprehensively test pumped to determine aquifer characteristics. Three other deep bores at Eneabba have also been tested. In the Perth metropolitan area three deep stratigraphic bores have been drilled. They provide important new information aiding the continuing study of water resources in the Perth region. Some additional shallow drilling has been completed in the Lake Thompson area for water resources evaluation and also in the Osborne Park area for sanitary land-fill studies.

Thirteen bores drilled east of the present Mirabooka water supply scheme have resulted in the discovery of a deep sand-filled trough, which adds substantially to the water resources of the area. A further nine bores were drilled in the same vicinity, at Mussel Pool, for special land-use studies.

Geological and hydrological surveys have been conducted on Rottnest Island and have resulted in the successful establishment of a new water supply scheme based on shallow groundwater.

Further drilling has been carried out in the Bunbury region as part of an investigation of the complex aquifer systems in that area. Detailed hydrogeological studies have commenced west of Leschenault Inlet to aid the management of acid-effluent disposal and minimize any environmental effects.

Work on the West Canning Basin study, east of Port Hedland, has been confined to preparing all the completed bores for comprehensive hydraulic testing in the coming year. In the West Pilbara, good progress has been made with drilling near Millstream. In all, 32 boreholes were drilled. A preliminary interpretation of the results indicates that substantial additional water yields will be possible from the limestone and weathered bedrock aquifers. Based on specially cored bores, joint studies with Public Works Department engineers have also resulted in improved estimates of groundwater storage in the limestone aquifer.

Inter-departmental studies of the effects on stream and groundwater hydrology of bauxite mining in the Darling Range and the Manjimup woodchip industry have continued. A total of 159 additional observation bores have been drilled by Alcoa, the Mines Department, and the Public Works Department. They aggregate 4 126 metres of drilling.

The demand for advisory services has continued at about the same level as last year; 80 inspections were undertaken for private landholders requiring advice on groundwater. Three field inspections were carried out for local authorities and a further four for the Department of Conservation and Environment. Liaison with other government departments regarding groundwater exploration and development, as well as research studies, has continued.

Engineering Geology

The work of the section was confined mainly to investigation for other government instrumentalities including

Department of Public Works:

(a) Cooya Pooya proposed dam site—geological mapping, geophysics and trenching.

(b) Robe River proposed dam site "D"—geological mapping, geophysics, drilling and trenching.

(c) Sherlock River proposed dam site—geological mapping, geophysics, drilling and trenching.

(d) Booyeemala proposed dam site—geological mapping.

(e) Port Denison—continued geological mapping and drilling of proposed quarry sites.

(f) Minor investigations including core logging for the foundation studies for new berths at Geraldton and Bunbury Harbours.

Metropolitan Water Board:

(a) Wungong Dam—continued geological mapping in the foundation area during construction.

(b) South Canning proposed dam site—geological mapping, geophysics and drilling for the foundation study of a new layout.

(c) North Dandalup proposed dam site—drilling in two proposed borrow areas.

(d) Victoria Dam—geological mapping for an alternative site.

(e) Beenyup Tunnel—geological mapping in the outlet cut during construction.

(f) Minor investigations associated with the safety review of existing dams.

W.A. Government Railways:

Geological advice given to aid the selection and development of quarry sites in five areas.

SEDIMENTARY (OIL) DIVISION

P. E. Playford (Supervising Geologist), K. A. Crank, W. J. E. van de Graaff (Senior Geologists), M. N. Megallaa (Geophysicist), P. D. Denman, R. W. A. Crowe, R. M. Hocking, B. P. Butcher.

The processing of voluminous petroleum exploration data from relinquished and surrendered permit areas continued during the year, and is now largely complete. Petroleum exploration continued at a low level, but many vacant areas were made available for application by prospective explorers during the year, and activity is expected to increase in the near future as new companies enter petroleum exploration in this State.

Mapping continued in the Carnarvon Basin, and was completed on the Quobba 1:250 000 Sheet and on the Phanerozoic parts of the Mount Phillips, Glenburgh, and Byro Sheets. Compilation of geophysical maps covering the southern and central parts of the basin as far north as latitude 23°S was largely completed.

The Canning Basin mapping project was continued, in conjunction with the Bureau of Mineral Resources. Mapping of the Mount Anderson and Derby 1:250 000 Sheets was completed during the year.

The geology and groundwater prospects of Rottnest Island was investigated in detail and a programme of drilling recommended which proved successful.

REGIONAL GEOLOGY DIVISION

R. D. Gee (Supervising Geologist), I. R. Williams (Senior Geologist), P. C. Muhling, J. A. Bunting, A. T. Brakel, R. J. Chin, M. Ellias, 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 Rudall, Collie, Wiluna, Kingston, Stanley, Nabberu and Southern Cross was completed.

Mapping on the following sheets is progressing toward completion in 1977: Mount Phillips (90 per cent completed), Glengarry (80 per cent).

Mapping in the Bangemall Basin was concluded with the completion of field work on Stanley and Nabberu. Re-appraisal work was undertaken in the previously mapped western and northeastern portions of the Basin in order to integrate the mapping for recent years.

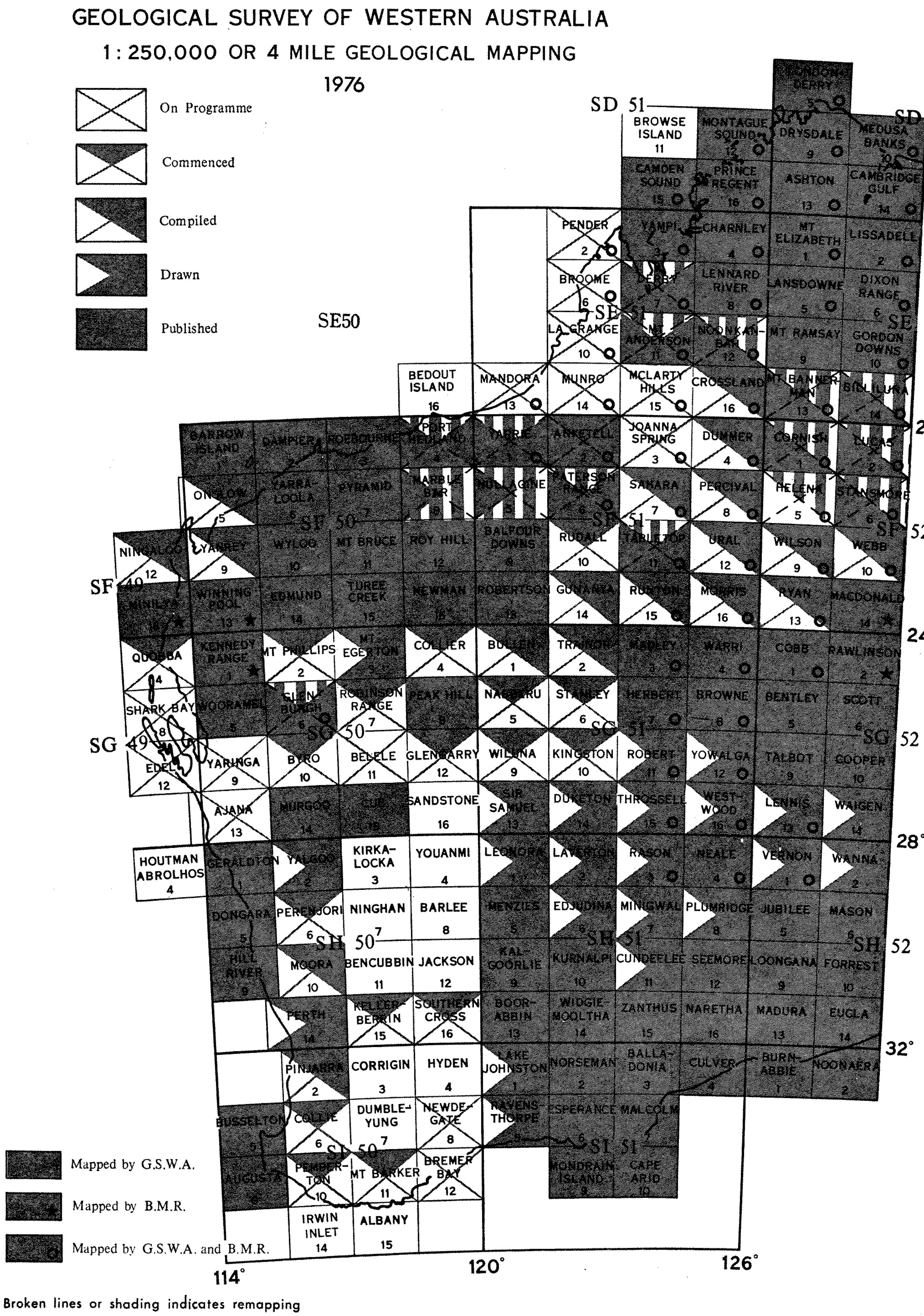

Figure 2. Progress of 1 : 250 000 or 4-mile geological mapping at end of 1976.

MINERAL RESOURCES DIVISION

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

Mapping of the Collie 1:250 000 Sheet was completed and results are being compiled. The Perenjori and Pemberton 1:250 000 Sheets were commenced during the year. Compilation of the Precambrian parts of the Port Hedland, Moora and Pinjarra 1:250 000 Sheets was finished and preliminary Explanatory Notes were issued for Pinjarra. All field work towards a Bulletin on the Pilbara Block has now been carried out.

Manuscripts on the State's tin and kaolin deposits were completed. The task of revising the copper Bulletin was again taken up, field work finalized and writing begun.

Further investigations were made of the barite deposits near Cooke Bluff Hill and the results compiled as a proposed record.

Sundry work included an assessment of limestone resources in the South West Metropolitan Corridor and an investigation of ore reserve computation techniques at Kalgoorlie.

During the year the Division answered about 250 enquiries from the public and other government departments and dealt with some 210 requests for access to company reports. About 500 new accessions were added to the collection of mineral exploration data administered by the Division, a decrease of 185 on 1975.

COMMON SERVICES DIVISION

Petrology (W. G. Libby, J. D. Lewis, D. F. Blight)

A continued increase in demand for petrological services resulted in the production of 118 petrological reports on 2 246 samples. More than one thousand further samples were classified by thin section for incorporation into the petrology data system. Over the past decade the average number of samples reported has increased by more than 235 samples per year.

The GSWA/WAIT co-operative geochronology programme continued during the year with work accomplished on sixteen projects. The results of three of these, the Gascoyne Regional, Tangadee Rhyolite, and East Margin Yilgarn projects were published. Four further projects were added for 1977.

The laboratory prepared 2 782 thin sections, of which 2 317 were petrological and 465 sedimentological. Thin sections stained for determination of carbonate or K-feldspar numbered 250. There were 12 heavy mineral determinations, 31 sieve analyses and 51 specific gravity determinations. Samples crushed for chemical or geochronological analysis numbered 501

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

Geophysics (D. L. Rowston, I. R. Nowak)

There was a reduction in geophysical well-logging activity in 1976 when 191 water bores were logged as compared with 258 in 1975. Cumulative total depths amounted to 20 900 m (29 900 in 1975) and logs recorded by various methods were equivalent to about 48 800 m of hole.

Numerous dam sites were investigated by seismic refraction surveys; they included the Sherlock, Robe and Cooya Pooya sites in the Pilbara, and, near Perth, the South Canning and Churchmans Brook localities. Five paired catchments, intended to assess salinity problems associated with the Manjimup woodchip industry, were also investigated.

Experimental ground magnetic observations clearly delineated the margins of the Bunbury Basalt. The location of areas not underlain by basalt is of material assistance to water-boring contractors. Successful application of a technique for deriving pseudovelocity logs from resistivity well-logs aided correlation of seismic events in the Carnarvon Basin.

As a result of various groundwater salinity monitoring projects, water sample conductivity measurements increased to 1 030. Normal electronic instrument servicing and calibration facilities were provided.

Palaeontology (A. E. Cockbain, J. Backhouse, K. Grey)

Requests for palaeontological information involved more long-term project work and consequently fewer (48) reports were written this year. Work continued on the palynology of Cretaceous rocks in the Perth Basin and on the Devonian faunas from the Canning Basin. Regional mapping of the Carnarvon Basin resulted in extensive collections of samples ranging in age from Permian to Quaternary. Detailed studies were made on stromatolites and microfossils from the Bangemall Basin.

Environmental Geology (E. R. Biggs, R. H. Archer)

Work on the 1:50 000 Urban Geology map series was continued with the completion of one sheet (Mandurah) and the completion of field mapping on ten sheets (Pinjarra, and nine sheets in the Dampier-Roebourne area).

A study of aggregate and dimension stone in the Perth region was completed and the results will be issued as a Record.

The appraisal of mineral tenement applications in the South West Mineral Field continues, with a view of protecting the environment while encouraging mining.

Examinations were made of a number of temporary excavations in and around Perth to expand knowledge of geological strata in the urban area.

Liaison with, and supplying geological information to, other departments and instrumentalities continues to occupy a large part of the section's activities and has included: studies of the geology of the Southeast, Northwest and Eastern (Perth Urban) Corridors; a study of the limestone resources in the area around the proposed Joondalup sub-regional centre; provision of geological maps and data for the System 6 study; a study of sediments and erosion problems at Lake Dumbleyung; provision of information on gravel resources in the Shire of Serpentine-Jarrahdale; attendance at meetings of several inter-departmental committees; and the assessment of various departmental and company reports.

Geochemistry (R. Davy)

The various reports on the geochemical study of Archaean bedrock of the Rason, Laverton, and Leonora 1:250 000 Sheet areas were completed. These are available through the Report series, and as file reports.

Investigations on the sulphur dioxide prospecting technique for identification of ore bodies at depth were carried out at Golden Grove, Burbidge, and Forrestania. A report on the results is included in this Annual Report.

A study of the mineral content of groundwater at Del Park was continued, and results made available in the Record Series.

The results of chemical and X-ray diffraction analyses of certain bauxites were completed by the Government Chemical Laboratories, and a report on the investigations completed.

A study of the mineralization in the Bangemall Basin was commenced.

The service of the Government Chemical Laboratories in the provision of chemical analyses is gratefully acknowledged.

Technical Information (W. B. Hill, M. E. Wenham, J. F. Cameron, and S. M. Fawcett)

Although the number of enquiries from the public has decreased over the last few years, there has been an increase in the number of manuscripts received by this section for preparation for the printer and proof-reading. One Bulletin was marked for the printer and sent to the press, and work continued on proof-reading of the two already at the press. Twenty-two records were edited and four Explanatory Notes published. One new information pamphlet was issued, and seven were reprinted. The stratigraphic nomenclature index was revised and updated.

Requisitions raised on the Surveys and Mapping Branch for drafting services and photography for the Survey totalled 1 129. Photocopying for the public of out-of-print publications numbered 1 058 requisitions, many of which contained several items.

During the year this section dealt with 764 requests for information including rock identification, and 1 526 members of the public visited the library for research purposes. Book loans to the staff totalled 5 621, and loans to other libraries 202.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

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

(i) Preparation of a Bulletin on the Officer Basin as a joint project with this Survey.

(ii) Continuation of mapping in the Canning Basin as a joint venture with this Survey.

(iii) Continuation of rock collection in the Pilbara area to test for trace element characteristics.

(iv) Completion of the aeromagnetic survey of the Officer Basin.

(v) Airborne magnetic and radiometric survey of Hyden, Newdegate and Dumbleyung 1:250 000 Sheets.

(vi) Preparation to use iron ore quarry blasts as seismic sources for a crustal structure survey in the Pilbara area.

PROGRAMME FOR 1977

HYDROGEOLOGY AND ENGINEERING DIVISION

A. Hydrogeology

1. Continuation of the hydrogeological survey of the Perth Basin including deep drilling, test pumping and report on Moora, Eneabba and Quindalup lines and at Irwin View.

2. Hydrogeological investigations and/or exploratory drilling for groundwater in the following areas:
   (a) West Canning Basin—test pumping and report writing.
   (b) Fortescue River area—continuing drilling and testing to assess the calcrete and other aquifers including Fortescue-Robe coastal areas and Millstream-Karratha pipeline.
   (c) Yule, De Grey and Gascoyne Rivers—continuing periodical reassessments.
   (d) East Pilbara—bore census and reconnaissance.

3. Town water supply investigations and/or drilling for the following: Albany, Bunbury, Geraldton and others as required.

4. Hydrogeological investigations for Metropolitan Water Supply Board.
   (a) regional studies.
   (b) deep drilling—Becher Point, Jandakot.
   (c) shallow drilling—Gnangara Mound, Mirrabooka East, Jandakot, Lake Thompson, Keysbrook, and Jandabup.
   (d) study of areas such as Hertha Road/Jones Street, Gnangara liquid waste, Alcoa red mud lake areas, etc. for pollution control.
   (e) study of water balance in coastal lakes.

5. Interdepartmental studies concerning groundwater salinity problems in the Darling Range area.

6. Continuation of bore census of selected areas.

7. Miscellaneous investigations and inspections as required by government departments and the public.

B. Engineering Geology

1. Pilbara area—further investigations of proposed dam sites at Cooya Pooya, Robe, Sherlock and Booyeemala.

2. Gascoyne River—investigations for a 'turkey nest' reservoir site.

3. Darling Range area—continuing investigations on Wungong, South Canning, North Dandalup and Victoria dam sites and Wungong Tunnel, commencing investigations on Marrinup Brook site and safety reviews of existing dams.

4. Miscellaneous investigations as required by government departments including quarry sites for Westrail, advice for Harbours and Rivers Branch of the Public Works Department.

SEDIMENTARY (OIL) DIVISION

1. Maintain an active interest in the progress and assessment of oil exploration and potential in Western Australia.

2. Continuation of the surface mapping and sub-surface study of the Carnarvon Basin including the Ajana, Yaringa, Edel and Wooramel 1:250 000 Sheets.

3. Continuation of geological mapping of the Canning Basin in conjunction with the Bureau of Mineral Resources on the Pender, Broome, La Grange, Mandora, Munro, McLarty Hills, Joanna Springs, Anketell, Paterson Range and Yarri 1:250 000 Sheets.

4. Continue the compilation of Bulletin on further studies of the Devonian reef complexes of the Lennard Shelf, Canning Basin.

5. Revise the Phanerozoic geology of the State for a revision of the 1:2 500 000 geological map.

6. Minor geological investigations as required.

REGIONAL GEOLOGY DIVISION

1. Continuation of the mapping of the Gascoyne Province on the Mount Phillips, Glenburgh and Byro 1:250 000 Sheets.

2. Completion of mapping on the Glengarry Sheet and continuing into the Belele 1:250 000 Sheet.

3. Commencement of mapping on the Mount Barker, Bremer Bay and Newdegate 1:250 000 Sheets.

4. Compilation and completion of the mapping and Bulletin on the Bangemall Basin.

5. Recapitulation and compilation of mapping on the Nabberu Basin and the commencement of a Bulletin.

6. Revision of the Precambrian geology of the State for a new 1:2 500 000 map.

MINERAL RESOURCES DIVISION

1. Maintain records and assess mineral exploration in Western Australia.

2. Completion of a Bulletin on the copper resources of Western Australia.

3. Completion of a Bulletin on the reassessment of the regional and economic geology of the Pilbara Block.

4. Continuation of regional mapping of the Darling Range area on the Pemberton and Perenjori 1:250 000 Sheets and a study of the bauxite occurrence. Also mapping the Precambrian portion of the Ajana Sheet.

5. Commence a regional study of the nickel occurrences in Western Australia for a future Bulletin.

6. Conduct a detailed study of the stratigraphy of the Marra Mamba Iron Formation.

7. Miscellaneous minor mineral investigations as required.

Petrology

1. Carry out petrological investigations as required by other Divisions.
2. Petrological study of the transition between the Gascoyne Province, and the adjacent Yilgarn Block.
3. Petrological study of the transition between the Yilgarn Block and the Albany-Fraser Province near the south coast.
4. A study of the granulite facies in the Collie area.

Palaeontology

1. Carry out palaeontological investigations as required by other Divisions.
2. Continuing a study of the Devonian stromatoporoids from the Lennard Shelf, Canning Basin.
3. Continuing a study of the stratigraphic palynology of the Cretaceous Yarragadee Formation.
4. Commence a detailed palynological study on the Warnbro Group of the Perth Basin.
5. Completion of a study of stromatolites from the Bangemall Basin.
6. Study of the macrofossils from the Carnarvon Basin as required by basin study group.

Geophysics

1. Well logging as required on groundwater drilling projects.
2. Seismic surveys for dam sites at Booyeemala Creek (West Pilbara), Victoria Reservoir, South Canning Spillway and Marrinup Brook.
3. Seismic surveys for groundwater on the De Grey River, Robe River, Albany and Esperance.
4. Trial geophysical surveys over the southern portion of the Darling Fault and also testing the possibility of mapping the subsurface occurrence of Bunbury Basalt.

Geochemistry

1. Continuation of the examination of the nature of the anomalous lead/zinc in parts of the Bangemall Basin.
2. Regional geochemical study of a belt of greenstones located near Mount Saddleback.
3. A study of the mercury content of sulphides in Western Australia.
4. Geochemical study of Mount McRae Shale in the Hamersley Basin.
5. Regional geochemical study of the Mundaring batholith.

Environmental Geology

1. Compilation of urban geology 1:50 000 mapping completed on the Dampier-Roebourne area.
2. Commencement of urban studies and mapping in the Port Hedland area.
3. A study of sand resources in the Perth metropolitan area.
4. Attend to environmental geological problems as required.

PUBLICATIONS AND RECORDS

Issued during 1976

Annual Report, 1975.

Geological map of Browne 1:250 000 Sheet (SG/51-8 International Grid) with explanatory notes.

Geological map of Madley 1:250 000 Sheet (SG/51-3 International Grid) with explanatory notes.

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Geological map of Kalgoorlie 1:1 000 000 Sheet (SH/51 International Grid).

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Geological map of Edjudina 1:250 000 Sheet (SH/51-6 International Grid) with explanatory notes.

Geological map of Lake Johnston 1:250 000 Sheet (SI/51-1 International Grid) with explanatory notes.

Geological map of Laverton 1:250 000 Sheet (SH/51-2 International Grid) with explanatory notes.

Geological map of Leonora 1:250 000 Sheet (SH/51-1 International Grid) with explanatory notes.

Geological map of Minigwal 1:250 000 Sheet (SH/51-7 International Grid) with explanatory notes.

Geological map of Plumridge 1:250 000 Sheet (SH/51-8 International Grid) with explanatory notes.

Geological map of Rason 1:250 000 Sheet (SH/51-3 International Grid) with explanatory notes.

Geological map of Ravensthorpe 1:250 000 Sheet (SI/51-5 International Grid) with explanatory notes.

Geological map of Vernon 1:250 000 Sheet (SH/52-1 International Grid) with explanatory notes.

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J. H. Lord,
Director.

22nd February, 1977.

THE HYDROGEOLOGY OF THE MIRRABOOKA EAST AREA, PERTH

by A. D. Allen

ABSTRACT

The Mirrabooka East area is underlain by a complex sequence of ?Pliocene-Holocene surficial formations resting unconformably on the Early Cretaceous Osborne Formation. The base of this sequence consists of sand up to 90 m thick in a north-south channel, 1 to 3.5 km wide eroded into the Osborne Formation. This is overlain by a more extensive sequence of beds 27 to 52 m thick which are mainly sandy in the northwest and which interfinger with predominantly clayey beds in the east and south. A complex southeasterly flowing groundwater system directly recharged from rainfall occurs in the surficial formations. Where it meets the clayey beds it is split into an upper non-pressure system discharging via springs and soaks, and a lower pressure system which probably discharges into the Swan River. Throughflow in the area is conservatively estimated to be 7.5 x 10^6 m^3/y. The groundwater ranges in salinity from 130 to 400 mg/l TDS but will require treatment for pH, turbidity, colour, and iron before use in public water supply.

INTRODUCTION

PURPOSE AND SCOPE

The Metropolitan Water Supply Sewerage and Drainage Board (MWB) abstract shallow unconfined groundwater for the Mirrabooka Scheme, immediately to the west of the Mirrabooka East area. The scheme has a maximum capacity of 12.5 x 10^6 m^3/y, but considerably more water is needed to meet the current and future demands of the service area.

It was known from previous exploratory drilling and from private boreholes, that the surficial formations from which the Mirrabooka Scheme draws its groundwater supplies became more clayey in an easterly direction. They are therefore likely to yield smaller supplies of groundwater.

An exploratory drilling programme to define the eastern limit of an expanded production borefield was carried out by the MWB in collaboration with the Geological Survey. The results of this investigation are described in the present paper.

LOCATION AND TOPOGRAPHY

The Mirrabooka East area is situated about 17 km northeast of Perth. It is bounded to the north by Gnangara Road; to the south by Marshall Road; and to the east and west by Beechboro and West Swan Roads respectively (Figs. 3 and 6).

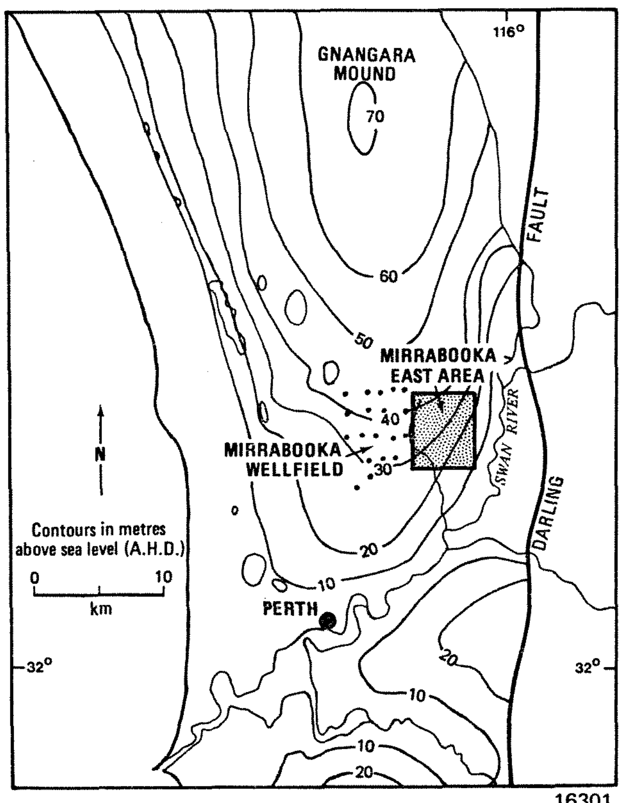

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Figure 3. Location map of the Mirrabooka East area.

The area is about 40 km^2 in extent and slopes down towards the southeast. It has an elevation of about 45 m near Gnangara Road falling to about 20 m along West Swan Road. The topography is relatively smooth above the 30 m contour but becomes uneven and dissected at lower elevations. Unlike most other areas of the coastal plain it is incised by several poorly defined drainage systems, the largest of which is Bennet Brook.

Along the drainage systems there are important wetland areas which total 15 km^2 in extent. In their natural state they support dense scrub, rushes or paperbark trees. They may be subject to flooding in the winter, while in the summer the water table is less than 1 m below the surface. Where the wetlands have been cleared for pastoral purposes they are usually traversed by a system of shallow open drains connected to the main drainage lines and support dense pasture.

CLIMATE

The climate is Mediterranean in character with a cool wet season from May to September and a warm dry season from November to March, with transition periods in April and October (Anon, 1969).

The average annual rainfall based on rainfall records from Henley Park and Caversham (Table 1) is about 855 mm of which about 90% falls between April and October. The hottest month is February when the mean maximum temperature is 31.9°C and the coolest month is July when the mean maximum temperature is 18.1°C. The average annual evaporation interpolated from Bureau of Meteorology maps is about 1 778 mm or about twice the annual average rainfall.

TABLE 1. AVERAGE MONTHLY RAINFALL AT CAVERSHAM AND HENLEY PARK

	Yrs	J	F	M	A	M	J	J	A	S	O	N	D	Year
Caversham, 1917–1955	38	6	10	17	49	120	179	171	139	94	53	20	12	857 mm
Henley Park, 1913–1963	47	8	13	19	44	117	173	177	131	77	54	24	13	850 mm

PREVIOUS WORK

The hydrogeology of the area was first described by Morgan (1964a, 1964b) who proposed an informal subdivision of the stratigraphy of the surficial formations and who gave a general account of the groundwater occurrence. Bestow (1970a, 1970b, 1971a, 1971b) presented a water table map covering part of the area and calculated the water balance and analyzed pumping test results from the adjacent Mirrabooka area. Later Balleau (1972a, 1972b, 1973) reanalyzed the pumping test data from Mirrabooka and noted wide areal variations in rainfall recharge on the northern and western fringes of the area. Allen (1976) gave a regional account of the hydrogeology of the coastal plain including generalized data for the area.

DRILLING AND SAMPLING

Twenty exploratory bores varying from 40 m to 80 m in depth and having an aggregate depth of 1 220 m were drilled between November 1975 and March 1976. The bores were drilled along four east-west lines, five bores per line, and about 1 km apart. The lines are about 2 km apart and form extensions to the existing lines of Mirrabooka Scheme production bores (Fig. 3).

The bores were numbered in sequence with the bores of the Mirrabooka Scheme and are distinguished from the Mirrabooka bores by the prefix ME (Mirrabooka East). The apparently inconsistent number ME81 results from the fact that there is already a bore Mirrabooka 90 (M90) in the Mirrabooka Scheme.

The drilling was done by two contractors using cable-tool drilling rigs. Each contractor drilled ten sites along two lines proceeding along each line from west to east.

During drilling, samples were collected at 2 m intervals for geological logging and sieve analysis. At the completion of drilling or after the bores had been cased and completed they were geophysically logged (gamma ray) to assist correlation between bores and to define bed boundaries.

The bores were cased with 75 mm class 9 PVC casing slotted through the saturated thickness of the "superficial formations" or the "channel sand" (described later) if it was encountered. An exception to this procedure was ME190 which was accidently left slotted in the Osborne Formation.

Graded gravel was used to fill the annulus between the borehole and the casing as the working steel casing was withdrawn. The use of the gravel envelope was to support the walls of the bore and to minimize clogging of the slots in the casing. After the gravel had been put into place the bore was bailed for 2 hours to settle the gravel envelope and to obtain an initial water sample for analysis. The PVC casing was left projecting about 0.3 m above the surface and for protection a short length of steel casing fitted with a hinged cap was sleeved over it and set in a cement block.

After completion of the bore the natural surface and reference points on the steel casing were levelled to an accuracy of 0.001 m. Further water samples were later collected with a portable submersible pump which yielded water at rates of up to 3.78 l/sec. The pump was operated for periods of 15 minutes to 2 hours depending on the drawdown. The bores were then left, and water levels in them measured at monthly intervals.

A summary of the drilling data is given in Table 2, and analyses of water samples are given in Table 4. Bore logs are available on file at the Geological Survey or the Metropolitan Water Board; sludge samples are stored at the Survey core library, and water level data are available from the Water Board's water levels retrieval system (GROWLS).

TABLE 2. SUMMARY OF BORE DATA

Bore No.	Commenced	Completed	R.L.n.s. m A.H.D.	R. L. steel casing m A.H.D.	R.L. P.V.C. casing m A.H.D.	Depth (m)	Slotting (m)	R.L. R.W.L. (m)	Date	Base Superficial Formations (m)	Underlying formation
50	1/12/75	4/12/75	37·329	38·121	....	46	0–46	28·66	9/3/76	42·0	Osborne Fm
60	8/12/75	11/12/75	25·222	25·859	25·684	40	0–32	23·44	9/3/76	Not reached	....
70	12/12/75	5/1/76	20·378	21·472	21·432	80	40–80	20·65	9/3/76	31·5	Channel sand
80	20/11/75	26/11/75	21·200	22·240	....	60	30–60	20·51	9/3/76	29·5	Channel sand
81	8/1/76	19/1/76	21·485	22·187	22·141	80	0–22	19·49	9/3/76	27·0	Osborne Fm
150	2/12/75	8/12/75	36·189	36·628	....	45	0–42	31·94	8/3/76	42·0	Osborne Fm
160	1/12/75	15/12/75	31·835	32·216	....	60	0–60	28·75	8/3/76	37·5	Channel sand
170	17/12/75	22/12/75	29·225	29·995	....	65	40–65	25·91	8/3/76	37·5	Channel sand
180	9/12/75	18/12/75	29·408	29·780	....	71	44–66	24·94	8/3/76	41·0	Channel sand
190	22/12/75	7/1/76	24·017	24·483	24·495	60	32–60	24·04	8/3/76	28·5	Osborne Fm
250	22/1/76	30/1/76	39·251	39·866	39·738	70	0–50	36·43	8/3/76	47·5	Osborne Fm
260	4/2/76	15/2/76	41·880	42·609	42·451	80	50–80	31·61	8/3/76	49·0	Channel sand
270	19/2/76	26/2/76	36·760	37·510	....	66	44–66	32·09	8/3/76	46·5	Channel sand
280	1/3/76	6/3/76	35·440	36·160	....	60	46–60	n.a.	....	42·0	Channel sand
290	11/3/76	15/3/76	33·620	34·360	....	41	0–25	n.a.	....	24·5	Osborne Fm
350	5/1/76	9/1/76	45·261	45·574	....	60	0–48	42·04	5/3/76	52·0	Osborne Fm
360	12/1/76	16/1/76	44·562	44·909	....	60	0–48	41·33	5/3/76	47·0	Osborne Fm
370	21/1/76	28/1/76	43·825	44·249	43·830	60	48–60	34·31	5/3/76	50·0	Channel sand
380	30/1/76	4/2/76	41·507	41·894	41·712	60	0–45	39·42	5/3/76	44·0	Osborne Fm
390	6/2/76	13/2/76	42·049	42·513	42·234	56	0–42	36·85	5/3/76	51·0	Osborne Fm

n.s. natural surface A.H.D. Aust. Height Datum R.W.L. Rest water level

GEOLOGY

STRATIGRAPHY

The Mirrabooka East area lies towards the eastern edge of the Perth Basin. It is underlain by more than 7 500 m of sedimentary rocks (Jones and Pearson, 1972) of which only the ?Pliocene-Holocene surficial formations 30 to ?200 m thick are of immediate concern.

The presently accepted subdivision of the surficial formations is based on surface geological mapping and limited borehole data (Playford and others, in press). However the subsurface geology of these formations is more complex than suggested by the mapping and for this reason it is preferred to recognize a bipartite division of the ?Pliocene-Holocene formations into the "channel sand" and the "superficial formations". In addition, the fact that the ?Pliocene-Holocene formations form a single aquifer system is a further justification for simplifying the nomenclature.

The stratigraphic subdivisions used in this report are given in Table 3, and are described separately below.

TABLE 3. STRATIGRAPHIC SEQUENCE

Formal age	Formation	Maximum thickness (m)	Lithology	Remarks
Quaternary-Late Tertiary	'Superficial formations'*	60	Sandy calcarenite, fine sand, feldspathic coarse sand, sandy clay, medium sand	Mapped as Bassendean Sand and Guildford Formation; becoming more clayey in east and south of area
			? UNCONFORMITY	
? Late Tertiary	'Channel sand'*	50+	Fine-medium slightly silty well sorted sand	Unnamed formation, possibly equivalent to the Rockingham Sand
			? UNCONFORMITY	
Early Cretaceous	Osborne Formation	150	Green glauconitic sandy siltstone, black sandy slightly glauconitic shale	Forms basement to 'channel sand' and 'superficial formations'

* Informal names used in this paper

Osborne Formation

The Osborne Formation (McWhae and others, 1958) consists of a green, glauconitic, sandy siltstone with minor beds of fine glauconitic sand, and glauconitic, black sandy shale. It is about 150 m thick and is unconformably overlain by the "channel sand" and the "superficial formations". The Osborne Formation was deposited in a marine environment and, based on micro-plankton studies, is of Early Cretaceous Cenomanian-Albian age (Cookson and Eisenack, 1958).

"Channel Sand"

The name "channel sand" is an informal name used here for a sequence of light-grey or greenish-grey fine to coarse, well-sorted sand. This contains minor layers of silty sand, pyrite-cemented sand, and frequent heavy mineral and glauconite grains. The unit unconformably overlies the Osborne Formation and infills a deep channel 1 km to 3.5 km wide to which it is apparently restricted. It is disconformably overlain by the "superficial formations" and is 91.5 m thick in Pacminex No. 1 bore and 67.5 m thick in MWB Whitfords Line No. 4 bore. The degree of sorting of the sands, the presence of heavy minerals, and absence of alluvial sediments indicate that the formation was deposited in a marine environment, possibly a submarine channel. The glauconite and many green-stained quartz grains present in the beds are probably derived from the Osborne Formation.

Beds belonging to the "channel sand" were first described by Morgan (1964a) from Gnangara No. 7 bore and later by Barnes (1971) from Pacminex No. 1 bore. The age of the beds is uncertain. Edgell (1963) examined samples from Gnangara No. 7 bore and concluded on the basis of contained spores and pollens that they were of Quaternary age, although the possibility of contamination could not be excluded. Subsequently other samples taken from the beds have proved barren.

The beds have lithological similarities (apart from a difference in colour, produced by the weathering of glauconite) with the Rockingham Sand (Passmore, 1970).

"Superficial formations"

The name "superficial formations" includes all the Late Tertiary-Quaternary sediments with the exception of the "channel sand". They consist of several units separated by disconformities. At the base is a discontinuous bed of yellow-brown to grey, sandy calcarenite, overlain by light grey and green, fine and very coarse bimodal sand containing local concentrations of heavy minerals. This in turn is overlain by beds of grey, medium-coarse feldspathic sand which interfinger to the east with beds of clay, and clayey sand. Finally this unit is overlain by a light grey, fine to medium sand interbedded with a few thin layers of clay or clayey sand. A layer of limonite-cemented sand of variable thickness is developed throughout the area at the water table. This is referred to as "coffee rock".

The "superficial formations" unconformably overlie the Osborne Formation, and are believed to overlie the "channel sand" disconformably. However the possibility exists that this sand was deposited after the basal calcarenite was laid down and subjected to erosion.

The "superficial formations" range from ?Pliocene to Holocene in age (Playford and others, in press).

STRUCTURE

The Osborne Formation dips gently to the west and forms a basement to the overlying "channel sand" and "superficial formations". Locally it has been deeply eroded to produce a northerly trending submarine channel infilled with predominantly sandy sediments. Elsewhere the basement is overlain by a sequence of flat-lying younger sediments about 40 m thick. Sections illustrating the structure are given in Figure 4.

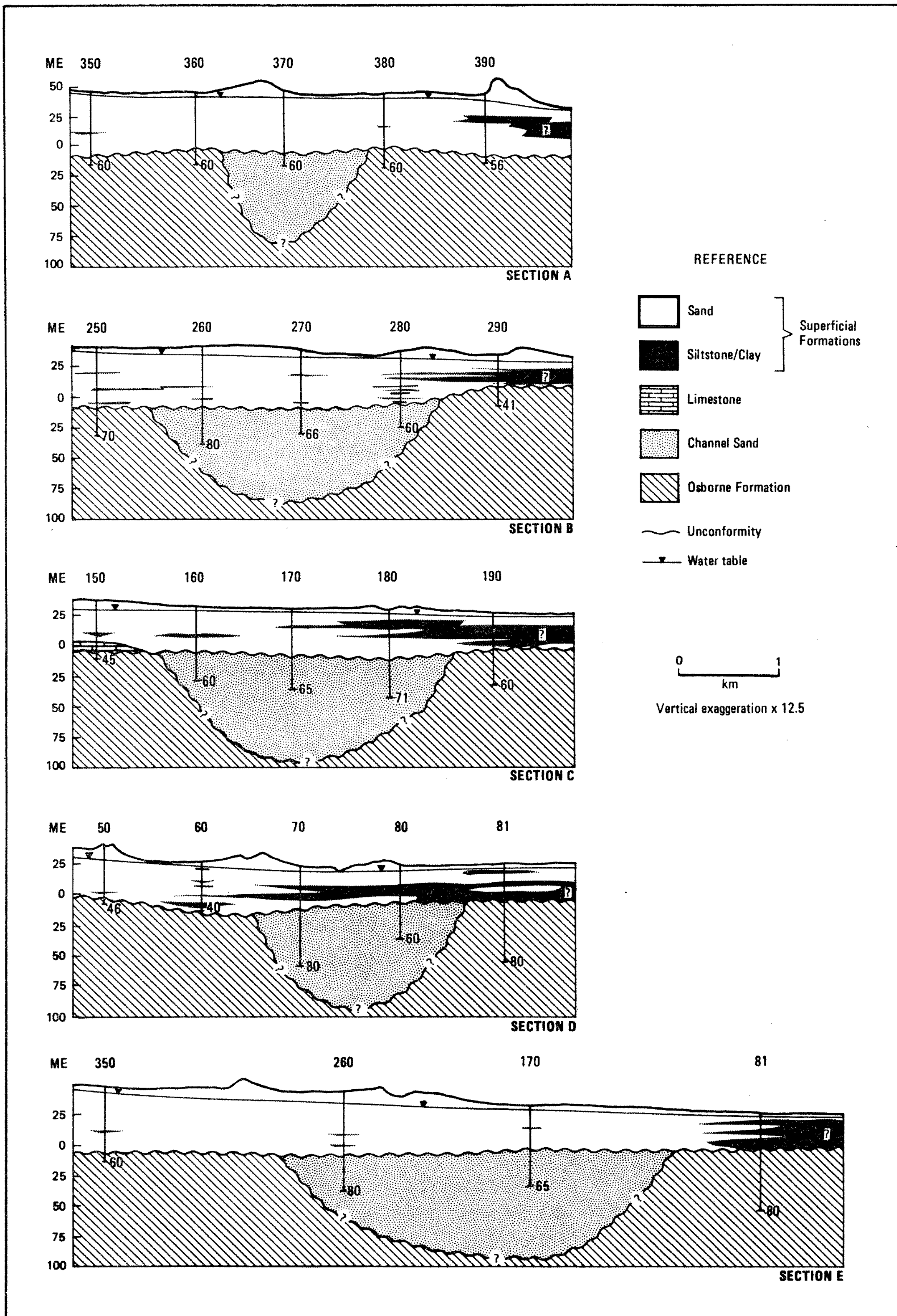

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Figure 4. Cross sections showing structure.

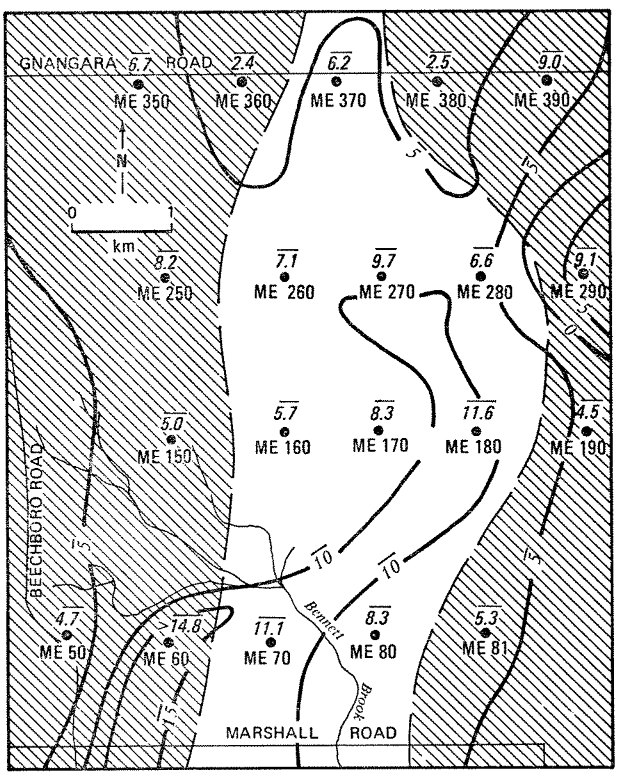
HYDROLOGY

SETTING

The Mirrabooka East area is situated in the south-eastern corner of the Gnangara Mound (Fig. 3) which is a regional body of generally unconfined groundwater (Allen, 1976) occurring in the "superficial formations" and "channel sand". The groundwater originates from rainfall recharge and moves under gravity to be discharged at the boundaries of the flow system, formed by the sea and the major rivers situated around the periphery of the mound. Discharge is also by evapotranspiration from wetlands and vegetation; by downward leakage into underlying formations; and by drainage works and groundwater usage.

GROUNDWATER FLOW SYSTEM

A major groundwater flow system occurs in the "superficial formations". It is in hydraulic connection with flow systems in underlying formations.



REFERENCE

Channel Sand

Osborne Formation

6.7 Bore R.L. contact, metres above and below A.H.D.

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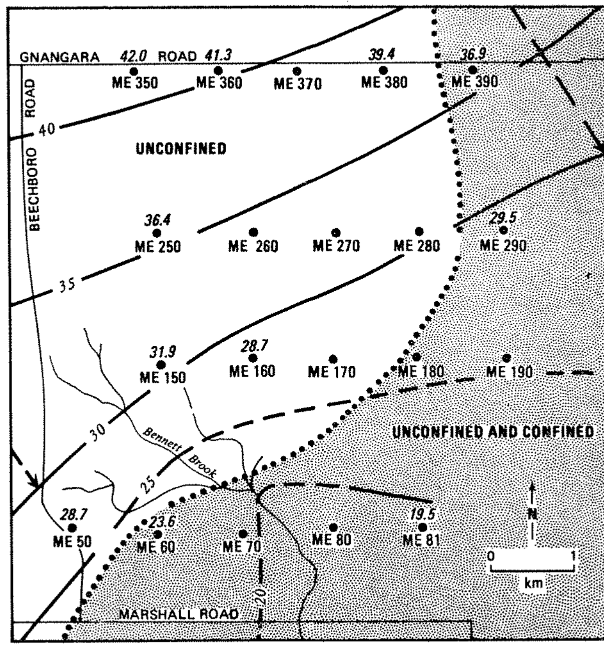
Figure 5. Subcrop map and contours on base of superficial formations.



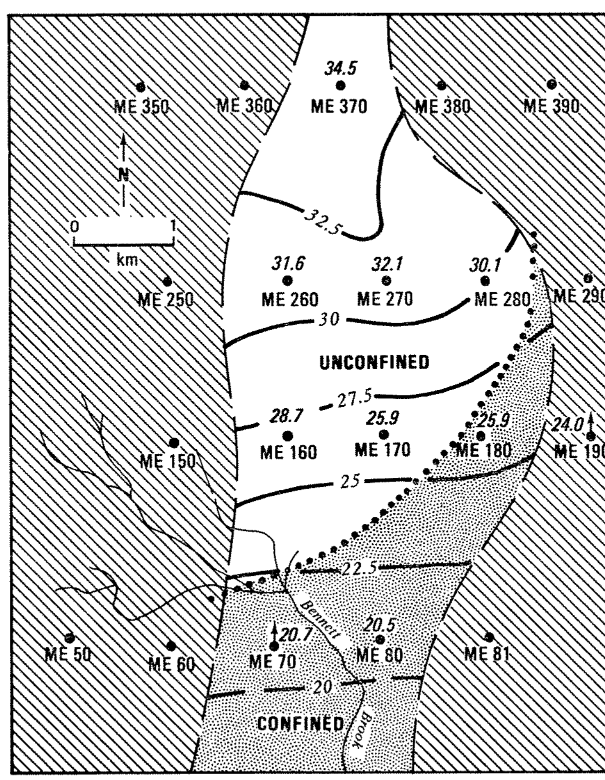
REFERENCE

36.9 ME 390 Bore with R.L. of water table, metres A.H.D.

Bounding flow lines for through flow calculation

16304

Figure 6. Water table contours (metres), March 1976.



REFERENCE

31.6 ME 260 Bore with R.L. of potentiometric surface, metres A.H.D.

ME 190 Artesian bore

16305

Figure 7. Isopotential contours (metres) for channel sand, March 1976.

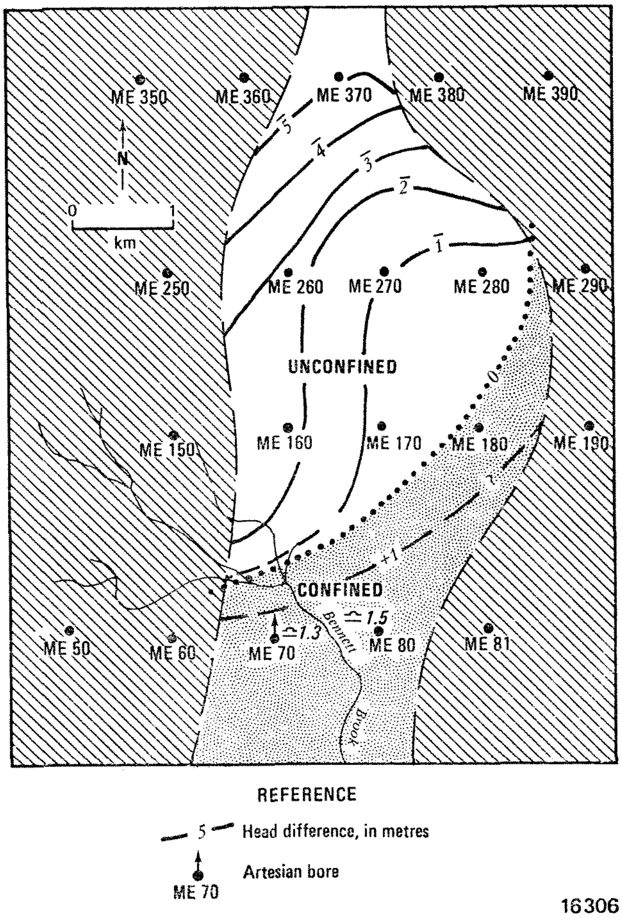


Figure 8. **Difference in head between the isopotential surface (channel sand) and the water table, March 1976.**

"Superficial formations" flow system

The configuration of the water table based on data from eleven of the bores for March 1976, is given in Figure 6. Because of the relative sparseness of control points the map is necessarily generalized, in particular, adjacent to the drainage lines where the water table contours must be more complex than shown, and also in the vicinity of the 20 m topographic contour where the water table and the surface contours converge and steep groundwater gradients must occur.

The water table contours show that the groundwater flows in a general southeasterly direction and has a gradient of about 3 m per kilometre. In the northwest of the area where the "superficial formations" consist predominantly of sand the groundwater is unconfined. However toward the east and south where the "superficial formations" become predominantly clayey (Section C, Fig. 4) the groundwater flow system is effectively split into an upper unconfined flow system in relatively thin beds of sand resting on the underlying beds of clay, and a confined system within and beneath the clayey beds.

In addition to splitting the flow system the "superficial formations" are less permeable and considerably thinner as a result of the decrease in topographic elevation (Section E, Fig. 4). Together these factors reduce the transmissivity of the "superficial formations" with the result that only a small proportion of the throughflow is transmitted, presumably to be discharged in the Swan River, while the rest is discharged into springs and soaks where it is lost by evapotranspiration or run-off.

"Channel sand" flow system

The groundwater flow system in the "channel sand" is in hydraulic continuity with those in the "superficial formations" and in the Osborne Formation. It is unconfined except where it is overlain by beds of clay in the "superficial formations" in the southern part of the area (Fig. 7).

The configuration of the isopotential surface in the "channel sand" groundwater system (Fig. 7) is based on data from nine bores slotted to varying depths in the upper 50 m of the "channel sand". It slopes downward in a southerly direction more or less at right angles to the long-axis of the channel, and has a gradient of about 2.9 m per kilometre.

The elevation of the water table and the potentiometric head in the "channel sand" groundwater system show considerable variation over the area. The head differential between the two surfaces drawn by overlaying Figures 6 and 7 is given in Figure 8. This shows that in the northern part of the area the head in the "channel sand" is about 5 m lower than in the "superficial formations" while in the southern part of the area it is several metres above the water table. The convergence and crossing over of the potentiometric surface in the "channel sand" with the water table takes place in the zone of transition between sandy and clayey "superficial formations" (Fig. 6).

Osborne Formation flow system

Although the Osborne Formation is composed mainly of siltstone and shale it does contain some minor beds of sand. These, and perhaps to a limited extent the siltstones, transmit small quantities of groundwater.

Bore ME190 was accidently left cased in the Osborne Formation. The bore flowed and was found to have a head comparable with that in the "channel sand". This probably results from the interception of minor permeable zones in the formation which are in hydraulic continuity with the "channel sand" in the west (Fig. 4, Section C).

GROUNDWATER RESOURCES

The complexity of the flow systems in the "superficial formations", "channel sand" and Osborne Formation, together with lack of data on stream flow, and evapotranspiration, make it impossible to prepare a reliable water balance for the area. Therefore the indicated groundwater resources are estimated by calculating throughflow for the area. These calculations are also approximate because of downward head potentials above the "channel sand" and convergence of flow lines around drainage lines and discharge areas.

The throughflow in the "superficial formations" is estimated across the 30 m groundwater contour (Fig. 6). This was chosen because it is well controlled by borehole data; because in this area the "superficial formations" are predominantly sandy; and because the downward head potential relative to the "channel sand" is minimal.

The annual throughflow (Q) was estimated from the following form of the Darcy equation:

$$Q = 365 \times T \times I \times L \qquad \ldots\ldots \quad (1)$$

where T is the transmissivity
I is the hydraulic gradient
L is the width of the flow cross section.

The transmissivity is estimated to be the adopted average hydraulic conductivity for the Gnangara Mound of 15 $m^3/d/m^2$ (Allen, 1976) multiplied by the average saturated thickness (35 m) obtained by comparison of Figures 5 and 6. The gradient was measured along nine equally spaced flow lines, averaged, and found to be 1:310. The width of the flow section spanning the proposed borefield is 8 km (Fig. 6).

Solving equation (1) for the given values:

$$Q = \frac{365}{1} \times \frac{15}{1} \times \frac{35}{1} \times \frac{1}{310} \times \frac{8\,000}{1}$$

$$= 4.945 \times 10^6 m^3/y$$

$$= \text{Say } 5 \times 10^6 m^3/y.$$

The throughflow in the "channel sand" cannot be accurately determined from available hydraulic data. However the order of magnitude may be derived by making the following assumptions: (1) flow past the 22.5 m isopotential contour is planar with a gradient of 7.5:2 500 (Fig. 7); (2) the channel is 95 m deep (based on Pacminex No. 1) and 2 400 m wide (i.e. rectangular in cross section); and (3) that the hydraulic conductivity of the "channel sand" is 10 $m^3/d/m^2$.

Substituting assumed and derived values in equation (1) and solving:

$$Q = \frac{365}{1} \times \frac{10}{1} \times \frac{95}{1} \times \frac{7 \cdot 5}{2\,500} \times \frac{2\,400}{1}$$

$$= 2.496 \times 10^6 \ m^3/y$$

$$= \text{Say } 2.5 \times 10^6 \ m^3/y.$$

Summing the throughflow calculations the indicated throughflow for the area is about 7.5×10^6 m^3/y.

GROUNDWATER QUALITY

On completion of each bore it was bailed for two hours, and a sample taken for analysis. Later most of the bores were resampled by pumping with a small submersible pump. The results are given in Table 4.

TABLE 4. WATER ANALYSES

Bore	Lab. No.	pH	Turbidity (APHA units)	Colour (APHA units)	Odour	T.D.S. (evap) mg/l	NaCl mg/l	Cl mg/l	Alkalinity (as $CaCO_3$) mg/l	Hardness (as $CaCO_3$) mg/l	Ca mg/l	Fe mg/l	Free CO_2 mg/l	Remarks
50	26131/75	6·9	....	160	Oily	390	204	124	....	155	....	....	....	Bailed 9/12/75
60	26366/75	6·2	....	320	H_2S	330	165	100	....	85	....	....	....	Bailed 12/12/75
	11127/76	5·6	850	530	Musty	300	160	....	22	....	7	1·3	111	Pumped ½ hour at 2·3 l/s
70	865/76....	6·7	....	20	Oily	270	152	92	....	75	....	....	....	Bailed 13/1/76
	11128/76	5·8	150	10	Nil	170	106	....	25	....	7	0·05	79	Pumped ½ hour at 1·9 l/s
80	25287/75	6·3	....	50	Oily	460	317	192	....	128	....	....	....	Bailed 1/12/75
	10730/76	6·2	14 000	30	Nil	170	101	....	48	....	11	0·10	61	Pumped ½ hour at 2·8 l/s
81	2468/76	7·0	....	50	Nil	340	226	137	....	68	....	....	....	Bailed
	10733/76	5·7	3 800	1 500	Musty	400	138	....	48	....	5	2·4	192	Pumped ½ hour at 3·8 l/s
150	27483/75	6·5	....	125	Oily	310	175	106	....	100	....	....	....	Bailed 9/12/75
	11130/76	5·4	450	130	Nil	240	158	....	15	....	4	0·2	119	Pumped ½ hour at 3·2 l/s
160	26927/76	5·5	....	60	Oily	260	185	112	....	45	....	....	....	Bailed 6/12/76
	11131/76	5·0	< 5	55	H_2S	240	170	....	5	....	3	0·4	100	Pumped ½ hour at 0·3 l/s
170	103/76....	6·8	....	38	Oily	330	213	129	....	104	....	....	....	Bailed 5/1/76
	11132/76	5·5	1 000	35	Nil	160	106	....	15	....	2	2·1	95	Pumped ½ hour at 1·9 l/s
180	27484/75	6·0	....	< 10	Oily	180	109	66	....	63	....	....	....	Bailed 9/12/75
	11133/76	6·3	17 500	30	Nil	170	94	....	53	....	14	1·6	53	Pumped ½ hour at 1·9 l/s
190	1415/76	6·7	10	20	Oily	420	120	73	....	170	....	....	....	Bailed
	11129/76	6·8	95	10	Nil	250	87	....	103	....	22	0·05	33	Pumped ½ hour at 0·3 l/s
250	2467/76	6·4	....	150	Nil	880	410	249	....	248	....	....	....	Bailed
	11203/76	5·4	950	90	H_2S	180	101	....	12	....	4	0·60	96	Pumped ½ hour at 3·8 l/s
260	4255/76	6·5	8 000	< 5	Earthy	280	157	95	60	....	....	....	....	Bailed
270	11204/76	5·4	12 000	100	H_2S	140	97	....	15	....	2	0·80	119	Pumped ½ hour at 1·7 l/s
280	11205/76	5·7	2 000	25	Paraffinic	150	101	....	15	....	2	1·9	60	Pumped ½ hour at 1·3 l/s
290	11206/76	6·2	175	40	Nil	170	110	....	45	....	6	3·5	57	Pumped ½ hour at 2·8 l/s
350	866/75	5·5	....	< 10	Previous contents	500	269	163	....	150	....	....	....	Bailed 13/1/76
	4728/76	5·4	1 400	35	H_2S	170	130	79	15	....	3	0·6	119	Pumped ¼ hour at 3·8 l/s
360	1416/76	6·0	4 500	40	Oily	390	204	124	....	110	....	....	....	Bailed
	4727/76	5·5	3 500	90	H_2S	190	138	84	18	....	3	3·0	114	Pumped ¼ hour at 3·8 l/s
370	2195/76	6·7	....	15	Present	250	162	98	80	....	....	....	....	Bailed 3/2/76
	15712/76	5·6	9 000	21	H_2S	160	115	....	20	....	2	0·37	100	Pumped 5¾ hrs at 0·8 l/s
380	2466/76	6·8	....	100	Present	290	186	113	....	63	....	....	....	Bailed
	4726/76	5·4	2 200	100	H_2S	250	180	109	18	....	4	0·3	143	Pumped ¼ hour at 3·8 l/s
390	4256/76	6·2	4 500	< 5	Earthy	200	119	72	60	....	....	....	....	Bailed
	4725/76	4·7	95	5	Present	130	97	59	3	....	3	0·1	120	Pumped ½ hour at 1·5 l/s

Comparison between the analyses of the bailed samples and the pumped samples shows that the total dissolved solid content of pumped samples is invariably the least. The reason for this may result from the bailing-process sampling a mixture of drilling water and groundwater, or from the fact that the best quality water is obtained from the most permeable bed(s) which also yield most of the water.

Comparison of the analyses from the "channel sand" and "superficial formations" shows that groundwater from the two systems is chemically very similar. However the physical properties of turbidity and colour are somewhat different. The "superficial formations" appear to have a generally higher colour content but lower turbidity than the "channel sand". The colour content is due to the presence of organic compounds which have been observed to occur in the highest concentration near the water table, and to decrease with depth. The turbidity results from the occurrence of kaolin in the aquifers. This varies significantly between different bores in both the "superficial formations" and "channel sand" and it is not possible to generalize about its occurrence.

The range of the more important chemical and physical properties is given in Table 5.

TABLE 5. RANGE OF PHYSICAL AND CHEMICAL COMPONENTS AFFECTING GROUNDWATER QUALITY (PUMPED SAMPLES)

pH	Turbidity APHA units	Colour APHA units	TDS (evap) mg/l	Fe mg/l	Free CO_2 (by calculation) mg/l
		'Superficial formations'			
4·7–6·8	95–900	5–1 500	130–400	0·05–3·5	33–192
		'Channel sand'			
5·0–6·3	10–17 500	<5–100	140–280	0·05–2·1	53–119

The data show that the water would need correction for pH, and treatment for turbidity, colour and iron before it could be used in a public water supply scheme.

DEVELOPMENT

The drilling programme has defined the easternmost extent of prospective sections of the "superficial formations." Thus the lithology at ME60, 70, 80, 81, 190 and 290 is not suitable for the construction of production bores in the "superficial formation", whereas they can be established at the remaining sites.

The lithology of the "channel sand" suggests that production bores could obtain economic yields of water from this formation, at sites ME70, 80, 160, 170, 180, 260, 270, 280 and 370. Confined conditions occur at ME70, 80 and 180, and abstraction at these sites may lead to mutual interference. A further complication is that the channel walls may behave as barrier boundaries and large drawdowns could be experienced in these production bores.

The presence of the "channel sand" provides a degree of flexibility to the proposed groundwater scheme. Should production bores in the "superficial formations" produce unacceptable water table drawdowns, bores in the "channel sand" could be used. They would produce water mainly from the "channel sand", as well as some water by induced downward leakage from the "superficial formations". However because of stratification the effect of this is expected to be smaller and more widespread than for abstraction directly from the "superficial formations".

Any pumping scheme based on the "superficial formations" will draw water from storage, underflow, and from the direct infiltration of rainfall. The effect will be to cause a small but widespread lowering of the water table and a reduction of spring flow which will cause a contraction of seepage areas. However such abstraction will probably have no effect on swamps in the low lying areas in the south and east which are maintained by essentially perched groundwater.

The lowering of the water table will cause a substantial decrease in transpiration losses (Bestow, 1971a) so that considerably more water than suggested by the underflow calculations can be abstracted.

CONCLUSIONS

The occurrence of groundwater in the Mirrabooka East area is complicated by the geology. A large proportion of the area is the site of groundwater discharge, where groundwater is lost by evapotranspiration or discharged via surface drains into the major streams.

The effect of a groundwater scheme would be to utilize this otherwise unused groundwater. Any undesirable effects caused by an expected widespread but small lowering of the water table could be offset to some extent by utilizing the "channel sand".

Based on conservative throughflow calculations at least 7.5 x 10^6 m^3/y of groundwater can be obtained from the area. A small lowering of the water table and clearing for pasture will substantially decrease evapotranspiration losses with the result that considerably more water than indicated by the throughflow calculation can be obtained.

Groundwater from the area would be suitable for public water supply after treatment.

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WUNGONG DAM – THE INFLUENCE OF ENGINEERING GEOLOGY STUDIES

by E. P. O'Driscoll and G. W. A. Marcos

ABSTRACT

Wungong dam site in the Darling Range is underlain by an Archaean basement complex. Starting in 1922, geological investigations continued intermittently until 1975, when construction began. Initially planned as a concrete structure, for engineering reasons this was changed to earth fill. As a result of detailed geological investigations, the centre line was moved and rotated to avoid a landslip area; the spillway was relocated on the opposite bank to reduce foundation difficulties; the control tower was moved for a similar reason; and the design finally adopted was for a composite earth and rock fill structure with a clay corewall. Predicted subsurface geological conditions proved remarkably reliable, despite poor outcrops which necessitated more than usual use of exploratory drilling and seismic refraction.

LOCALITY

Originally referred to as Lower Wungong Damsite, Wungong Dam is on Wungong Brook about 32 km south-southeast from Perth (Fig. 9).

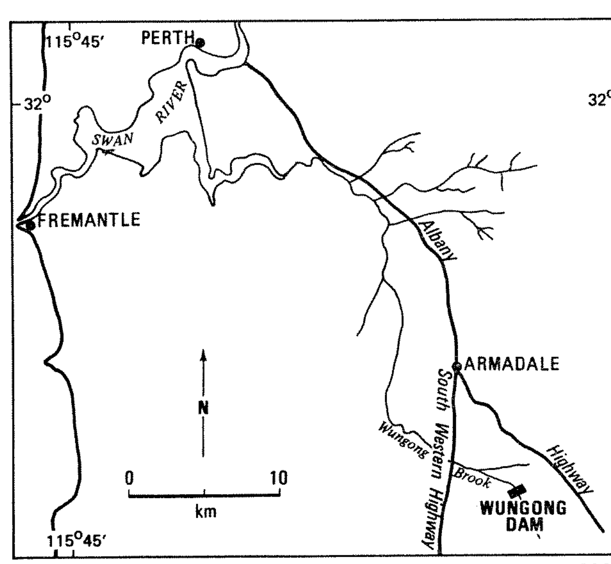

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Figure 9. Locality plan, Wungong Dam.

GEOLOGY

ENVIRONMENT

The geological environment is the usual one for a dam in the ranges close to the Darling Fault. The country rock consists of Archaean igneous and metamorphic rocks intruded by variably dipping mafic dykes, the whole having once formed part of a peneplain covered by laterite. Beneath the laterite is a zone of weathered rock which may be as much as 30-35 m thick, predominantly of sandy kaolinitic material, the depth to its base having been controlled

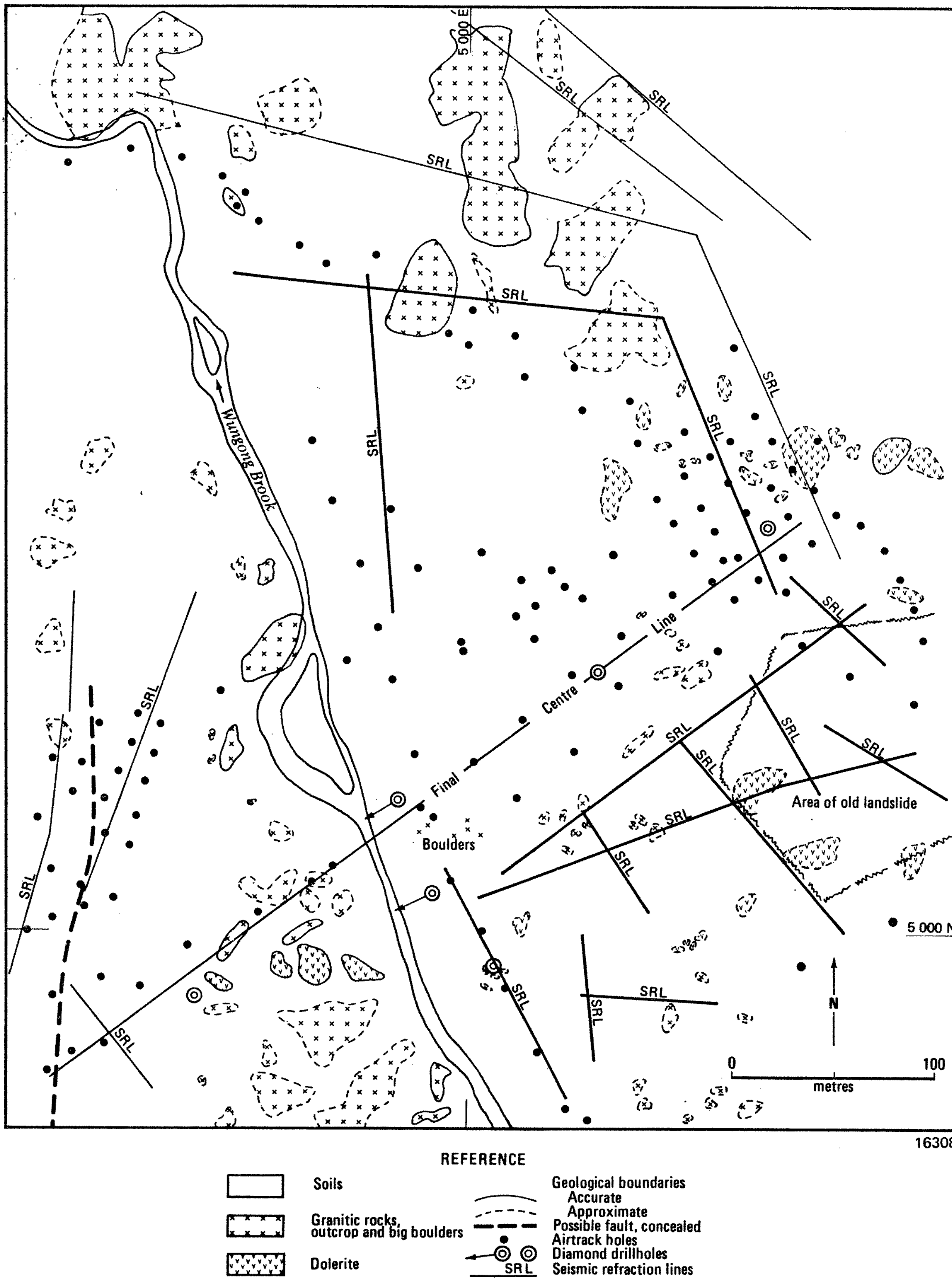

Figure 10. Site plan showing outcrop, geophysical traverses, and drillholes.

during weathering by the existence of sheet or pressure-relief joints. Although much has been removed by subsequent erosion, the valley flanks and floors are still fairly extensively covered by colluvium and slope wash, which conceal the underlying rocks and make factual mapping difficult. The weathered material varies in mineralogical composition even over short distances, depending on the nature of the parent rock and other factors. Its engineering properties also differ, necessitating careful investigation of borrow areas for suitable spoil, and supervision of its excavation.

Because of the poor exposure of basement rock at the site of the structure, a common difficulty in the Darling Range, field investigation must include more subsurface probing by drilling and geophysics than is usually the case.

ROCK TYPES

The Archaean basement rock comprises banded granitic gneiss, migmatitic gneiss and even-grained granite, with minor pegmatite and quartz veins. Deciding on a suitable name for common reference in itself is a difficulty, because the rock is not always gneissic or even granitic. Around Wungong the granitic phase is tonalitic, while the origin of the migmatite is obscure. The physical properties of the hard rocks and the overlying weathered material vary from site to site in ways important to the engineer, and at each new structure it is necessary to decide on a name for reference, and specify in some detail the types of rock to which this name refers. Furthermore, to avoid misunderstanding it sometimes has been found desirable to use a different name even for fairly similar suites of rocks, when investigators and design engineers move their attention from one area to another. At Wungong the term "granitic rock" has been adopted.

Doleritic dykes are common, varying in width from a few centimetres to possibly 50 m or so. They pose a nomenclature difficulty because the rock is usually a metadolerite, quite often with relatively abundant free quartz. Many dykes appear to have been injected along almost vertical joint planes, narrow intrusions sometimes being offset along minor joints, but they may also unpredictably cut across the present joints, or unexpectedly divide. Being well jointed, narrow dykes tend more readily than the country rock to be softened by weathering, especially at locations where they intersect. This necessitates prediction of stability problems for concrete structures such as at the original site of the Wungong inlet tower; or the increase in the volume of excavation in a small area, when hard basement is needed beneath a foundation.

ROCK STRUCTURE

Structurally the granitic rock usually has a southeasterly foliation with a westerly dip, the variable joints having a predominantly northeasterly master direction. Shearing has been superimposed, so that in some places the rock is closely fractured.

In both granitic and doleritic rocks it was difficult to determine from surface outcrops just what the joint patterns and frequencies were, and therefore to predict rock strengths and excavation characteristics. Even the sheet joints were found to be more strongly developed in the right bank than the left, and to occur as deeply as 22 m below the top of the hard rock.

GEOLOGICAL INVESTIGATIONS

Concrete wall

Geological studies for the building of a concrete structure in the general area were spasmodically conducted from 1922 to 1952. They included three diamond drillholes and 78 pits, but the geological structure was still unresolved and no centre line had been selected (of four being considered) when investigations were discontinued. They were not resumed until 1960, when construction methods and materials had changed. The use of earth or rock fill and other alternatives to concrete meant that design engineers needed rather different and in some ways more comprehensive geological information about foundation conditions, and the availability of materials (Fig. 10).

Earth fill wall

A centre line for an earth fill dam had to be tentatively chosen; and the thickness, nature, and state of consolidation of the subsoil became important, because whereas a rigid concrete wall would be keyed into hard rock, much of the weathered zone material could possibly be left unexcavated beneath the foundations of a homogeneous earth fill structure. On the other hand, possible leakage could be more critical beneath the structure or around the flanks. Because the straight course of the river along its deeply incised valley might have been fault-controlled, the possibility of leakage along a shatter zone crossing beneath the wall existed for any type of structure. This was therefore checked by two inclined diamond drillholes, which detected no zone of weakness.

For the earth fill structure a large volume of suitable clayey materials would be needed for the wall and its impermeable core, and its availability from borrow areas below full supply level and within economic transport distance had therefore to be investigated by drilling. Dimension stone would also be required as protection for the wall face, which meant finding a suitable quarry site nearby.

Recent experience has shown that some of the weathered material overlying basement rock is unsuitable for use, its physical properties especially when emplaced as compacted fill being adversely affected by the presence of minerals such as halloysite and mica. Because some *in situ* soils might not be removed by excavation, but left in place to form part of the foundations, careful sampling by drilling beneath the wall area would be needed.

From 1960 to 1965, a renewed and more intensive investigation of the wall area was continued along a specific centre line, including geologic mapping, hammer seismic traverses, auger and diamond drilling, and soil sampling for laboratory tests. This disclosed a substantial variation in the thickness of weathered material suitable for leaving undisturbed beneath an earth fill structure; and also that the volume of fill could be reduced if the centre line were slightly rotated and moved less than 100 m upstream. A new centre line was therefore adopted.

At this stage the investigation was interrupted, work being transferred to a site on the South Dandalup River where a dam was subsequently constructed.

Work was resumed at Wungong in 1972, and the geological conditions beneath the wall, the control tower, and the proposed spillway on the left bank were now examined in detail, particular interest being centred on the depth to hard rock and the variations in the nature of the overburden.

Earlier attempts to supplement exploratory drilling by seismic work had been unsuccessful because of the very shallow depth which could be probed by hammer seismic methods. More sophisticated seismic refraction equipment was now available, and proved very valuable in use, enabling a reasonably accurate assessment to be made of bed-rock depths along the length of each traverse. In critical areas such as the spillway centre line, the method was capable of indicating deep bed-rock depressions of limited area, whose presence would have remained undetected by drilling except on an uneconomically closely spaced grid.

As information accumulated, the siting of the traverse lines and of the supplementary drillholes was under constant review by the geologist.

Seismic refraction methods were found to be capable of indicating the probable depth of the contact between slopewash and the underlying soft weathered bedrock material which was in an undisturbed state and could be left in place. Seismic methods had an important advantage over drilling, which was much slower because each bore always had to be continued on for 3 m or so into hard rock to ensure that the drill hole had not encountered a boulder, or an unweathered kernel of hard rock rather than true basement. Furthermore, to manoeuvre a drilling plant on steep slopes was sometimes slow and difficult.

Seismic refraction work is not a substitute for drilling, but it does indicate target areas at which the drilling should be directed, and the two methods were successfully used in conjunction at Wungong. More than 2 500 m of seismic refraction lines were accompanied by about 250 additional drillholes and pits. The results of this work meant several changes in design.

(i) There was an old landslip mass on the right bank. The centre line of the dam was therefore moved to avoid this unstable area.

(ii) A spillway on the left bank could have its downstream end anchored on a stable mass of gneiss, but the depth to sound bedrock beneath its centre line was very variable, and there were several deep depressions which posed stability problems. The left bank was considered so unsatisfactory that the spillway site was moved to the right bank, where three possible lines were considered, which meant extra mapping, seismic investigation, and drilling. It also meant designing a fully concrete-lined spillway.

(iii) The intake tower site upstream of the dam toe was underlain by both gneiss and dolerite, and these two different rock types were differentially and deeply weathered. To provide adequate stability, excavations for the tower would be expensive enough to warrant moving the structure elsewhere, which in fact was done for this and other design reasons. The tower site was moved farther downstream and placed inside the dam toe. The culvert on the right bank was then moved slightly uphill.

Figure 11 shows the final dam site layout.

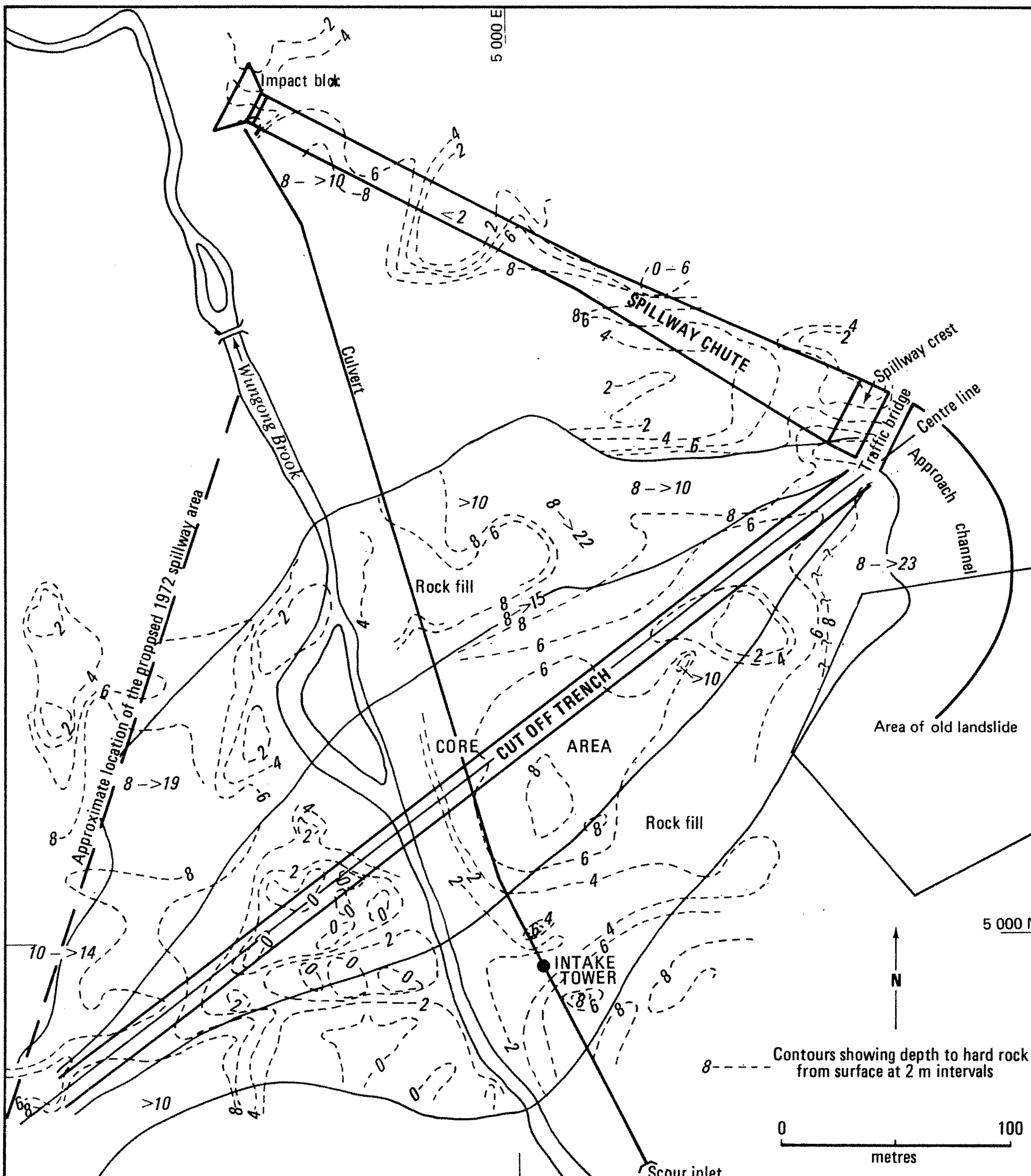

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Figure 11. Site plan showing bed-rock depths, and final position of structure.

Composite earth and rock-fill wall

While the above investigations were proceeding, extensive drilling in the earth borrow and rock quarry areas had shown that suitable earth fill was not as readily available as expected. The engineers decided again to change the design, this time from an earth fill to a composite earth and rock-fill structure with a wide impervious clay core. This in itself posed two further problems. Firstly, material beneath the wall area consisted of three layers; slope wash which would have to be removed from beneath all parts of any structure; weathered rock material which could be left in place beneath emplaced earth fill but not rock fill; and hard rock. Becuse the weathered rock layer could not be left as a foundation beneath rock fill, a substantial extra volume of excavation would now be needed. Secondly, much greater quantities of rock were needed for the rock fill. Fortunately, an examination of two quarry sites showed that one about 6 km upstream from the dam site could supply all that was needed.

CO-OPERATION

By December, 1976, excavation work at the site was far enough advanced to check the reliability of what had been predicted. Time and warrantable expenditure both tend to restrict geological investigations, against which must be weighed the likelihood of undetected subsurface conditions causing trouble during construction. Whether to extend investigations or to intensify them in particular areas must be decided in consultation between geologist and engineer, and involves mutual appreciation of the problems involved. At Wungong several design modifications resulted from frequent discussions, and the predicted subsurface geological conditions correspond with those exposed during excavation, with two minor exceptions. One inclined dolerite dyke less than 10 m wide was found, the weathered margin of which apparently had been reached in one airtrack borehole, although the material recovered had not been correctly identified. In another place, weathering at the point of intersection of several nearly vertical dykes was deeper than expected. These had no serious adverse effects, and the successive changes in the position and design of the structure, which resulted from progressive geological and other investigations, were fully justified. These decisions were made by the engineers, to whom the value of geological investigations greatly depends on how well these are performed within the limits of available finance; and on how well the results are interpreted and presented for their information. Wungong Dam is a good example of co-operation and communication, (Table 6).

ACKNOWLEDGEMENT

The writers are grateful to the Metropolitan Water Board for facilities granted and for permission to use information included in this report.

TABLE 6. SUMMARY OF PROGRESS

Period	Type of construction planned	Methods of investigation	Resultant engineering action	Comment
1922–1952	Concrete wall	Pits; diamond drilling; geological mapping		Investigations incomplete; geological structure not resolved; four possible centre lines still being considered
1960–1965	Earth fill wall; spillway on left bank	Geological fact mapping; hammer seismic refraction; drilling; soil sampling	(i) Centre line tentatively chosen (ii) Centre line moved slightly upstream to reduce volume of fill needed	General geological conditions apparent Detailed information needed of foundation area
1972–1975	(i) Earth fill wall	Geological mapping; drilling; seismic refraction	(i) Spillway removed from left bank to right bank (ii) Centre line slightly rotated and moved upstream (iii) Control tower site moved downstream	(i) Original spillway centre line underlain by depressions in bedrock which posed stability problems (ii) This avoided placing the abutment on a landslip area, right bank (iii) Original site underlain by two differentially weathered rock types posing stability difficulties
	(ii) Combination earth and rock fill with impervious clay core	Rock quarries drilled. Site investigations continued	Redesign of structure	Insufficient suitable earth fill material economically available. New design meant more excavation for placement of rockfill, and more dimension stone needed
1976	Construction commenced	Progress geological mapping during construction		Subsurface conditions found to match predictions closely

PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1976

by K. A. Crank

ABSTRACT

The low level of activtiy in oil exploration in Western Australia continued in 1976.

Only six wells were completed in the year, the same number as in 1975, and two were drilling ahead at the end of the year for a total of 22 171 metres, an increase of 5 056 metres over 1975. Drilling activity was restricted to the Carnarvon Basin, apart from a shallow stratigraphic test hole drilled onshore in the Bremer Basin. The only significant discovery during the year was at Perentie No. 1 on Barrow Island a follow-up to West Australian Petroleum Pty Ltd's deep tests of previous years, Biggada No. 1 and Barrow Deep No. 1.

Geophysical activity, consisting of land and marine seismic surveys and a limited amount of magnetic and gravity surveys, increased threefold compared to the very low level of 1975.

INTRODUCTION

Exploratory drilling carried out in the search for petroleum in Western Australia over the past two years is shown in the following tabulation:

	Wells completed		Wells drilling on 31st December	
	1975	1976	1975	1976
New field wildcats	5	5	1	1
Extension wells	0	0	0	1
Deeper pool tests	1	0	0	0
Stratigraphic tests	0	1	0	0
	6	6	1	2

Total effective drilling: 1975—17 115 m
1976—22 171 m

Only one successful well was drilled in 1976, Perentie No. 1, a new field wildcat on Barrow Island classified as a shut-in gas well.

Geophysical survey and surface geological survey activity for 1976 is shown below (with 1975 figures in brackets):

Type of survey	Line km	Party months or geologist months
Land seismic	443 (484)	....
Marine seismic	8 599* (2 737)	....
Magnetic	490 (Nil)	....
Gravity marine....	108 (Nil)	....
Geological	....	3·0 (5·0)

* This does not include 7 757 line kilometres of marine seismic conducted outside permit areas by Geophysical Services International which was classed as a "Scientific Investigation".

PETROLEUM TENEMENTS

During the year two onshore permits were surrendered in the Canning Basin (EP 32, EP 34). Surrender was pending on one offshore permit in the Perth Basin (WA-20-P) and on two onshore permits, EP 70 in the Canning Basin, and EP 85 in the Perth Basin. Eight onshore permits were partially relinquished: EPs 40, 41, 54, 61, 62, 63, 65 and 66. Two new offshore and seven new onshore tenements were granted during 1976. Large areas are currently available for application in all basins.

Petroleum Tenements current on December 31st, 1976 are shown in Figure 12, and the following tabulation lists details of the various holdings.

PETROLEUM TENEMENTS UNDER THE PETROLEUM (SUBMERGED LANDS) ACT, 1967

Exploration permits

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
WA-1-P R1	178	14/11/79	Woodside Oil N.L., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil N.L., North West Shelf Development Pty. Ltd., BP Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-13-P R1 Part 1 R1 Part 2	110 } 194 84 }	29/8/79	West Australian Petroleum Pty. Ltd.
WA-14-P R1 Part 1 R1 Part 2	77 } 198 121 }	28/8/79	
WA-16-P R1	40	16/4/80	Arco Aust. Ltd., Australian Aquitaine Petroleum Pty. Ltd., Esso Exploration and Production Aust. Inc.
WA-18-P R1	105	16/4/80	
WA-19-P R1	49	20/3/80	Alliance Oil Development Aust. N.L.
WA-20-P* R1	15	10/10/79	West Australian Petroleum Pty. Ltd.
WA-23-P R1	199	3/10/79	
WA-24-P R1	104	17/10/79	
WA-25-P R1	128	16/10/79	
WA-28-P R1 Part 1 R1 Part 2	52 } 178 126 }	24/3/80	Woodside Oil N.L., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil N.L., North West Shelf Development Pty. Ltd., BP Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-29-P R1 Part 1 R1 Part 2	36 } 120 84 }	18/5/80	Woodside Oil N.L., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil N.L., North West Shelf Development Pty. Ltd., BP Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-31-P R1	80	18/5/80	Woodside Oil N.L., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil N.L., North West Shelf Development Pty. Ltd., BP Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-32-P R1	100	2/7/80	Woodside Oil N.L., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil N.L., North West Shelf Development Pty. Ltd., BP Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-33-P R1	194	18/5/80	
WA-34-P R1	149	2/7/80	
WA-35-P R1	123	2/7/80	
WA-36-P R1	18	18/5/80	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil N.L., North West Shelf Development Pty. Ltd., BP Petroleum Development Aust. Pty. Ltd.
WA-37-P R1	59	2/6/80	
WA-58-P	222	11/7/82	Western Energy Pty. Ltd.
WA-59-P	190	18/6/82	Esso Exploration and Production Aust. Inc., Western Mining Corp. Ltd.
WA-62-P	226	Appn.	Oxoco-International Inc., Mid-American Oil Co., Peyto Oils Ltd., Voyager Petroleums Ltd., Australian Oil & Gas Corp. Ltd., Bridge Oil Ltd., Endeavour Oil Co. Ltd., AAR Ltd., Offshore Oil N.L.
WA-63-P	250	Appn.	
....			
WA-64-P	22	Appn.	Offshore Oil N.L., Southern Cross Exploration N.L., Hallmark Minerals N.L.
WA-65-P	235	Appn.	Getty Mining Pty. Ltd.
WA-66-P	239	Appn.	Meekatharra Minerals (Aust.) Pty. Ltd.
WA-67-P	226	Appn.	
WA-68-P	249	Appn.	Oxoco-International Inc., Mid-American Oil Co., Peyto Oils Ltd., Voyager Petroleums Ltd., Bridge Oil Ltd.
WA-69-P	251	Appn.	
WA-70-P	251	Appn.	Getty Oil Development Co. Ltd., Union Texas Australia Inc.
WA-71-P	251	Appn.	Crusader (Surat) Pty. Ltd.
WA-72-P	242	Appn.	Oberon Oil Pty. Ltd.
WA-73-P	251	Appn.	Magnet Metals Ltd., Malita Exploration Pty Ltd.
WA-74-P	253	Appn.	Pelsart Oil N.L.
WA-75-P	247	Appn.	
WA-76-P	251	Appn.	

Production Licenses

WA-1-L	5	Appn.	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., Woodside Petroleum Development Pty. Ltd.

* Surrender pending

PETROLEUM TENEMENTS UNDER THE PETROLEUM ACT, 1936

Petroleum Leases

Number	Area (square kilometres)	Expiry date of current term	Holders
1H	160	9/2/88	West Australian Petroleum Pty. Ltd.
2H	160	9/2/88	

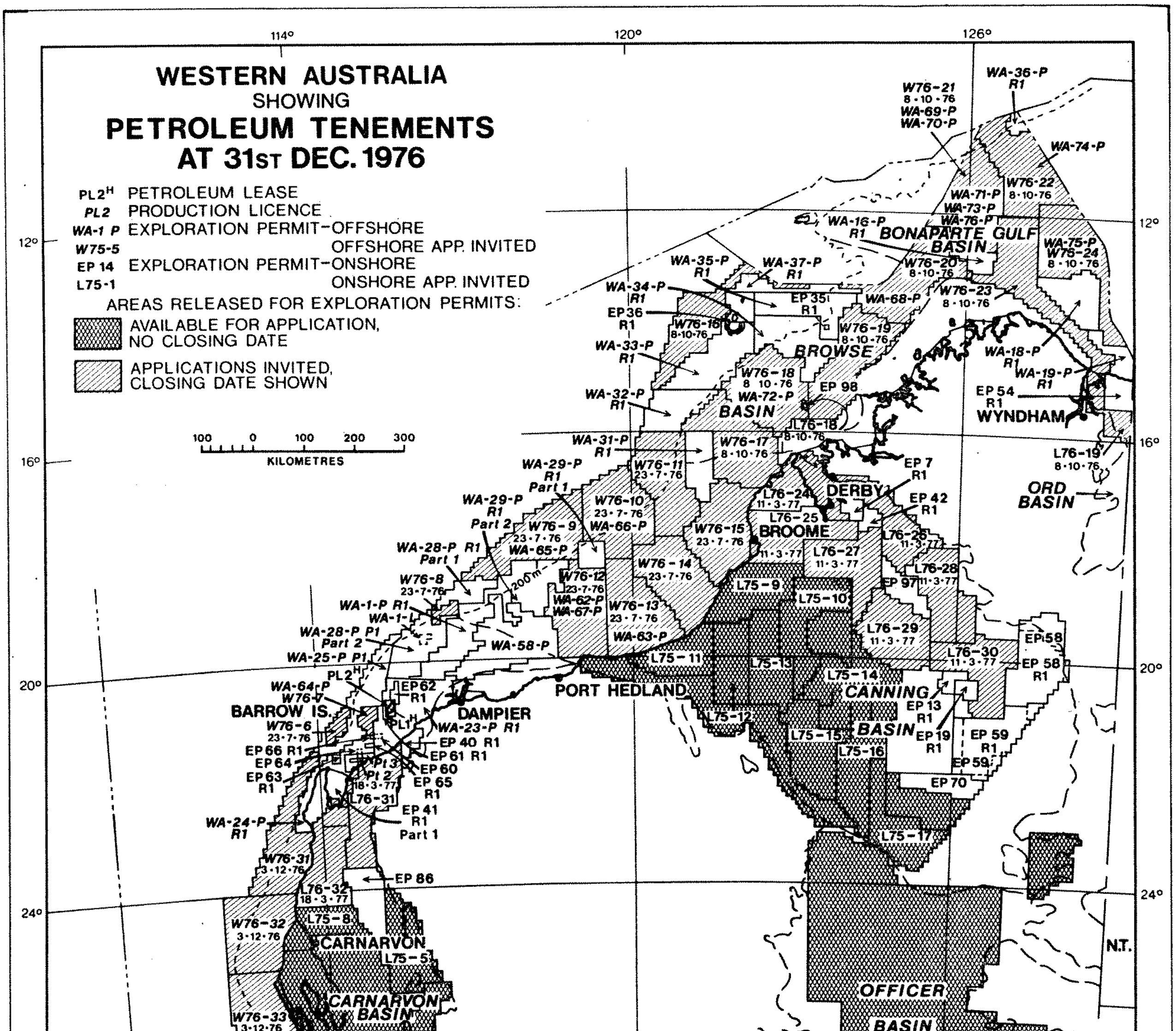

Figure 12. Petroleum tenements at 31st December 1976.

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PETROLEUM TENEMENTS UNDER THE PETROLEUM ACT, 1967

Exploration permits

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
EP 7 R1	24	27/8/80	
EP13 R1	23	27/8/80	
EP19 R1	18	27/8/80	
EP21 R1	32	26/7/80	West Australian Petroleum Pty. Ltd.
EP 23 R1	33	6/8/80	
EP 24 R1 Part 1 R1 Part 2 R1 Part 3	39 24 } 85 22	6/8/80	
EP 25 R1	36	6/8/80	
EP 35 R1	1	15/4/81	Woodside Oil N.L., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil N.L., North West Shelf Development Pty. Ltd., BP Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
EP 36 R1	1	15/4/81	
EP 40 R1	19	26/7/81	West Australian Petroleum Pty. Ltd.
EP 41 R1 Part 1 R1 Part 2 R1 Part 3	102 1 } 106 3	18/7/81	West Australian Petroleum Pty. Ltd.
EP 42 R1	19	1/9/80	
EP 50 R1	18	1/9/80	West Australian Petroleum Pty. Ltd.
EP 54 R1	47	22/9/80	Alliance Oil Development Aust. N.L.
EP 58 R1	200 150	20/7/76 Appn.	AAR Limited, Australian Aquitaine Petroleum Pty. Ltd., Abrolhos Oil and Investments Ltd., Ashburton Oil N.L., Flinders Petroleum N.L., Longreach Oil Ltd., Pursuit Oil N.L.
EP 59 R1	186 139	18/7/76 Appn.	
EP 60	2	Appn.	
EP 61 R1	4	19/9/81	
EP 62 R1	8	19/9/81	West Australian Petroleum Pty. Ltd.
EP 63 R1	4	19/9/81	
EP 64	1	Appn.	
EP 65 R1	2	19/9/81	West Australian Petroleum Pty. Ltd.
EP 66 R1	1	19/9/81	
EP 68	175	27/7/77	W. I. Robinson
EP 70*	71	25/9/77	AAR Limited, Australian Aquitaine Petroleum Pty. Ltd., Abrolhos Oil and Investments Ltd., Ashburton Oil N.L., Flinders Petroleum N.L., Longreach Oil Ltd., Pursuit Oil N.L.
EP 85*	4	19/7/80	Endeavour Oil Co. N.L., Target Minerals N.L., IOL Petroleum Ltd., AAR Limited Alliance Minerals (Aust.) N.L.
EP 86	118	9/1/80	XLX N.L.
EP 88	1	18/6/81	
EP 89	2	18/6/81	Esso Exploration & Production Aust. Inc., Western Mining Corp. Ltd.
EP 90	4	18/6/81	
EP 91	7	18/6/81	
EP 96	3	3/11/81	XLX N.L.
EP 97	64	16/9/81	Whitestone Petroleum Aust. Ltd., Amax Iron Ore Corp., Pennzoil Producing Aust. Ltd., Australian Consolidated Minerals Ltd.
EP 98		Appn.	Oberon Oil Pty. Ltd.

Production Licenses

PL 1	5	24/10/92	West Australian Petroleum Pty. Ltd.
PL 2	4	24/10/92	

* Surrender pending

PETROLEUM TENEMENTS UNDER THE PETROLEUM PIPELINES ACT, 1969

Pipeline licenses

Number	Expiry date of current term	Registered holder or applicant
1	1/12/91	California Asiatic Oil Co., Texaco Overseas Petroleum Co., Shell Development (Aust.) Pty Ltd., Ampol Exploration Ltd.
2	1/12/91	
3	1/12/91	
4	1/12/91	
5	1/12/91	

DRILLING

The positions of wells drilled for petroleum exploraation in Western Australia during 1976 are shown in Figures 13 and 14. Details relating to wells drilled during the year are given in Table 7. All petroleum exploration wells drilled in Western Australia up to the end of 1976 are listed in the Geological Survey Record 1977/1 (Crank, 1977). A summary of the principal results of drilling in each basin during the year is as follows:

BREMER BASIN

Silfar Pty Ltd (W. I. Robinson) completed a stratigraphic test, Ocumup No. 1 in the onshore Bremer Basin. The well was plugged and abandoned at total depth 83 metres after reaching Precambrian basement. There were no oil or gas shows.

CARNARVON BASIN

Two wells were completed by the Woodside (formerly BOCAL) group in the Carnarvon Basin during 1976. Lewis No. 1A was located on the Legendre-Rosemary Trend in the Dampier sub-Basin about 20 km southwest of Legendre No. 1. The well was abandoned as a dry hole after reaching a total depth of 3 400 m. No shows of oil or gas were encountered. Withnell No. 1 was drilled near the south end of the Madeline Trend in the Dampier sub-Basin. There were many gas shows but no effective reservoir was encountered, and the well was plugged and abandoned after reaching a total depth of 4 650 m. Woodside was drilling an extension well, North Rankin No. 5, at the end of the year.

Wapet completed one offshore and two onshore wells in 1976. Spar No. 1 was drilled 50 km west-northwest of Barrow Island to test an interpreted large domal structure within the Barrow sub-Basin. Several formation tests were made in this well including 15 formation interval tests. Two successful drillstem tests were over the intervals 3 289 to 3 311 m and 2 621 to 2 630 m, the former flowing at the rate of $1.7 \times 10^3\ m^3$ gas/day and the latter at a maximum of $311 \times 10^3\ m^3$ gas/day with 250 barrels of condensate per day. The well was plugged and abandoned at a total depth of 3 721 m and was considered to be non-commercial.

Two wells were drilled on Barrow Island by Wapet. Perentie No. 1 was a deep test-well drilled at the southern end of the island where potential gas production was discovered at a depth similar to that discovered in Barrow Deep No. 1 and Biggada No. 1 which were drilled in 1973 and 1975 respectively. Whitlock No. 1 was drilled to a total depth of 2 400 m, on a small domal feature to the north of Barrow Field. Testing results were disappointing, with no significant hydrocarbon production, and the well was plugged and abandoned.

PERTH BASIN

At the end of the year, Wapet was drilling one well, Denison No. 1, on a fault block to the west of Dongara Gas Field.

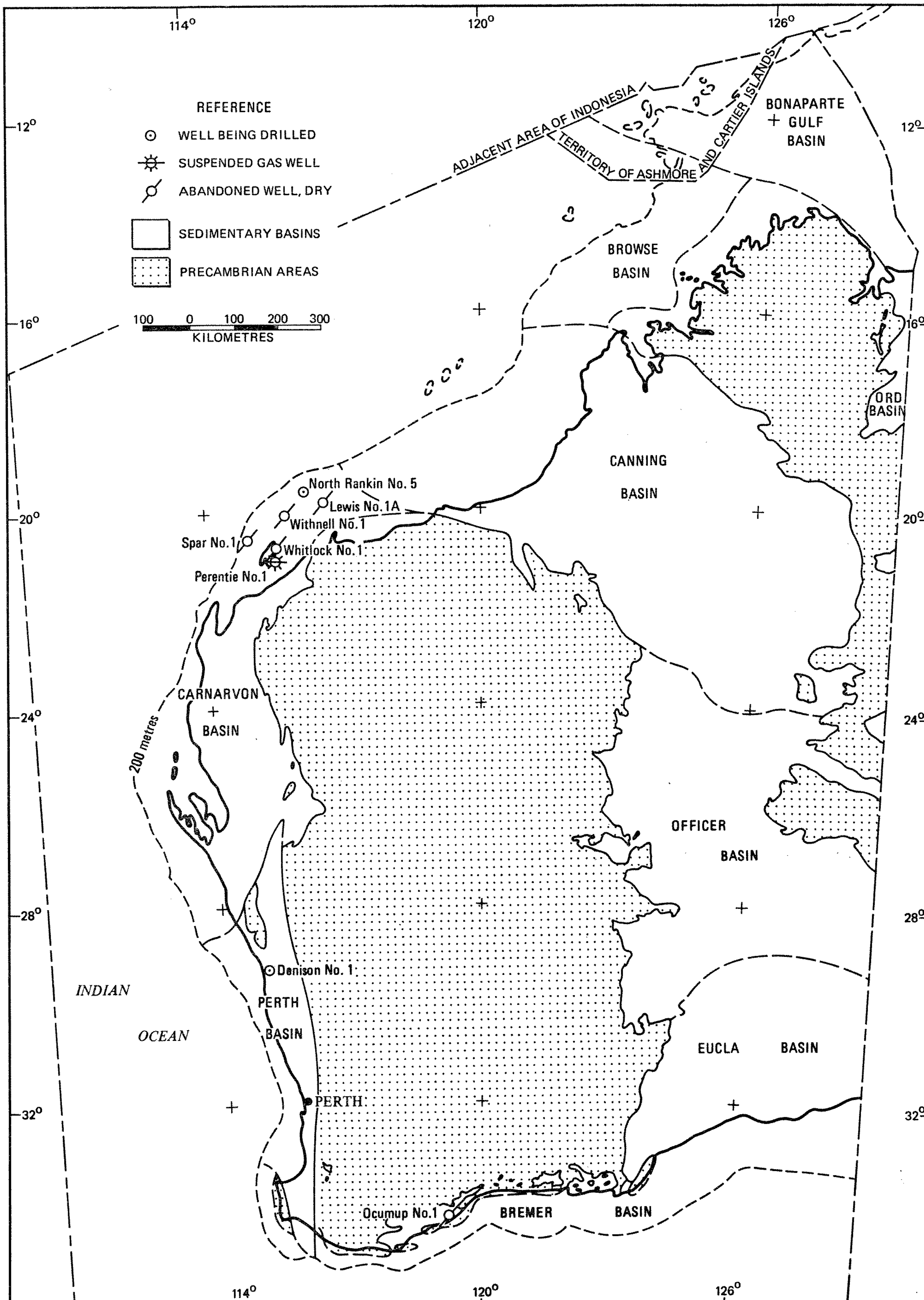

Figure 13. Wells drilled for petroleum exploration in W.A. during 1976.

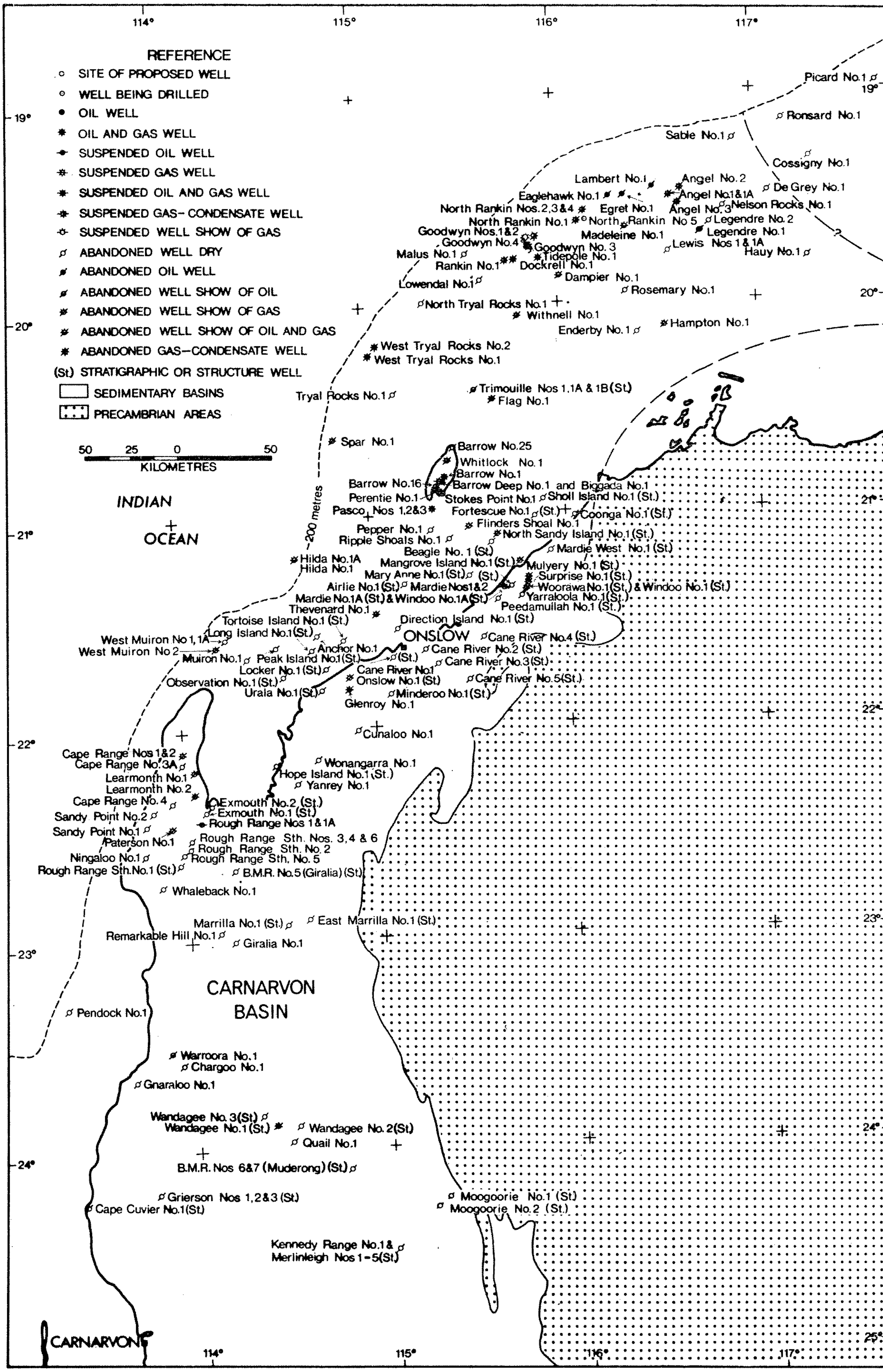

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Figure 14. Northern Carnarvon and southwestern Canning Basins showing wells drilled for petroleum to 31st December 1976.

TABLE 7. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1976

Basin	Well	Concession	Operating company	Type	Position		Elevation and water depth (metres)			Dates			Total depth (or depth reached) m	Bottomed in	Status on 31/12/76
					Latitude south ° ′ ″	Longitude east ° ′ ″	GL	RT	WD	Commenced	Reached TD	Rig released			
Perth	Denison No. 1	PL2	Wapet	NFW	29 13 32	114 57 17	27	35	....	23/12/76	....	....	969	....	Drilling
Carnarvon	North Rankin No. 5	WA–28–P	Woodside	EXT	19 34 19	116 09 30	....	30	123	8/10/76	....	....	3 048	....	Coring
	Perentie No. 1	PL 1H	Wapet	NFW	20 53 02	115 23 41	7	15	....	14/1/76	7/5/76	21/6/76	3 900	M. Jurassic	Shut-in gas well
	Spar No. 1	WA–25–P	Wapet	NFW	20 36 54	114 53 07	....	30	116	25/6/76	26/8/76	30/9/76	3 721	?U. Jurassic	Gas shows, p & a
	Whitlock No. 1	PL 1H	Wapet	NFW	20 43 46	115 24 56	41	49	....	8/7/76	1/8/76	10/8/76	2 400	?U. Jurassic	Gas & oil shows, p & a
	Withnell No. 1	WA–28–P	Woodside	NFW	20 01 11	115 48 15	....	30	75	5/3/76	16/6/76	23/6/76	4 650	M. Jurassic	Dry, p & a
	Lewis No. 1A	WA–1–P	Woodside	NFW	19 47 36	116 36 04	....	30	60	24/12/76	19/2/76	4/3/76	3 400	M. Jurassic	Dry, p & a
Bremer	Ocumup No. 1	EP68	Silfar	STR....	34 23 45	119 12 53	38	40	....	15/6/76	29/6/76	30/6/76	83	Precambrian	Dry, p & a

Woodside = Woodside Petroleum Development Pty. Ltd.
Wapet = West Australian Petroleum Pty. Ltd.
Silfar = Silfar Pty. Ltd.
EXT Extension test well

NFW = New field wildcat well
STR = Stratigraphic well
p & a = Plugged and abandoned

GEOPHYSICAL SURVEYS

SEISMIC

During 1976 seismic surveys were conducted in the Perth, Carnarvon, Canning, Browse and Bonaparte Gulf Basins. Details are as follows:

SEISMIC SURVEYS

Basin	Tenement	Company	Line kilometres	
			Marine	Land
Perth	EP 21	West Australian Petroleum Pty. Ltd.	....	21
,,	EP 23	,, ,, ,,	....	2
,,	EP 24	,, ,, ,,	....	42
,,	WA-13-P	,, ,, ,,	333	....
,,	WA-14-P	,, ,, ,,	484	....
,,	WA-20-P	,, ,, ,,	1	....
Carnarvon/ Perth	WA-59-P	Esso Exploration and Production Inc.	2 404	....
Carnarvon	EP 41	West Australian Petroleum Pty. Ltd.	65	....
,,	WA-23-P	,, ,, ,,	172	....
,,	WA-24-P	,, ,, ,,	196	....
,,	WA-25-P	,, ,, ,,	66	....
,,	WA-1-P	Woodside Petroleum Development Pty. Ltd.	304	....
,,	WA-28 P	,, ,, ,,	894	....
Canning	EP 97	Whitestone International Inc.	....	378
,,	WA-31-P	Woodside (Amax Petroleum (Aust.) Inc.—farminee)	116	....
Browse	WA-32-P	Woodside Petroleum Development Pty. Ltd.	294	....
,,	WA-33-P	,, ,, ,,	687	....
,,	WA-34-P	,, ,, ,,	658	....
,,	WA-35-P	,, ,, ,,	639	....
,,	WA-37-P	,, ,, ,,	408	....
Bonaparte Gulf	WA-16-P	Acro Australia Ltd.	145	....
,,	WA-18-P	,, ,,	571	....
,,	WA-19-P	Alliance Oil Development (Aust.) N.L.	94	....
,,	WA-36-P	Woodside Petroleum Development Pty. Ltd.	3	....
Outside Permit Areas	....	Woodside Petroleum Development Pty. Ltd.	64	....
		Totals	8 599	443

GRAVITY

Gravity surveys were carried out in conjunction with offshore seismic surveys in the Browse Basin as follows:

GRAVITY SURVEYS

Basin	Tenement	Company	Line km
Browse	WA-33-P	Woodside Petroleum Development Pty. Ltd.	39
,,	WA-37-P	,, ,, ,,	69
		Total	108

MAGNETOMETER

Magnetometer surveys conducted in conjunction with offshore seismic surveys were as follows:

MAGNETOMETER SURVEYS

Basin	Tenement	Company	Line km
Browse	WA-33-P	Woodside Petroleum Development Pty. Ltd.	213
,,	WA-35-P	,, ,, ,,	1
,,	WA-37-P	,, ,, ,,	274
Outside permit areas	....	,, ,, ,,	2
		Total	490

GEOLOGICAL SURVEYS

XLX N.L. carried out two party months of surface geological surveys in the Carnarvon Basin (EP86) and WAPET spent one party month in the Canning Basin (EPs 7 and 42).

REFERENCES

Crank, K. A., 1977, Wells drilled for petroleum exploration in W.A. to the end of 1976: West. Australia Geol. Survey Rec. 1977/1.

EMERGENT QUARTERNARY MARINE DEPOSITS IN THE LAKE MACLEOD AREA, W.A.

by P. D. Denman and W. J. E. van de Graaff

ABSTRACT

Two emergent marine erosion terraces and terrace deposits, now at 2 to 4 m and 7 m above Mean Low Water Springs level, occur along the east shores of Lake Macleod. Two similar terraces and deposits occur on the coast at Cape Cuvier and Red Bluff, where their elevations are 1 to 3 m higher.

Correlation with Cape Range and Shark Bay units indicates that the terraces and terrace deposits are of Pleistocene age.

Late Quaternary tectonism is indicated in the area by the fact that the terraces and marine deposits are folded along the Cape Cuvier Anticline. In addition the terraces are at higher elevations than those on the east side of Lake Macleod. This together with previous work indicates the Western Australian coast between North West Cape and Shark Bay has been tectonically unstable during the Quaternary.

The elevation of shoreline features and distribution of marine deposits indicate that the Macleod Pleistocene marine embayment extended over an area 50 per cent greater than Lake Macleod, and was open to the ocean at both its southern and northern ends. This configuration allowed normal oceanic salinities to exist in the embayment, and permitted the growth of corals that mark the shoreline benches.

INTRODUCTION

Emergent Quaternary deposits have been studied at six localities in the Lake Macleod region. Associated emerged marine erosion terraces are exposed at four of the localities. The purpose of the study was to estimate levels of emergence relative to present sea level, and to determine whether Quaternary tectonism has occurred, as in the Cape Range area where emerged Pleistocene marine terraces have been uplifted and warped (van de Graaff and others, 1976). U/Th series dating on corals is being done to establish absolute ages and correlations between the two areas.

Two of the localities described are coastal—Cape Cuvier and Red Bluff; and four are marginal to Lake Macleod-Texada road pits, Grierson Anticline, Yankie Tank Anticline and Chirrida Anticline (Fig. 15). Vertical sections for four of the locations are shown in Figures 16 to 19.

Condon (1954) recorded marine deposits on the shores of Lake Macleod consisting of calcarenite and molluscan coquinite, which extend from "below the lake floor to about 20 feet above it". He notes (1955) that such deposits extend north of the lake and along the Lyndon and Minilya Rivers (Fig. 15). He did not mention any emerged terraces. Teichert (1957, p. 70) comments on "the remarkable terrace which is cut into the west flanks of the anticlines on the east side of

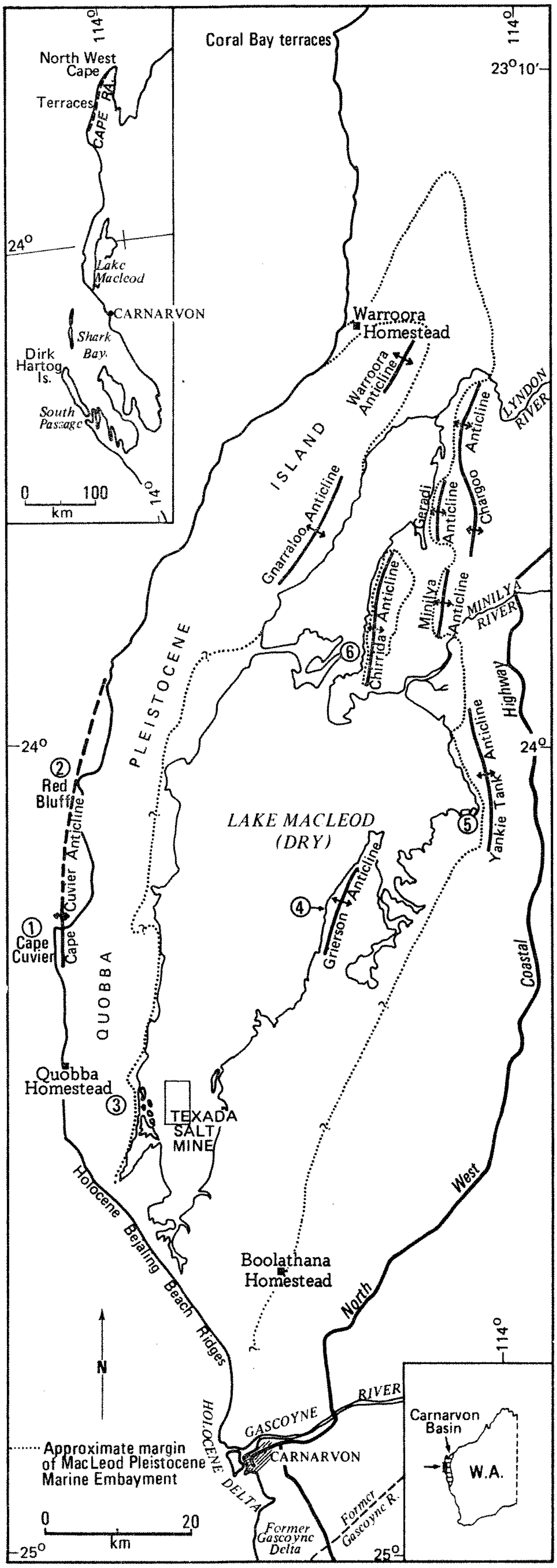

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Figure 15 Locality map of the Lake MacLeod area. Measured Sections: (1) Cape Cuvier, (2) Red Bluff, (3) Texada Road Pits, (4) Grierson Anticline, (5) Yankie Tank Anticline, (6) Chirrida Anticline.

this generally dry lake". "This terrace . . . along the entire west side of Chirrida anticline . . . lies at 11 to 12 feet above lake bottom . . . and consists of loose deposits, partly shell layers and partly sand". Condon (1954) correlated the marine deposits with the Bundera Calcarenite of Cape Range which has been redefined by van de Graaff and others (1976) to comprise two members, the Jurabi and Tantabiddi Members, each containing marine and eolian facies. The deposits described in this paper correlate to some degree in lithology and stratigraphy with the Bundera Calcarenite, and it seems likely that equivalents of both members are present. Correlation with the Shark Bay sequence, described by Logan and others (1970), is yet to be made. The eolianite underlying the marine deposit at Cape Cuvier and Red Bluff looks identical to the eolian facies of the Bundera Calcarenite in the Cape Range area, but as it extends below sea level it may be older, as it must have formed during a low-sea-level stand. It is equivalent to part of the Tamala Limestone (Playford and others, in press), which is a Quaternary eolianite unit mapped from Shark Bay southwards.

The coastal sections were measured by Brunton compass from the high water mark on the shore, which is assumed to be the Mean High Water Springs level (MHWS). The levels of the erosional terraces and *in situ* coral shown in the sections are given relative to the Mean Low Water Springs level (MLWS) which is 0.9 m below MHWS at Carnarvon (Aust. Nat. Tide Tables, 1976). We consider the MLWS level to be the most meaningful level as:

(1) the erosional terraces are assumed to have formed by mechanical erosion in the surf zone (Gill, 1976), at surf base (Russell, 1964) or by a combination of surf erosion, biocorrosion and chemical erosion in the tidal zone (Hodgkin, 1964, 1970), and

(2) coral growth requires permanent submergence and the highest level given by *in situ* coral is likely to be close to the former mean low water springs level. Present-day reefs on this coast do not appear to grow above lowest tide level.

The levels for the Lake Macleod sections are based on detailed ground surveying carried out for West Australian Petroleum Pty Ltd by Ray Geophysics (1955, 1956), supported by spot heights and contours from 1:100 000 scale maps and field measurements. These surveyed levels are above mean sea level and have been reduced by 0.5 m to be consistent with MLWS levels, though this degree of accuracy is not implied The surveyed data were plotted on 1:40 000 air-photographs before section drawing. The Yankie Tank section (Fig. 18) may be unreliable due to lack of survey data at that location and to a discrepancy between data from Ray Geophysics and the 1:100 000 map. Here Brunton levels to the local lake bed were used to produce section A, and section B is mainly based on photo-interpretation.

DESCRIPTION OF LOCALITIES

CAPE CUVIER (Fig. 16)

Two marine erosion terraces with overlying marine deposits occur at Cape Cuvier. The lower is well exposed, although discontinuously, from the point at Cape Cuvier southward, and occurs at 3 to 7.4 m above MLWS level (Fig. 16, Sections A, B). Very little of the upper terrace is preserved, being exposed at only one location 100 m south of the point (Fig. 16, Section B), where the terrace is at 10 m and overlying algal limestone at 10.5 m above MLWS level. The existence of the upper terrace and terrace deposit here is supported by a remnant marine deposit containing an *in situ* coral at 9.4 m elevation, 100 m to the north (Fig. 16, Section A).

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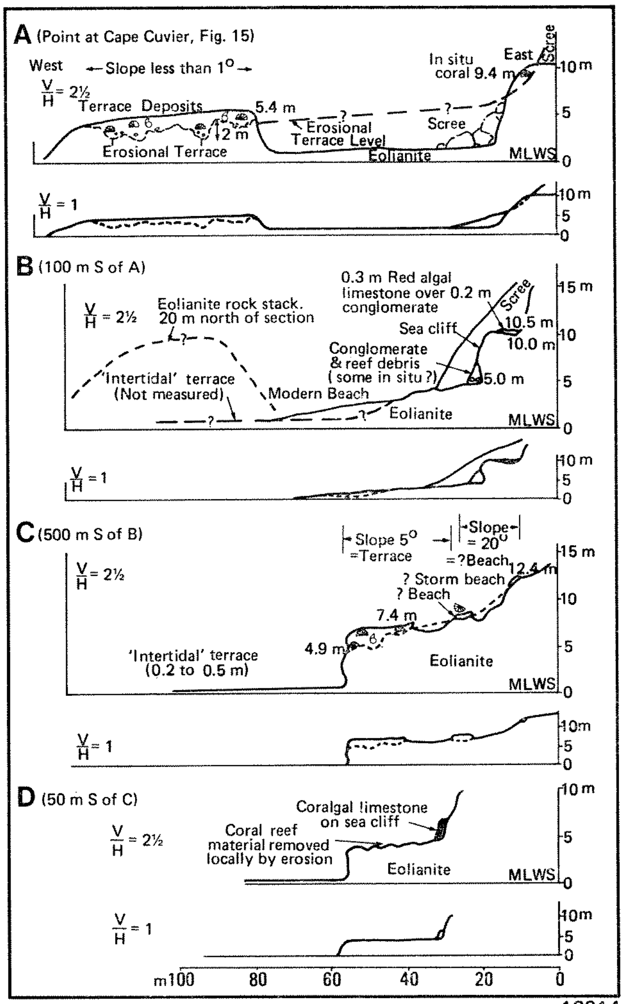

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Figure 16 Cape Cuvier Coastal Sections.
Section A is at the point of the Cape: 113°23′30″E, 24°13′15″S.

The lower erosional terrace, cut into fine- to medium-grained quartzose calcarenite (eolianite) has a very irregular surface with pockets to at least 2 m depth. It is covered by reef deposits of coral-algal boundstone and calcarenite to calcirudite, commonly containing pebbles and cobbles at the base. At one location (Fig. 16, Section C) ?beach facies of cemented calcarenitic reef detritus was observed at a higher level (7-12 m) to the east. Outcrops such as that of Figure 16, Section C indicate that in most places the terrace is preserved only close to the original shoreline, but an outlier shows that at about 100 m from the former shore, the terrace has a gentle slope of less than 1° (Fig. 16, Section A). It appears to steepen to about 5° near the former beach, which sloped at 20° or more (Fig. 16, Section C). The beach deposit occurs at 5 m or more above the low-water level indicated by *in situ* corals. Such features were also recorded from this region by Russell (1964) who cautioned against using beach deposits as former sea-level indicators. The features suggest that eolianite headlands with occasional rock stacks alternated with small bays at 50 to 500 m intervals along the former shoreline.

The upper erosional terrace, at about 10 m (Fig. 16, Section B), is irregular on a 0.1 to 0.2 m scale, and is overlain by 0.1 to 0.2 m of eolianite conglomerate, and this in turn by 0.3 m of hard, laminated red-algal limestone, the surface of which is relatively smooth. In Figure 16, Section A, an *in situ* coral at 9.4 m occurs with coquinite and reef detritus on an irregular steep surface assumed to be part of a sea cliff. This deposit is correlated with the upper terrace. Unfortunately, at the point of the Cape, scree resulting from the construction of salt-loading facilities has either covered or destroyed significant parts of the terraces and terrace deposits.

RED BLUFF

An erosional terrace with overlying marine deposits about 40 m wide is exposed at Red Bluff. The lowest exposed part of the terrace is at 3.2 m and the highest *in situ* coral at 10.6 m. A cover of loose blocks of reefal terrace deposits above about 8 m obscures the terrace deposit/bedrock relationships at the level where an upper terrace would be expected. The terrace level of 3.2 m compares closely with the lower terrace at Cape Cuvier, and the *in situ* coral at 10.6 m compares with the coral on the upper terrace deposit at Cape Cuvier, so that the presence of two terrace levels at Red Bluff is inferred, the lower being at 3 to ?5 m and the upper (obscured) at about 8 m.

TEXADA ROAD PITS

In situ compound corals up to 2 m diameter in a weathered groundmass of mollusc-rich calcarenite-calcirudite form the marine deposits exposed between 1.3 m and –0.5 m. No erosional terrace is exposed but to the north the deposits are backed at intervals by eolianite cliffs along the west shore of the lake. About 22 km north of the pits corals and molluscs are abundant on the lake shore at –1 m; and 3 km inland to the west, at about 4 m, is an exposure of possible beach material—cemented coral and shell fragments in interlaminated coarse- and medium- to fine-grained quartzose calcarenite.

GRIERSON ANTICLINE (Fig. 17)

The west flank of this anticline shows a clear terrace, cut in Miocene Trealla Limestone, at about 2 m elevation (Fig. 17). No marine deposits are preserved on the terrace but coral and shell fragments remain as float. In a gully 1 to 2 m deep, a lithified conglomerate is exposed, consisting of abundant molluscs and coral fragments, with rounded Trealla Limestone pebbles and cobbles. The roundness suggests extensive reworking, as on a beach. It is very similar to Mowbowra Conglomerate of the North West Cape (Fig. 15) (van de Graaff and others, in prep.).

On the east flank of the anticline two levels of marine deposits occur, which appear to overlie terraces cut in the underlying Trealla Limestone. The upper deposits at about 7 m elevation are poorly exposed, but the corals found appeared to be in growth position. The extent of the lower unit is indicated by rare shelly calcarenite outcrops and fairly common 10 to 100 m patches of coquinite float. It is extensive in this area, continuing more than 5 km east of Grierson Anticline, and about 50 km south to Boolathana homestead, and over 20 km to the northeast to the Yankie Tank Anticline area (Fig. 15). Through this extensive area the ground elevation is mostly below 3 m, and in many places near the lake shores it is below 0 m. Definite *in situ* fossil shells and corals have very rarely been found on this terrace (e.g. Fig. 18, Section A).

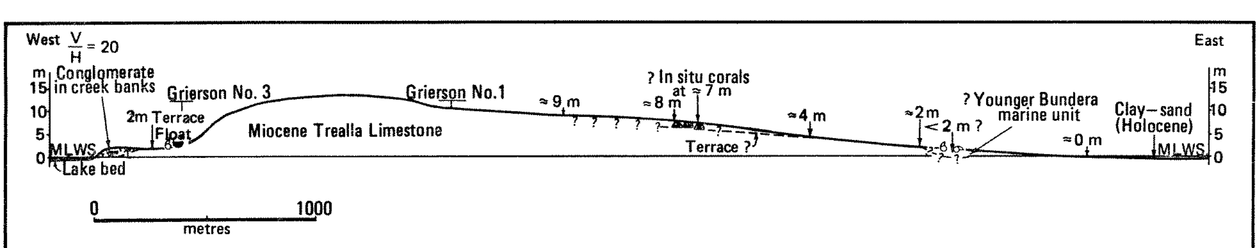

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Figure 17 Grierson Anticline Section showing relationship of the upper and lower units of the Bundera Calcarenite to present-day mean low water level (MLWS).
The Section is from 113°45′15″E, 24°12′00″S to 113°48′00″E, 24°12′30″S, through Grierson No. 1 Well.

YANKIE TANK ANTICLINE (Fig. 18)

On the west flank of this anticline are two clear bench levels, at about 2 to 4.5 m and 7 to 8 m elevation. Erosion terraces are not exposed, being veneered by more recent sand and colluvium, with remnants of marine deposits indicated by shell float on both benches. The only *in situ* coral located was about 1 m elevation (Fig. 18, Section A). About 100 m north of this, the banks of a small gully showed patches of lithified conglomerate derived from Trealla Limestone and coral pieces, at about the same level, and this may represent the level of the lower terrace. The upper level has been traced for at least 5 km to the south (Fig. 18, Section B) and 1 km to the north. The lower level, a continuation of that on the east side of Grierson Anticline, can be traced northward to the Chirrida-Minilya Anticlines region (Fig. 15), though it is mostly covered by more recent alluvium and colluvium. Because of this, the elevations of both the marine deposits and the erosional terrace below, are unknown, but ground elevations throughout the area, which is inferred to be underlain by marine Bundera Calcarenite (Fig. 15), are mostly below 3 m elevation.

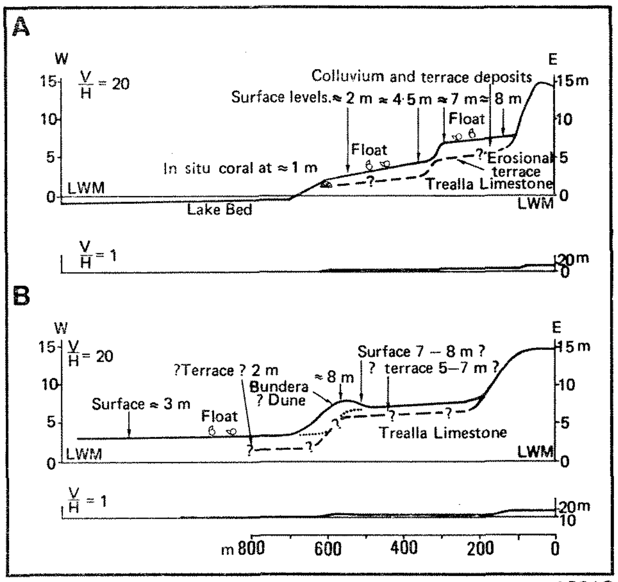

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Figure 18 Yankie Tank Anticline Sections.
Section A is centred at 113°13′10″E, 24°4′30″S. Section B is 2 km south of A.

CHIRRIDA ANTICLINE (Fig. 19)

Air-photographs show a terrace 100 to 200 m wide close to the lake shore, extending for about 18 km along the west flank of this anticline. It was examined at one locality 4 km from the south end. Here the erosional terrace was not exposed, but is veneered by 1 to 2 m of sand (elevation 3 to 4 m). Trealla Limestone crops out on the lake edge, and the terrace cut in this limestone may be at 1 to 2 m elevation. A seismic shot hole on the terrace showed about 2 m of sand over Trealla Limestone, and the spoil contained shell and coral fragments, so the terrace may be thinly covered by marine Bundera Calcarenite.

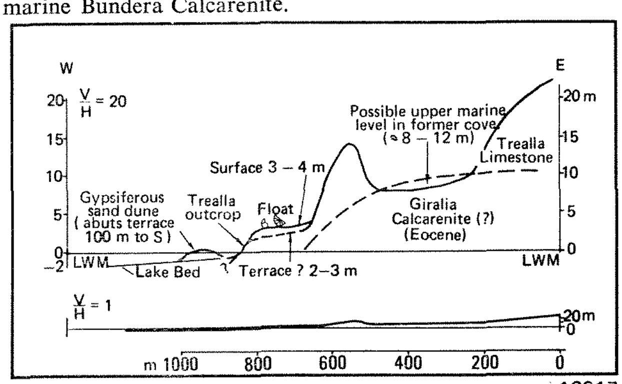

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Figure 19 Chirrida Anticline Section.
The Section is centred at 113°48′20″E, 23°53′5″S.

OTHER LOCALITIES

Two distinct erosional terraces, both sloping from north to south, are cut into a headland of Pleistocene eolianite 1.5 km south of Coral Bay (Fig. 15). Over a distance of 150 m the lower terrace, containing pockets of cemented calcarenite, shells and coral pieces, slopes from 3 to 5 m above Mean Low Water Springs level. The upper terrace, poorly preserved over some 50 m, is at 6.9 to 7.6 m elevation.

At Boolathana homestead (Fig. 15), dam spoil comprising fragamental fossiliferous beach or near-shore facies of Bundera Calcarenite, occurs at 2 to 3 m elevation. This rock type is seen in numerous road pits 7 to 8 km to the southwest at 0 to 1 m elevation.

DISCUSSION

1. Emergent marine erosion terraces and terrace deposits occur extensively throughout this area, with elevations ranging from below present sea-level to some 10 m above it. At Cape Cuvier *in situ* corals and algal material occur at two levels, 3 to 7.4 m and 9.4 to 10.5 m (Fig. 16, sections A to D). Section A (Fig. 16) is discontinuous and the relationships between the terrace and its deposits on the west side at 3 to 5 m and those on the east side at 9 to 10 m, are not seen. The deposits could be interpreted as having formed on the same sloping terrace, but this does not explain why the reef top on the west side is at about 5 m when, 70 m to the east, *in situ* coral occurs at 9 m. Section B (Fig. 16) 100 m to the south, shows the existence of two terraces, at about 5 m and 10 m, indicating that the west and east sides of the point section (Fig. 16, Section A) were cut by two different sea levels. Evidence on the east side of the lake supports the interpretation of different sea levels, which here cut a lower erosional terrace at about 2 m and an upper one at about 7 m above modern Low Water Springs level.
2. The Lake Macleod region is characterized by pronounced structural control of the landforms, with the elevated areas coinciding with anticlines and the depressions coinciding with synclines. Playford and Cockbain (1976) inferred a similar configuration for the Shark Bay area as Dirk Hartog Island overlies a known anticline in Tertiary rocks. These and other fold structures in the northern part of the Carnarvon Basin are commonly considered to have formed after the early Miocene and before the late Pliocene (Johnstone and others, 1976), but in recent years evidence has come to light to indicate that, for at least some of the folds, tectonism continued into the Quaternary and probably is continuing today. In the Shark Bay area Logan and others (1970, p. 82) suggested tectonic movement took place in the Pleistocene and also mentioned "the possibility that uplift also has occurred in the Holocene". Playford and Cockbain (1976) believe that the emergence of the older stromatolites is most likely to be a result of periodic uplift in Holocene times. Van de Graaff and others (1976) established Quaternary tectonism in the Cape Range area. At Cape Cuvier similar Quaternary tectonism is proved by the tilting of the terraces and their deposits. This tilting is clearly shown by the maximum elevations of *in situ* corals and of the erosional terraces, which drop progressively away from the anticlinal axis on both the east and the west flank of the anticline (Fig.20). Directions of tilt are the same as dip directions of the underlying folded Miocene rocks. The landward slope of the terrace on the east flank of the anticline strongly suggests warping, as coastal terraces normally slope seaward. In addition the Cape Cuvier terraces and marine deposits have greater elevations, by 1 to 3 m, than those east of Lake Macleod. This indicates late Quaternary uplift on the Cape Cuvier axis relative to the anticlines to the east. Elevations of the marine terrace deposits on the anticlines east of Lake Macleod may also have been affected by late Quaternary tectonism, but altimetric and geological control is insufficient to prove this. However there is no obvious indication of warping, and for the Lake Macleod region these terraces may be taken to indicate Quaternary sea levels of approximately 2 to 4 m and 7 m above present Mean Low Water Springs level.

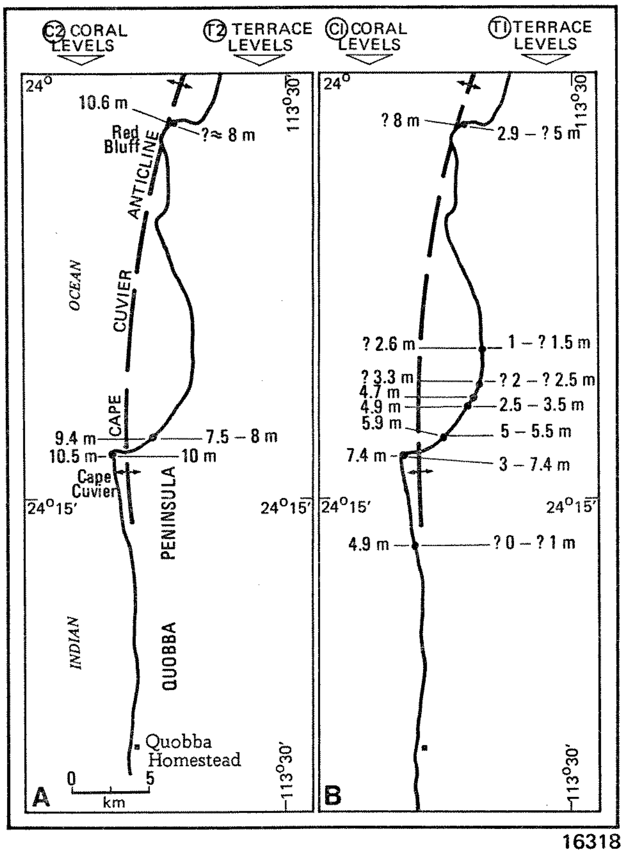

Figure 20 Fossil shoreline features in the Cape Cuvier Anticline Area.
Elevations in metres above Mean Low Water Springs level:

A. Upper Erosional Terrace (T2) and highest in situ fossil coral (C2).

B. Lower Erosional Terrace (T1) and highest in situ fossil coral (C1).

3. Altimetric data in the Warroora homestead-Lyndon River area show a broad area below the 5 m contour with a 2 to 3 km-wide connection to the sea. The occurrence of corals up to 7 m elevation thus indicates the MacLeod embayment was open to the sea both in the north and the south. This is supported by the earlier mapping of Condon (1955) who mapped Pleistocene "marine coquinoid calcarenite" in these northern areas. This and the altimetric data combine to suggest the embayment margin shown in the northern part of Figure 15. A northern connection with the sea also explains the prevalence of oceanic salinities in the lake area, as indicated by the abundant corals. If the embayment had been open only in the south, one would expect higher salinity gradients than would allow coral growth (e.g. Heckel, 1972), as is the case in Shark Bay (Hagan and Logan, 1974). The extent of the original embayment indicated by mapping of Pleistocene marine sediments, must have been about 50 per cent greater than the present area of the lake, with a southern opening to the ocean about 25 to 30 km wide. The Quobba Pleistocene Island (Fig. 15) would have had a northern strait similar to today's Dirk Hartog Island (Fig. 15 inset) and its 3 km-wide South Passage, which allows oceanic salinities east of the island (Logan and Cebulski, 1970). The closing of the northern end of the embayment appears to have been mainly a matter of a relative drop in sea level although some coastal dune building took place. In the south however, the shifting of the Gascoyne Delta and building up of the Bejaling Beach Ridges, described by Johnson (1974), appear to have been important factors in the closing of the embayment.

4. Tentative correlation of the terraces and terrace deposits with the Bundera Calcarenite units of the Cape Range and with radiocarbon dating at Shark Bay (Noakes and others, 1967) indicates the terraces and terrace deposits are older than 40 000 years and probably not older than the Riss-Würm Interglacial, or about 150 000 years.

CONCLUSIONS

1. Emergent marine erosion terraces overlain by marine deposits occur at 2 to 4 m and at 7 m above Mean Low Water Springs level along the east side of Lake Macleod. Two similar terraces and deposits occur on the coast at Cape Cuvier and Red Bluff but at elevations 1 to 3 m higher than those east of the lake.

2. Late Quaternary tectonism is indicated by the slope of the terraces and marine deposits in the Cape Cuvier region and by their greater elevations compared with those to the east. This evidence of folding, together with previous work, indicates that the Western Australian coast between North West Cape and Shark Bay has been tectonically unstable during the Quaternary.

3. The marine erosion terraces and terrace deposits may have emerged because of a Pleistocene eustatic sea level fall, or as a result of uplift due to tectonism or, most likely, a combination of both.

4. The elevation of shoreline features and distribution of marine deposits indicates that the Macleod Pleistocene marine embayment was open to the ocean at both its southern and northern ends. This configuration allowed normal oceanic salinities to exist in the embayment, and permitted the growth of corals that mark the shoreline benches.

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REVISED STRATIGRAPHIC NOMENCLATURE AND INTERPRETATIONS IN THE EAST-CENTRAL CARNARVON BASIN, W.A.

by W. J. E. van de Graaff, R. M. Hocking, and P. D. Denman

ABSTRACT

Stratigraphic nomenclature for the Lower Permian sequence in the Carnarvon Basin is simplified by changing the Lyons "Group" to formation rank, and its constituent "formations" to members of local significance only. The names "Nunnery Sandstone", and "Congo", "Monument", "One Gum", and "Curbur Formations", which have been used for various parts of the basal sandstone unit of the Wooramel Group, are discarded in favour of Moogooloo Sandstone.

The unconformity between the Callytharra Formation and the Moogooloo Sandstone marks a period of regional uplift with local faulting and tilting, and widespread subaerial erosion with karst development in places.

A new type section for the ?Tertiary Pindilya Formation is proposed, as the original type section consists of Permian Moogooloo Sandstone and is invalid.

INTRODUCTION

In 1976 the Phanerozoic sections of the Mount Phillips, Glenburgh and Byro 1:250 000 Sheet areas were mapped as part of the Carnarvon Basin mapping project. The area mapped covers the Bidgemia and Byro sub-Basins, and the easternmost part of the Merlinleigh sub-Basin (Fig. 21).

Condon (1967) presented a detailed nomenclature for the stratigraphic sequence in the area, and his scheme has essentially been followed in recent publications (e.g. Playford and others, 1975; Johnstone and others, 1976). Condon's terminology, which to a large extent follows usage in earlier publications by himself and his co-workers (e.g. Condon, 1954; Konecki and others, 1958) needs revision. Our reasons are the non-recognition of the formations of the Lyons "Group", the wish to stress the lateral continuity of the Moogooloo Sandstone, to simplify nomenclature, and the original selection of invalid type sections for the "Nunnery Sandstone", "One Gum Formation", and Pindilya Formation.

No nomenclature changes are yet proposed for the Carrandibby and Callytharra Formations, Jimba Jimba Calcarenite, Billidee, Keogh, Coyrie, and Madeline Formations, Bogadi Greywacke, and Warra Warringa Formation.

LYONS FORMATION

The name "Lyons Conglomerate", used by Maitland (1912) for the Permian glacial sediments in the Gascoyne River area, was changed to "Lyons Series" by Raggatt (1936) and was again amended to "Lyons Group" by Teichert (1950). Condon (192a, b; 1967) recognized the following formations within that group: "Austin Formation", "Coyango Greywacke", "Dumbardo Siltstone", "Koomberan Greywacke", "Mundarie Siltstone", "Thambrong Forma-

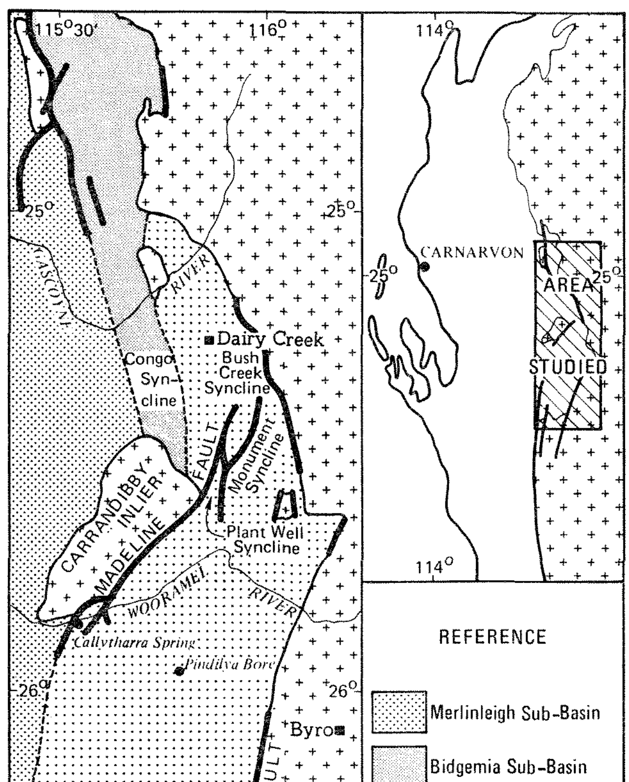

Figure 21. East–central Carnarvon Basin – localities discussed.

tion", and "Weedarra Shale". These formations were mapped in the Kennedy Range and Glenburgh 1:250 000 Geological Sheet areas by photo interpretation after completion of the field work (Condon, 1967, p. 14). However, Playford and others (1975) doubted whether they were valid mappable units. We have been unable to map these formations, although locally rock types have been found that fit the description of a formation previously mapped at that spot. Just as commonly, the exposed rocks do not resemble the formation descriptions at all. We therefore propose to change the Lyons "Group" to formation status, with the seven component formations being reduced to member rank. These members are of limited areal extent due to facies changes.

Konecki and others (1958) interpreted the contact between the Lyons Formation and the overlying Callytharra Formation as a disconformity. This contention is based on the absence of the Carrandibby Formation away from the Carrandibby Inlier. Condon (1962b, 1967, p. 14) however, considered the contact as an angular unconformity. This was based on his interpretation of virtually all faults in the Carnarvon Basin as angle-of-rest or abutment unconformities (Condon, 1956; 1968). Within the study area we have not seen any evidence of an unconformable relationship between these two units; on the contrary, gradational contacts between Lyons Formation and Callytharra Formation suggest a conformable relationship. The Carrandibby Formation is considered to be a lateral equivalent of the upper part of the Lyons Formation.

MOOGOOLOO SANDSTONE

The Moogooloo Sandstone, which is the basal unit of the Wooramel Group in the study area, was mapped by Condon (1962b; 1967, p. 84) as far south as the Congo Syncline. The formation consists of interbedded medium- to very coarse-grained to pebbly sandstone with minor interbeds of siltstone and fine-grained sandstone.

Lithologically very similar units, with identical stratigraphic position, crop out in the Bush Creek, Monument and Plant Well Synclines. In the Bush Creek Syncline these sediments have been called "Congo Formation", whereas in the other two synclines they were previously mapped as "Monument Formation" (Konecki and others, 1958; Condon, 1962b; 1967). Because of the homotaxial stratigraphic position and the lithological similarities we propose to drop the names "Congo Formation" and "Monument Formation" in favour of Moogoloo Sandstone.

On the southeastern side of the Carrandibby Inlier the basal sandstone unit of the Wooramel Group has previously been mapped as "Nunnery Sandstone" and "One Gum Formation". These two units have only been recognized in the vicinity of the type localities. In this area the Madeline Fault abruptly changes course from a northeasterly trend to an easterly trend for about 5 km, and then reverts to a northeasterly trend. Because of this change in course, a number of splay faults have formed to alleviate space problems. Previous workers mapped the splay faults that cut across the strike of the sequence, but did not recognize the most important subsidiary fault parallel to the strike, which causes a partial repetition of the basal sandstone unit of the Wooramel Group. The intense crumpling and drag folding in interbedded siltstone and sandstone, which occurs along part of the fault trace, was mistaken by Konecki and others (1958, p. 32) for synsedimentary slumping. This "slumping" they considered to mark the contact between the "Nunnery Sandstone" and the "One Gum Formation". In our structural interpretation, the "One Gum Formation" is largely a repetition by faulting of the "Nunnery Sandstone" which unconformably overlies the Callytharra Formation. Moreover, as both units are lithologically similar to the Moogooloo Sandstone, we propose to drop the names "Nunnery Sandstone" and "One Gum Formation" in favour of Moogooloo Sandstone.

On the Byro Sheet area the basal part of the Wooramel Group was mapped by Konecki and others (1958) as "Cubur Formation". In the type area along the northern part of the Meeberrie Fault (new name), the "Curbur Formation" unconformably overlies ?Carrandibby Formation or Lyons Formation. This resembles the situation west of Callytharra Spring, where the lithologically similar Moogooloo Sandstone oversteps the Carrandibby and Lyons Formations. Because of this we propose to drop the name "Curbur Formation" in favour of Moogooloo Sandstone. The sequence overlying the "Curbur Formation" was mapped by Konecki and others (1958) as Madeline Formation. It is, however, more similar to the generally well-bedded Keogh Formation and we map it as such.

SIGNIFICANCE OF PRE-MOOGOOLOO SANDSTONE UNCONFORMITY

The unconformity between the Moogooloo Sandstone and the underlying Callytharra Formation represents a major break in sedimentation. During this break significant erosion and gentle regional tilting took place, as well as localized, more pronounced tilting on the southern side of the Carrandibby Inlier.

The importance of this period of erosion is demonstrated in the Bidgemia—Congo Syncline area, by the presence beneath the Moogooloo Sandstone of stack-like pinnacles and mounds up to 30 m high, formed of resistant calcarenites of the Callytharra Formation. The "stacks" which were briefly described by Condon (1967, p. 85; 1968, p. 48) have been partly exhumed in the area centred on lat. 25°08′15″S, long. 115°36′45″E. They are elongate and aligned in rows in a roughly rectangular ground plan. The main elongation and alignment trends 120°-130°, reflecting a master-joint orientation which is clearly visible on aerial photographs. The joints were eroded out to form corridors 5 m to over 20 m wide, and these are filled with Moogooloo Sandstone which drapes over the "stacks" Clearly, deposition of the Moogooloo Sandstone was influenced by the joint-controlled erosional topography on the lithified and jointed Callytharra Formation. The basal part of the Moogooloo Sandstone that fills the corridors consists of fine- to medium-grained sandstone with rare trace fossils that indicate a shallow-marine origin. No coarse-grained siliciclastic deposits or limestone conglomerates have been seen overlying or between the "stacks". The known area with easily recognizable "stacks", i.e. higher than a few metres, measures about 11 km by 8 km (about 65 km^2) and the area where "stacks" are common is of the order of 330 km^2.

Condon (1962b; 1967, p.85) and Playford and others (1975) interpreted these pinnacles as sea stacks. We do not see how an extensive field of closely spaced sea stacks could be formed and preserved under the high-energy conditions prevailing along modern coasts with stacks. The large areal distribution and the lack of coarse-grained clastics, however, can be understood if the pinnacles and mounds formed a cone or tower-karst terrain with corridors, which was flooded and covered by sediment when the sea transgressed the area at the start of Moogooloo Sandstone deposition. The usage of the terms cone- and tower-karst does not imply that a tropical or subtropical origin is inferred for these forms. A cool to temperate climate is more likely to have prevailed during the Early Permian.

Further to the south, where the Callytharra Formation consists of less resistant, impure limestones, the evidence for important erosion is not as spectacular as in the Bidgemia area. South of the Congo Syncline the relatively pure, cross-bedded calcarenites of the upper Callytharra Formation disappear, and the formation consists of calcareous shale, marl and impure limestone. This facies transition represents a change from a relatively high-energy, shallow-marine environment to a lower energy, somewhat deeper environment. Significant uplift must therefore have occurred in those areas where this deeper water facies has been subaerially eroded prior to deposition of the Moogooloo Sandstone.

In the Callytharra Spring area both significant tectonic tilting, and reversal of movement along the Madeline Fault, took place prior to deposition of the Moogooloo Sandstone. West of Callytharra Spring flat-lying Moogooloo Sandstone, previously mapped as Pindilya Formation, progressively oversteps the Callytharra, Carrandibby, and Lyons Formations, which have an average tilt of about 8°. This tilting is due to the uplift of the Carrandibby Inlier along the Madeline Fault, which is a normal fault with east-block-down displacement. The type section of the Callytharra Formation is located on the up-thrown (western) block, and is about 100 m thick. A monotonous, poorly bedded claystone and siltstone sequence forms the upper 40 m of the type section. The fine grainsizes and the monotonous aspect of the sequence indicate a quiet, probably somewhat deeper marine environment for this part of the section. In the nearest occurrence of Callytharra Formation on the downthrown block, about 10 km to the northeast, this upper unit of claystone and siltstone is very thin or absent. This suggests more erosion prior to Moogooloo Sandstone deposition on the present down-thrown block than on the up-thrown block, which in turn suggests reversal of movement along the Madeline Fault in this area.

Just to the south of Callytharra Spring, at the "type" locality of the Pindilya Formation (see section on Pindilya Formation) movement of the Madeline Fault ceased during deposition of the Moogooloo Sandstone. At the southern end of the exposed Madeline Fault, the Moogooloo Sandstone consists of flat-lying sandstone and siltstone. Within this little-deformed sequence is a local, angular unconformity with beds tilted up to 15° because of fault drag along the Madeline Fault. The tilted sequence is unconformably overlain by flat-lying beds of identical facies which have not been noticeably affected by the Madeline Fault. Within 125 m the angular unconformity changes into a disconformity marked by scattered pebbles within an undisturbed flat-lying sequence.

The unconformity between the Callytharra Formation and the Moogooloo Sandstone thus represents a period of regional uplift and sub-aerial erosion, with locally important faulting and karst development.

PINDILYA FORMATION

The name Pindilya Formation was proposed by Konecki, Condon, Dickins, and Quinlan *in* McWhae and others (1958) for a ?Tertiary sandstone and conglomerate unit which unconformably overlies the Permian sequence in the Byro sub-basin and the southern part of the Bidgemia sub-basin. The "type" section is at lat. 25°53'24"S, long. 115°43'00"E, about 3 km southwest of Callytharra Spring. The "type" section which is 30 m thick, and its neighbouring cliffs, were carefully examined by us, and we consider that they consist of typical Moogooloo Sandstone. However, we do recognize a ?Tertiary sandstone and conglomerate unit which has the stratigraphic relationships and lithology of the Pindilya Formation as mapped by previous workers. Neither the current Australian Code of Stratigraphic Nomenclature nor its proposed revision are clear about procedures to follow in this situation. To avoid proliferation of names we propose to designate a new type section for the Pindilya Formation, and a full definition is given below:

Derivation of name: Pindilya Bore on Byro Staton, lat. 25°57'36"S, long. 115°46'12"E, Glenburgh Sheet area.

Distribution: Occurs as mesa cappings in the Dairy Creek-Muggon area.

Revised type section locality: Lat. 26°22'39"S, long. 115°47'24"E, Curbur Station, Byro Sheet area; on the western side of a low mesa, where the track from Salt Well to Swelt Bore joins the fence.

Lithology: Sandstone and granule to pebble conglomerate; commonly silcreted. At the revised type section the formation overlies with a sharp, erosive contact a well-developed soil that formed in Permian claystone. The basal 1.7 m consists of indistinctly bedded, well-sorted pebble conglomerate with pebbles ranging in size from 0.2 cm to 3 cm. This conglomerate unit grades up into 1.1 m of more distinctly bedded, very coarse-grained sandstone to granule conglomerate. The whole sequence is intensely silcreted.

Thickness: 2.8 m at the type locality; maximum thickness of up to about 5 m in karst-type solution pipes; commonly only a thin veneer of weathered-out pebbles.

Age: Morphostratigraphic and lithostratigraphic relations suggest a correlation with the Eocene Merlinleigh Sandstone.

Fossils: The only fossils found *in situ* are root casts. Konecki and others (1958, p. 56) stated: "Poorly preserved fossils (bryozoans, corals) were found on the surface of the basal siltstone of the One Gum Formation in its type section; these fossils were in similar chalcedonic preservation to those in the Merlinleigh Sandstone. Pindilya Formation caps nearby mesas." Because of their chalcedonic preservation the fossils, which were not determined, were thought to be derived from the Pindilya Formation. Our re-examination of the locality produced no further evidence as to whether these fossils are indeed from this formation.

Relationships: The Pindilya Formation unconformably overlies the Permian sequence. The unconformity is commonly marked by deep solution pipes that formed during a later period of lateritic weathering.

Mappability: The Pindilya Formation is a widespread mappable unit, but its recognition by photo-interpretation is difficult. The formation was laid down on an ?Early Tertiary erosion surface, and after erosion and dissection of both the pre-existing landscape and its Pindilya cover, intense lateritization and silcretization took place. These two types of duricrust have photopatterns which are little affected by changes in bedrock. Because of this it is difficult or impossible to determine by photo- interpretation whether or not a particular hill top has been completely stripped of its cover of Pindilya Formation.

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STRATIGRAPHIC TERMINOLOGY OF THE EARAHEEDY GROUP, NABBERU BASIN

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ABSTRACT

A sequence of Lower Proterozoic rocks in the eastern part of the Nabberu Basin is defined as the Earaheedy Group. Two subgroups are recognized, which reflect two major transgressive-regressive cycles of sedimentation. The lower is the Tooloo Subgroup, which consists of a basal clastic unit (Yelma Formation) overlain by iron-formation and shale (Frere Formation) with a carbonate and clastic unit (Windidda Formation) at the top. The Minigarra Subgroup consists of three predominantly clastic formations (Wandiwarra Formation, Princess Ranges Quartzite and Wongawol Formation) overlain by the Kulele Creek Limestone, with a clastic and minor carbonate unit (Mulgarra Sandstone) at the top of the sequence. The Earaheedy Group is possibly equivalent to parts of the Padbury Group in the western part of the Nabberu Basin, and either unconformable on, or equivalent to, parts of the sequence in the Glengarry Sub-basin.

INTRODUCTION

Lower Proterozoic sedimentary rocks flank the northern margin of the Archaean Yilgarn Block over a distance of 700 km between longitudes 117°E and 124°E. They are overlain unconformably in the north by the Middle Proterozoic Bangemall Group, in the east by Phanerozoic sediments of the Officer Basin, and in the west they become involved in the Gascoyne Mobile Belt. The term Nabberu Basin was introduced by Hall and Goode (1975) to include the repository of all these Lower Proterozoic rocks. Bunting and others (1977) express doubts on the validity of the term, but for the purposes of the present paper the term Nabberu Basin is used in the sense of Hall and Goode. The eastern part of the basin now forms a broad, east-southeast-trending synclinorium with a gently dipping southern limb and a tightly folded, and in places overturned northern limb. In the Glengarry Sub-basin gently folded sediments extend southwards onto the Yilgarn Block, and to the west the Padbury Group (Barnett, 1975) is tightly folded between Archaean basement highs.

Geologists of the Broken Hill Proprietary Co. Ltd (B.H.P.) began mapping the eastern part of the Nabberu Basin in 1973 and subsequently continued westwards into the Peak Hill and Robinson Range 1:250 000 Sheet areas and eastwards into the Stanley and Kingston 1:250 000 Sheet areas. New stratigraphic names were invoked to describe the sequence in the eastern part of the Nabberu Basin. These names have appeared in publications without adequate definition.

Systematic mapping of the eastern part of the Nabberu Basin by the Geological Survey of Western Australia began in the Kingston Sheet area in 1975, although parts of the southern and eastern edges had been mapped in 1973 (Bunting and Chin, 1975; Bunting, Jackson and Chin, 1975) and in 1972 by the Bureau of Mineral Resources (Jackson, in prep.). Mapping was completed in the Nabberu, Stanley and Wiluna 1:250 000 Geological Sheet areas in 1976 and mapping in the Glengarry 1:250 000 Geological Sheet area is in progress.

The purpose of this paper is to define the stratigraphic units used by B.H.P. which, with minor modifications, were used in the G.S.W.A. mapping.

STRATIGRAPHY

The area occupied by the Earaheedy Group is shown in Figure 22. Eight formations are recognized, comprising some 6 000 m of shallow water marine sediments. The type sections have all been established on the southern limb of the main synclinorium because of relatively easy access, better exposure and lack of structural complexity compared with the northern limb.

The unconformity between the Earaheedy Group and the underlying Archaean granitic and metamorphic rocks is well exposed in parts of the southern limb of the synclinorium, over the Malmac Dome (Horwitz, 1976) and in the northwest Nabberu Sheet area. To the west, however, the Earaheedy Group appears to be underlain by a thick sequence of sedimentary and basaltic rocks which may be either equivalent to, or unconformable beneath, the Yelma Formation. A similar situation exists along the central part of the northern limb of the synclinorium where a mixed unit of slate, phyllite, arenite and chert lies north of, and stratigraphically below, the arenites of the Yelma Formation. For the present these older rocks are excluded from the Earaheedy Group.

The division of the Earaheedy Group into the Tooloo and Miningarra Subgroups is based on the recognition of two distinct cycles of sedimentation, each comprising a transgressive phase followed by a period of regression. The subgroups are locally separated by a disconformity.

TOOLOO SUBGROUP

The Tooloo Subgroup consists of the Yelma, Frere and Windidda Formations.

Yelma Formation

The Yelma Formation is named from exposure 6 km northwest of Yelma outstation in the Kingston Sheet area. It is the unit of medium to coarse-grained quartz-rich clastic rocks which lies unconformably on the Archaean basement and conformably below the Frere Formation. At the type section, between grid references 473711 and 473712 on the Kingston Sheet, the formation is about 130 m thick. It thins to about 10 m in the southeastern part of the basin (Bunting and others, 1975).

The type Yelma Formation consists of buff-weathering, white to cream, medium to very coarse-grained, clean quartz sandstone, in places arkosic, with minor bands of quartz pebble or quartz cobble conglomerate near the base. The sandstone is generally flat bedded, with occasional cross bedding and ripple marks, and rare mud pellets. Thin chert and silicified carbonate beds occur locally within the sandstone along the southern limb of the synclinorium. On the northern limb the formation is much thicker (up to 500 m) and contains shale and chert beds. It is equivalent to the Malmac Formation of Horwitz (1976).

Frere Formation

The Frere Formation is a sequence of dominantly ferruginous chemical sediments and fine-grained clastics with minor carbonates and is named from the Frere Range along the northern side of Lake Nabberu in the Nabberu Sheet area. The base is taken at the top of the quartz sandstone of the Yelma Formation. In the Kingston Sheet area the top is taken at the first carbonate band which marks the base of the Windidda Formation, whereas to the west and around the northern side of the synclinorium, it is taken at the base of the fine-grained clastic sediments of the Wandiwarra Formation in which there are only rare and thin bands of iron-formation.

The type section is in the Frere Range in the Nabberu Sheet area, between grid references 364804 and 367809, where the middle part of the formation is well exposed in gorges. The total thickness of the formation is estimated to be 1 300 to 2 000 m, shallow dips making accurate measurement difficult.

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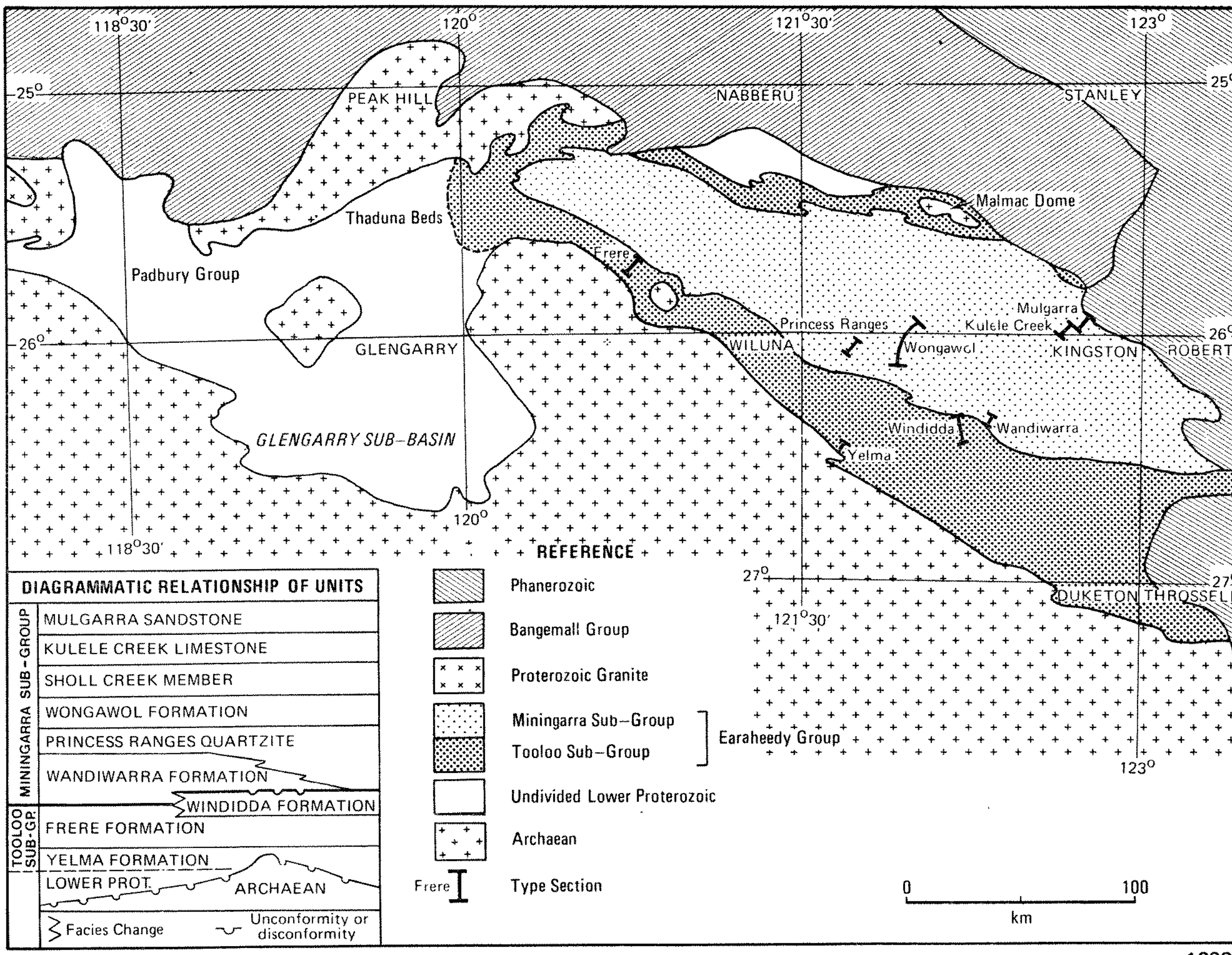

Figure 22. Regional setting of the Earaheedy Group.

The most conspicuous rock type is a clastic or pelletal-textured ferruginous chert in which rounded to angular grains of chert or ferruginous chert are set in a chert matrix. Locally this iron-formation is prominantly meso-banded, consisting of alternating layers of pelletal ferruginous chert and nonpelletal chert or hematitic shale. The ferruginous chert pellets are occasionally oolitic.

Clastic sequences up to 100 m thick form the bulk of the Frere Formation in the southeast part of the basin where the predominant rock type is buff, brown or maroon shaley siltstone with minor fine-grained sandy shale. The siltstone beds are finely laminated, with small-scale cross-bedding, and include thin chert bands in places.

Along the northern limb of the synclinorium the shale units have a strong slaty cleavage.

Stromatolitic carbonate, which marks the boundary between the Yelma and Frere Formations at several localities along the southern limb of the synclinorium, also occurs within the Frere Formation. These carbonate units form lenticular bodies up to 20 m thick and several kilometres long.

Windidda Formation

The Windidda Formation is that unit of carbonate and fine-grained clastic sediments lying between the Frere Formation and the Wandiwarra Formation. The base is taken at the base of the first carbonate unit above the thick iron-formations of the Frere Formation, and the top is the top of the uppermost carbonate-clast conglomerate band on which the sandstone of the Wandiwarra Formation rests. The type section is between points 8 km south and 5 km north-northwest of Windidda homestead, between grid references 533714 and 530727. Here the formation is approximately 1 200 m thick.

In the type section a basal unit consisting of a few metres of brown ankeritic carbonate with chert and stromatolitic bands is overlain by grey to pink laminated limestone. The limstones are locally conglomeratic and are interbedded with calcareous shales. The shales become more common higher in the sequence. The top of the Windidda Formation is not exposed in the type section, but about 25 km to the west-northwest the top is marked by a prominent 1 to 2 m-thick band of intraformational limestone conglomerate.

The Windidda Formation is confined to the southeastern limb of the synclinorium. In the Nabberu Sheet area, and along the northern limb, the stratigraphic position of the Windidda Formation is occupied by siltstone and fine-grained sandstone indistinguishable from similar rocks of the Wandiwarra Formation. This probably represents a deeper water facies in which carbonates were not deposited. A local disconformity occurs at the top of the formation where it is overlain by the transgressive Wandiwarra Formation.

MININGARRA SUBGROUP

The Miningarra Subgroup consists of the Wandiwarra Formation, Princess Ranges Quartzite, Wongawol Formation, Kulele Creek Limestone and Mulgarra Sandstone.

Wandiwarra Formation

The Wandiwarra Formation is named from Wandiwarra Well, 12 km east of Windidda homestead in the Kingston Sheet area, and is the unit of medium to fine-grained clastic sediments between the uppermost carbonate member of the Windidda Formation and the lowermost mature quartzite of the Princess Ranges Quartzite. In the type section (between grid references 547722 and 548724) it consists of fine-grained, pink to grey, finely laminated, cross-bedded micaceous sandstone with occasional ripple marks and small mud pellets. Interbedded with the fine-grained sandstone are 1 to 2 m bands of grey-brown, impure micaceous quartz arenite, and finely laminated micaceous shale. Total thickness in the type section is 350 m.

Where the Wandiwarra Formation overlies carbonates of the Windidda Formation, the basal bed is a poorly sorted glauconitic sandstone, but where the carbonates are absent, in the northern and central parts of the synclinorium, the shale unit overlying the Frere Formation is taken as the base of the Wandiwarra Formation.

The contact between the Wandiwarra Formation and the overlying Princess Ranges Quartzite is diachronous: the mature quartzites marking the base of the Princess Ranges Quartzite rest directly on the Windidda Formation in the east; to the west the Wandiwarra Formation thickens and the first mature quartzite appears higher in the sequence.

Princess Ranges Quartzite

The Princess Ranges Quartzite is named from the Princess Ranges in the Kingston Sheet area. It is the unit of predominantly medium to coarse-grained, quartz-rich clastic rocks that lies conformably between the Wandiwarra and Wongawol Formations. The base and the top are respectively, the bottom of the first massive, pale, crystalline quartzite overlying the Wandiwarra Formation; and the last bed of similar quartzite beneath the Wongawol Formation. The type section is along the unnamed creek that crosses the Princess Ranges between grid references 479762 and 483764.

The Princess Ranges Quartzite is dominated by three main units of massive orthoquartzite interbedded with fine sandstone and sandy siltstone. The formation is about 200 m in thickness at the type section, but it thickens to the southeast due to the diachronous nature of the lower contact.

The diagnostic rock type is a medium to coarse-grained, supermature, quartz-cemented orthoquartzite. Glauconite is present in some units, and fine lamination, cross bedding, ripple marks and mud pellets are common. Ferruginous spots up to several centimetres across give the quartzite a speckled or blotchy appearance. The spots are probably weathered rhombs of carbonate cement.

Wongawol Formation

The Wongawol Formation ("Wongawol Sandstone" of Hall and Goode, 1975) is named from Wongawol homestead in the Kingston Sheet area, and is the unit of fine-grained sandstone, siltstone and minor carbonate rocks between the Princess Ranges Quartzite and the Kulele Creek Limestone. The type section is along the Wiluna-Carnegie road between grid references 504752 (Kingston Sheet) and 513777 (Stanley Sheet).

The lower part of the Wongawol Formation is a monotonous sequence of grey to pinkish brown, finely laminated, very fine sandstone and siltstone. Abundant sedimentary structures include small-scale festoon cross-bedding, ripple marks, small scour channels, load casts, slump rolls and rare mud cracks.

Thin carbonate beds and carbonate breccia beds are interbedded with the sandstone in the upper part of the Wongawol Formation. The *Sholl Creek Member* (equivalent to "Sholl Creek Formation" of Hall and Goode, 1975) is taken from the lowermost carbonate bed to the top of the Wongawol Formation, and is well exposed along Sholl Creek between grid references 531779 and 528786 (Stanley Sheet). The base of the member marks a transition towards carbonate sedimentation, but the basal carbonates are lenticular. The Sholl Creek section supplements the Wongawol Formation type section, the corresponding part of which is poorly exposed. The most abundant rock type in the Sholl Creek Member is a fine-grained, arkosic micaceous sandstone similar to that in the lower part of the Wongawol Formation. In addition to the carbonate interbeds, micaceous maroon and chocolate shales are also interbedded and these become abundant towards the top of the Sholl Creek Member.

Total thickness of the Wongawol Formation is estimated at 2 000 m, of which the upper 600 m constitute the Sholl Creek Member. However, the shallow dips and gentle folds make calculations difficult, and these figures may be over-estimates. The formation represents a transition from shallow water clastic to carbonate sedimentation.

Kulele Creek Limestone

The Kulele Creek Limestone, which is named from Kulele Creek in the Stanley Sheet area, is the formation of carbonate and minor clastic sediments lying between the Wongawol Foramtion and the overlying Mulgarra Sandstone. The formation is about 300 m thick at the type section, which is in the vicinity of Mount Throssell between grid references 581767 (Kingston Sheet) and 586770 (Stanley Sheet). The base of the Kulele Creek Limestone is taken at the appearance of metre-thick stromatolitic carbonate and cross-bedded calcarenite beds, a horizon which approximately corresponds to the predominance of carbonate beds over shale beds, as distinct from the reverse in the upper part of the Wongawol Formation. The top is taken at the top of a thick carbonate band beneath the arenite of the Mulgarra Sandstone.

The Kulele Creek Limestone consists of bands of calcarenite, carbonate conglomerate, stromatolitic limestone, oolitic limestone and purple shale, commonly forming cyclic sequences 5 to 10 m thick. The stromatolites form domal structures several metres across, commonly with carbonate clasts and ooliths in the interdomal areas. These are particularly well preserved in an outlier of the lower part of the sequence, 60 km west of the type section, at grid reference 516777 (Stanley Sheet). Several prominent sandstone bands occur in the Kulele Creek Limestone between 150 and 200 m above the base.

The Kulele Creek Limestone conformably overlies the Sholl Creek Member of the Wongawol Formation, and the top is marked by the sudden incoming of a transgressive arenite sequence.

Mulgarra Sandstone

The Mulgarra Sandstone is named from Mulgarra Pool in the northeast corner of the Kingston Sheet area. Its type section is in the Timperley Range area between grid references 589767 (Kingston Sheet) and 594776 (Stanley Sheet), where it is only poorly exposed. Total thickness is probably greater than 100 m. At the base, a thick quartz arenite rests with a sharp, probably disconformable, contact on the underlying Kulele Creek Limestone.

The dominant lithology is a medium-grained grey to brown ferruginous quartz arenite with minor glauconite. The middle part of the exposed sequence contains minor shale and carbonate bands. Sedimentary structures include shale pellets, small slump rolls, small cross beds and rare load casts.

The Mulgarra Sandstone is the youngest known unit of the Earaheedy Group. It is exposed only in the extreme eastern part of the Nabberu Basin where it occupies the centre of the synclinorium.

AGE AND REGIONAL CORELATIONS

The Earaheedy Group is considered to be Lower Proterozoic in age for several reasons. The group unconformably overlies Archaean rocks and is unconformably overlain by the Bangemall Group which has been dated at about 1 100 m.y. The thick pelletal iron-formations of the Frere Formation are of the Lake Superior type which is generally considered characteristic of the Lower Proterozoic. Microfossils from the Frere Formation are identical to those from the Lower Proterozoic Gunflint and Biwabik Iron Formations of the Lake Superior district (Walter and others, 1976).

Glauconite from the Yelma Formation in the Duketon Sheet area (southeast Nabberu Basin) gave K-Ar ages of around 1 700 m.y. and Rb-Sr ages of between 1 590 and 1 710 m.y. (Preiss and others, 1975). Horwitz (1975) reports a K-Ar age of 1 685 m.y. for glauconite which, using his coordinates, comes from the base of the Wandiwarra Formation in the northwest corner of the Kingston Sheet area. Because of the possibility of argon loss these must be regarded as minimum ages.

Relationships between the Earaheedy Group and the Lower Proterozoic Padbury Group (Barnett, 1975) to the west are uncertain. Pelletal iron-formations are present in the Padbury Group, although they are a minor constituent, and a correlation of at least the upper part of the Padbury Group with the Frere Formation is possible. The bulk of the Earaheedy Group may therefore be younger than the Padbury Group.

The Glengarry Sub-basin (Fig. 22) contains a basal quartz arenite unit overlain by a mixed unit of shale, marl, carbonate, greywacke and arenite. This mixed unit is probably a facies variant of the Thaduna Beds. It is not clear at present whether the basal arenite is a diachronous shore facies of the mixed unit and continuous with the Yelma Formation, or whether the Yelma Formation is unconformably above the entire sequence in the Glengarry Sub-basin.

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PRELIMINARY SYNTHESIS OF LOWER PROTEROZOIC STRATIGRAPHY AND STRUCTURE ADJACENT TO THE NORTHERN MARGIN OF THE YILGARN BLOCK

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ABSTRACT

An east-west elongated synclinorium, filled with Lower Proterozoic sediments, unconformably overlies the northern margin of the Yilgarn Block and is unconformably overlain by the Middle Proterozoic Bangemall Group. Two sub-basins are described. The western, Glengarry Sub-basin, contains the oldest sediments, which are a basal sandstone followed in the southeast by a shelf sequence of shales, marls and carbonates and in the northwest by an axial sequence of shale, arkose, greywacke and interbedded basalt. The youngest sediments in the sub-basin are the thick coarse-grained clastics, iron-rich shales and banded iron-formation of the Padbury Group. The Earaheedy Group occupies the eastern (Earaheedy) sub-basin and unconformably overlies part of the older sequence in the Glengarry Sub-basin. The basal pelletal iron-formations and iron-rich shales are possible equivalents of the upper part of the Padbury Group. The succeeding quartzites, fine sandstones and limestones are the youngest rocks in the basin.

The Lower Proterozoic rocks are located on an east-west trending junction between Archaean granite-greenstone and gneissic terrains, marking the transition from cratonic to mobile basement, and the basin structure is related to this underlying major crustal suture. On the southern margin of the present extent of the Lower Proterozoic rocks, the sediments are relatively flat lying on the Kingston Platform. The Stanley Fold Belt lies to the north of the Kingston Platform and is an arcuate zone of tight folding. In the centre the north-northwest trending Wiluna Arch narrows the present basin extent, and the sediments there are faulted by the Celia Lineament. In the extreme west, sediments have been involved in the dynamothermal metamorphism associated with the Proterozoic Gascoyne Province, forming banana-shaped synclinal zones truncated by the basement highs of the Yarlarweelor Gneiss Belt, and the Marymia Dome. Within the fold belt narrow zones occur where tectonically active basement has controlled sedimentation and extrusion of basic volcanics. The Goodin Dome is associated with such zones. In the east, tight folds are oriented east-west and are overturned to the south. Granite basement comes to the surface in the Malmac Dome.

Correlation between these Lower Proterozoic rocks and the Hamersley Basin has been suggested by several previous authors, but is considered to be unlikely due to differences in lithology and radiometric ages.

INTRODUCTION

A complex arcuate belt of Lower Proterozoic sedimentary rocks lies with marked angular unconformity on the Archaean Yilgarn Block along its northern margin, and is unconformably overlain by Middle Proterozoic rocks of the Bangemall Basin. Hall and Goode (1976) introduced the term "Nabberu Basin" to include all these lower Proterozoic rocks, and this term has been subsequently used in a number of publications. However, in view of the uncertainties over relationships between the two sub-basins (described below) we feel that it is premature to say whether the sub-basins have sufficient stratigraphic and structural unity to justify inclusion within a single named (Nabberu) basin; it may be that when better evidence is available concerning their relative ages it will be more appropriate for each to be raised to basin status. We nevertheless find the term Nabberu Basin convenient in describing these rocks, and use it in this paper in the sense of Hall and Goode, with the proviso that further work is required to prove its validity.

Systematic mapping by the Geological Survey of Western Australia has previously skirted around this basin (Bunting and Chin, 1975; Barnett, 1975), and only recently have programmes been directed to the basin itself. Although much of this current work is incomplete, and previously mapped areas need further reappraisal, a preliminary synthesis of recent mapping is warranted, particularly in view of the considerable differences of opinion that are emerging regarding the stratigraphy, age and evolution of the basin. This paper is based on systematic mapping of the Kingston, Stanley, Nabberu, Glengarry and Robinson Range 1:250 000 Sheet areas, and a re-examination of the Peak Hill Sheet area. This re-examination, which has resulted in a major reinterpretation of the earlier work by MacLeod (1970), but still left many problems outstanding, was an attempt to relate the Lower Proterozoic rocks (formerly thought to be Archaean) of Robinson Range (Barnett, 1975) to those rocks in the Glengarry and Nabberu Sheet areas.

STRATIGRAPHY AND SEDIMENTATION

The usage of the term Nabberu Basin, given in the introductory section, refers only to the present aspect of the unit, rather than its palinspastic limits before the tectonic effects of the Gascoyne Province, or the unconformable deposition of the Bangemall Group. The basin is broadly synclinorial, and neither the southern unconformity with the Archaean Yilgarn Block, nor the basement highs along the northern margin signify its shape as a sedimentary basin, although the basement highs may have directly influenced sedimentation.

For description and analysis of the basin, it has been divided into sub-basins (Fig. 23). Here again, the areas (or volumes) occupied by these sub-basins do not necessarily describe the original extent of the sub-basin.

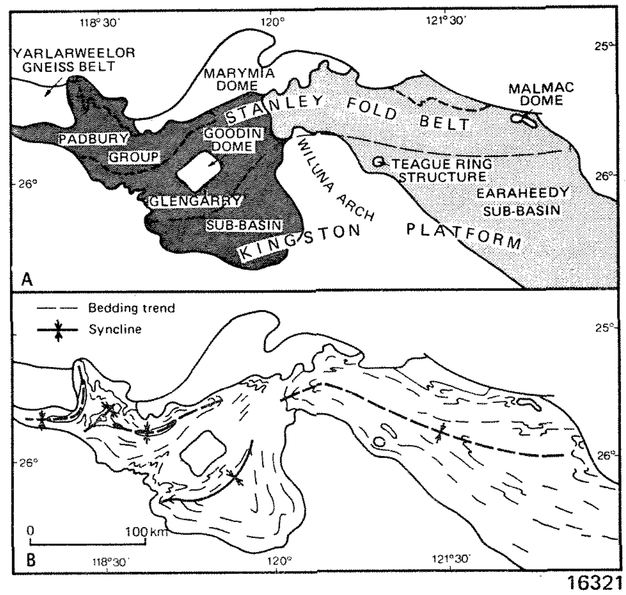

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Figure 23. A – Major structural units of the Nabberu Basin. B – Lithological trends and major synclines of the Nabberu Basin.

GLENGARRY SUB-BASIN

This sub-basin contains the oldest rocks in the Nabberu Basin. It is presently revealed as a lobe or embayment of transgressive shelf-type sediments onto the Yilgarn Block, together with a mixed sequence of arkose, greywacke and mudstone in the axial portion abutting the Marymia and Goodin Domes, and a younger succession (Padbury Group) of coarse-grained clastics passing upwards into iron-rich shale and banded iron-formation (Fig. 24).

The stratigraphy is not fully known, due mainly to complex facies changes within the flysch-type sequence in the axial portion. However, a relatively simple stratigraphy is recognized in the shelf-type sequence in the lobe to the south, as outlined below. The terms Finlayson Sandstone and Maraloou Formation are new names and will be defined by Elias and Bunting (in prep.).

Finlayson Sandstone

This is a basal formation, consisting of fine-grained, supermature, silica-cemented quartz arenite with interbedded shales. The sandstone displays cross bedding and ripple marks and is considered to be a transgressive beach deposit. It is about 1 000 m in thickness, and blankets the contact along the entire southern extent of the unconformity. It appears to floor the entire sub-basin, since it occurs around the Goodin Dome, and identical quartz arenites occur along the tectonized northern margin with the Marymia Dome north of Thaduna.

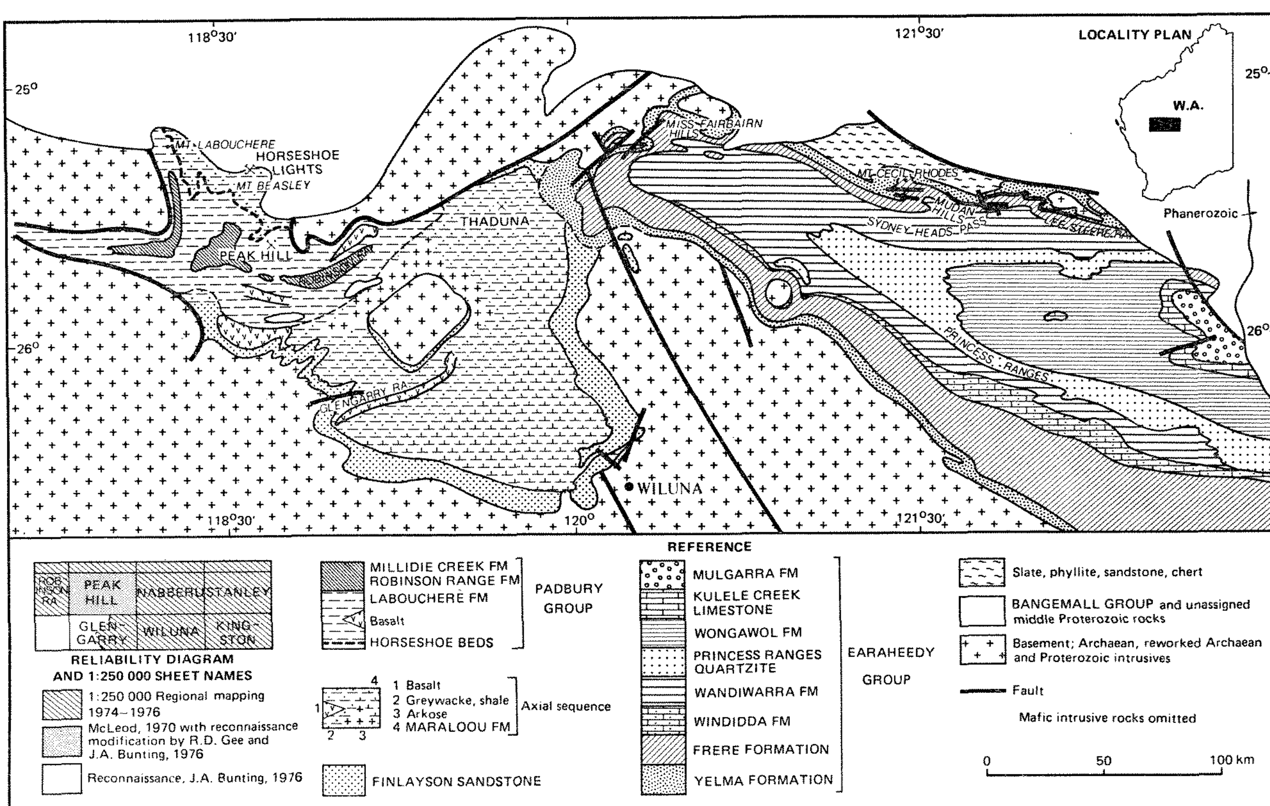

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Figure 24. Stratigraphy of the Nabberu Basin.

Maraloou Formation

This overlies the Finlayson Sandstone and consists of interbedded shale, siltstone, marl, stromatolitic carbonate, silicified carbonate and thin arenite beds. It is about 1 000 m in thickness in the southern lobe, and thickens considerably to the north and west toward the axial portion of the sub-basin, where arkose, greywacke and basalt become important. At the furthest traceable westerly extent along the southern margin, the level of the Maraloou Formation (immediately overlying the Finlayson Sandstone) is occupied by talcose siltstone and magnetite-rich lithic wacke with abundant cross bedding.

The Axial Sequences

Thick interbedded cleaved greywacke and purple slate containing volcanic debris (Trendall, 1970) occur in the Thaduna area, where they have been called Thaduna Beds (MacLeod, 1970). The stratigraphic position and significance of these rocks have long been a mystery. MacLeod envisaged them to have accumulated from turbidity currents flowing off an actively rising and eroding volcanic pile. This model is supported by the association of greywacke and basalt elsewhere in the axial portion of the Glengarry Sub-basin, particularly on the southern sides of basement highs.

Sequences of arkose, up to 400 m thick, occur in areas lacking the basalt volcanicity, for example on the northern side of the Goodin Dome where they overlie poorly developed Finlayson Sandstone, and in the nose of the Robinson Range Syncline. Interbedded greywacke and arkose also occur east of the Glengarry Range.

A thick sequence of mafic greywacke and purple slate occurs in the Horseshoe Lights mine area, apparently conformably below the Horseshoe Beds (MacLeod, 1970). These are identical to, and are here correlated with, the Thaduna Beds, and are considered to be the northwesterly extension of the rocks of the axial sequence beneath the Padbury Group. These rocks pass downwards (northeasterly) into recrystallized chert, quartz-muscovite-albite schist and sheared felsic volcanic agglomerate.

The greywacke rocks of the Horseshoe Lights mine area were mapped as "Peak Hill Beds" by MacLeod (1970). However, this stratigraphic term is not used here, because the Peak Hill Beds were intended for those rocks in the Peak Hill mine area, which are now largely assigned to the Labouchere Formation.

These thick greywacke, shale, basalt and arkose sequences in the axial part of the sub-basin are a deeper water facies of the shelf sediments represented by the Maraloou Formation.

Padbury Group

The Padbury Group occupies a complex-shaped synclinal zone in the western part of the Nabberu Basin. The group was defined by Barnett (1975) after mapping in the Robinson Range Sheet area, to include the conformable sequence of Labouchere, Robinson Range and Millidie Creek Formations. The lower two of this group were extensions of the stratigraphic units of MacLeod (1970) in the Peak Hill Sheet area.

The reappraisal in the Peak Hill mine-Horseshoe Lights mine area has cast doubts on the identity of the Peak Hill Beds. This term was applied to quartz-muscovite phyllite, chlorite schist, conglomerate and quartz arenite in the Peak Hill mine area, but these are now considered to be the direct continuation of the arenaceous Labouchere Formation from the type section at Mount Labouchere. The Labouchere correlatives at the Peak Hill mine area are in tectonic contact with the reworked Archaean basement rocks in the Marymia Dome, and so the stratigraphically lower units are structurally eliminated.

Stratigraphic units lower than the Labouchere Formation, which include the type Horseshoe Beds (banded iron-formation) and a thick greywacke sequence, do occur in the Mount Beasely-Horseshoe Lights mine area. The greywacke is correlated with the Thaduna Beds.

The Horseshoe Beds, a unit of laminated iron oxide and chert with hematitic maganiferous shale, 100 m thick, can be followed apparently conformably beneath the Labouchere Formation to the Peak Hill mine area, where it is structurally cut out against the Marymia Dome. It does not reappear on the southern side of the Robinson Range Syncline.

The Labouchere Formation therefore appears to be the lowest continuous unit of the Padbury Group, below which there may be a regional disconformity. In this synthesis, the Horseshoe Beds are grouped with the axial sequence, although their exclusion from the Padbury Group is arbitrary and provisional at this stage.

The stratigraphy of the Padbury Group is summarized below.

Labouchere Formation (lowermost): This is 5 000 m thick, and consists of mature quartz arenite, granule and boulder conglomerate, sericitic schistose sandstone, sericitic and chloritic phyllite and lenticular basalts. The boulder conglomerates are unusual, consisting of boulders, up to 2 m in diameter, of mature quartz arenite very similar to the Finlayson Sandstone, in a semimature quartz arenite matrix. Another unusual rock type is talc-chlorite phyllite, in which ghost outlines of rod-shaped clasts of talc-chlorite rock up to 10 cm in diameter, can be recognized in a similar matrix.

Robinson Range Formation: This is about 3 500 m thick, consisting dominantly of hematitic phyllite, commonly with small porphyroblastic magnetite, and laminated quartz-magnetite-hematite-chlorite rocks.

Millidie Creek Formation: This is at least 1 500 m in thickness, and consists of hematitic shale, feldspathic wacke, chert, carbonate, and prominent banded iron-formations. The iron-formations are chert-magnetite-hematite rocks, and clastic oolitic textures have been observed.

In summary, the rocks of the Padbury Group are dominated by iron-rich shales, banded iron-formation and shallow water arenaceous rocks. This contrasts with those in the axial sequence, but has broad similarities with the Earaheedy Group.

EARAHEEDY SUB-BASIN

The eastern part of the Nabberu Basin is occupied mainly by the Earaheedy Group, a shelf-facies sequence of shale, sandstone, limestone and pelletal iron-formation, 6 000 m in thickness. New stratigraphy has been presented (Hall and others, 1977), and this group will be fully described in later publications.

Two cycles of marine transgression and regression have been recognized, the first cycle deposited arkose, sandstone and conglomerate of the Yelma Formation directly onto the peneplaned Archaean basement to the south, and onto Glengarry Sub-basin sediments to the west. This was followed by shallow water deposition of pelletal iron-formation of the Frere Formation and stromatolitic limestone and shale of the Windidda Formation.

A disconformity is present at the base of the Wandiwarra Formation, a shallow water shale and sandstone unit with edge-wise limestone breccia, marking the beginning of the second transgressive cycle. This is overlain by the mature, orthoquartzitic Princess Ranges Quartzite, then interbedded fine sandstone, siltstone, mudstone and limestone of the Wongawol Formation. This unit probably records the deepest marine deposition in the Earaheedy Group and is overlain by the Kulele Limestone, which contains reef stromatolites and calcarenites. The highest unit is the Mulgarra Sandstone which resembles the Wongawol Formation.

A sequence of magnetite phyllite, schistose wacke, and chert occurs below the Earaheedy Group on the northern side of the Earaheedy Sub-basin. Its stratigraphic position is uncertain, but it lies below the basal unit of the Earaheedy Group, and consists of phyllitic and schistose rocks of higher metamorphic grade than the adjacent Earaheedy Group. An unconformity, or more probably, a tectonised unconformity, is inferred, but not established. These rocks are included in the Earaheedy Sub-basin for convenience, but possibly correlate with rocks in the Glengarry Sub-basin.

REGIONAL CORRELATIONS

Earaheedy and Glengarry Sub-basins

Lithological contrast is the basis for distinction between these two sequences. This distinction even extends to the basal orthoquartzitic sandstones of each basin. The Yelma Formation is less well sorted and much more feldspathic than the Finlayson Sandstone. Each formation displays its identifying features for distances of over 300 km.

The nature of the boundary between the two sequences has not been conclusively established, but the regional pattern of rock distribution and structure (Fig. 24) is *prima facie* evidence that the Earaheedy Group unconformably overlies the rocks of the Glengarry Sub-basin. Thus lithological trends in the Thaduna area appear to be truncated by the closure of the Yelma Formation around the regional syncline.

This interpretation conflicts with that of Horwitz (1975) who infers that the rocks of the Glengarry Sub-basin are younger than the basal formation of the Earaheedy Group. It also does not accord with Hall and Goode (in prep.) who equate the Yelma Formation and Finlayson Sandstone, and postulate that the Maraloou Formation is an offshore facies of the Yelma-Finlayson unit.

Padbury Group—axial sequence

The Padbury Group (from the Labouchere Formation upwards) undoubtedly overlies the rocks of the axial sequence north of the Goodin Dome and in the Horseshoe Lights mine area. The outstanding question is the nature and status of the dividing surface, whether it is conformable or unconformable. Possible correlatives of the Labouchere Formation may exist in the axial sequence east of the Glengarry Range.

Earaheedy-Padbury Groups

In view of the above relationships, it is possible that the Earaheedy and Padbury Groups may be facies variants of temporal equivalents. Both contain shale, carbonates, quartz arenite, and more significantly pelletal-textured iron-formation. These textures, whilst not being common in the Robinson Range and Millidie Creek Formations are sufficiently distinctive and rare in Western Australia to suggest a correlation with the Frere Formation. Precise correlation can be rejected as thicknesses, lithologies and sequences do not match at the formation level.

However, it may be that the Millidie Creek-Robinson Range interval is a deeper water facies of the Frere Formation. In this respect it is notable that Hall and Goode (in prep.) consider the Frere Formation to have formed in shallow water progressively deepening to the north and west.

STRUCTURE

WILUNA ARCH

The regional structure of the Nabberu Basin is an arcuate synclinorium in which fold trends swing from east-northeast in the west to east-southeast in the east (Fig. 23). The inflection of the arc lies on the narrowest part of the basin. This corresponds to the separation of the Glengarry and Earaheedy Sub-basins, and is a structural culmination, caused by a broad gentle northwest-trending high called the Wiluna Arch.

A north-northwest trending fault lies centrally in the Wiluna Arch in the Archaean basement. It cuts the unconformity and displaces the Yelma and Frere Formations. It seems to be a young expression of the Celia Lineament (Gower, 1974; Bunting and Williams, 1976), a major lineament that has played a role in greenstone belt evolution in the Archaean.

The Wiluna Arch and the Celia Lineament are examples of the north-northwest structural grain of the Yilgarn Block influencing the evolution of the Nabberu Basin.

KINGSTON PLATFORM

The term platform is used in the sense of Gary and others (1972), and is applied to that part of the Yilgarn Block that is covered by gently tilted Nabberu Basin sediments.

The demarcation between the Kingston Platform and the Stanley Fold Belt is taken as the appearance of minor folds with related slaty cleavage. It is postulated that this line represents, in the cover sequence, the buried expression of the northern margin of the Yilgarn Block. South of this line the basement escaped post-Archaean dynamothermal reworking.

Two directions of minor folds, lacking related slaty cleavage, are recognized in that part of the Kingston Platform occupied by the Earaheedy Sub-basin; (1) an early period of monoclinal to asymmetrical folds with axial surfaces striking 300° and dipping steeply north; (2) open symmetrical folds with axes trending approximately 030°. A late period of warping along north-south axes has resulted in gentle dome and basin style of folding in the vicinity of the main synclinorial axis north of the Princess Ranges.

Teague Ring Structure

Only the Teague Ring Structure disturbs the gentle undulatory nature of the Kingston Platform. It contains a circular core of adamellite and syenite surrounded by a circular rim syncline in the cover sequence. Steeper dips on the northeastern arc than on the southwestern arc define a plane of symmetry trending approximately 040°.

Two possible explanations for this unusual structure were advanced by Butler (1974); a meteorite impact, and a diapiric intrusion. Horwitz (1975) suggested an origin by interference of mild folds. There is sufficient evidence to relate this structure to both the regional structural pattern, and the occurrence of syenite. The favoured interpretation involves cold re-emplacement of a plug of syenite, possibly at high strain rates, by localized compression stresses related to the regional 300° fold trend. Further work including radiometric dating of the syenite is being undertaken on this structure.

STANLEY FOLD BELT

This term is applied to that part of the basin that is affected by moderate to tight folding, low grades of metamorphism, cleavage generation and the tectonic emplacement of basement domes. It is the easterly continuation of the intense dynamothermal Proterozoic deformation that affected the Archaean basement and Lower Proterozoic supracrustal rocks of the Gascoyne Province.

Western part

Four main synclines arranged in a crude echelon fan are recognized in the western part of the Stanley Fold Belt. The westernmost syncline is banana shaped in plan, being an arcuate structure trending approximately north-south and wrapping around the bulbous eastern edge of the Yarlarweelor Gneiss Belt. The western limb of this syncline is sheared out and is completely missing. The next syncline to the east is an irregularly crumpled amoeboid-shaped structural basin that displays both north-south trends and east-northeast trends. The Robinson Range Syncline further to the east again has a banana shape but is oriented east-northeast and is arcuate to the southwestern edge of the Marymia Dome. The easternmost syncline, on the southern side of the Goodin Dome, is north-northeasterly in trend and defines the transition into the Kingston Platform in the Glengarry Sub-basin. All these folds result from the interaction of the regional east-northeast trend and the interference effects of rising and merging basement domes, and demand at least two phases of regional folding. Regional and minor structures along the contacts indicate that the Yarlarweelor Gneiss Belt has been upthrust towards the east and the Marymia Dome upthrust towards the south.

Evidence of polyphase deformation on a minor scale is common. This includes transposition of phyllitic schistosity to produce a second generation phyllitic schistosity, refolded structures in the Peak Hill mine area, and a number of late penetrative strain-slip and crenulation cleavages.

In the area surrounding the Goodin Dome, folds on north-northeast axes are developed in corridors on either side of the rhomb-shaped dome. Shadow effects are present adjacent to the northeastern and southwestern faces of the dome implying basement block tectonics. Deformation in the flanking corridors has certainly affected the basement as the unconformity on the southwestern margin of the Glengarry Sub-basin is tightly folded. This northeasterly fold trend continues into the Thaduna area where the fold plunges are variable.

West-to-east transition

Interference fold patterns are again developed in the connecting zone between the eastern and western parts of the Stanley Fold Belt, in the Miss Fairbairn Hills area. Domes and basins are developed particularly along the unconformity of the Yelma Formation and the underlying granite. This gives the false impression of intrusive domes. These interference patterns are related to the easterly transition from east-northeast to east-southeast fold trends.

The age relations of the regional folds in this part of the fold belt need to be resolved as they should provide valuable evidence on the relative ages of the sequence in the Glengarry Sub-basin, and the Earaheedy Group. The folding may either be the result of one phase of arcuate, non-cylindroid folding that swings in harmony with the inferred buried position of the stabilized Yilgarn Block, or the expression of regional folding of the Earaheedy Group still later than the polyphase deformation to the west.

Eastern part

The transition from the Kingston Platform to the Stanley Fold Belt is quite rapid, and was originally mapped as an unconformity by Talbot (1928). Within the fold belt concentric-style folds, generally with very gentle east-southeast plunging axes, progressively tighten and increase in amplitude to the northeast. At the same time the folds develop asymmetry indicating overfolding from the northeast, and slaty cleavage becomes stronger.

Deformation is most intense along the northern margin of the basin, in the zone from Malmac Dome to 80 km to the west-northwest. Granite basement of presumed Archaean age (Horwitz, 1975) is exposed in the Malmac Dome which is unconformably beneath the Yelma Formation. On the southern side, the Yelma Formation dips off the dome quite steeply and is immediately involved in folding; however, on the actual dome and to the north, dips are gentle. Here again, basement has participated in the deformation.

Subparallel ridges of Yelma and Frere Formations extending west-northwest from the Malmac Dome outline large tight parasitic folds with strong slaty cleavage. Axial surfaces dip steeply north and the long limbs are generally overturned. To the east of Sydney Heads Pass, folds display Z-symmetry and plunge west at 10-20°, whereas those to the west near Mount Cecil Rhodes display S-symmetry and plunge 30-60° east. This change in plunge may represent a late synclinal cross fold. The western group of parasitic folds contain numerous sinistral faults. Small steep north-dipping thrusts associated with the asymmetric folds in the Sydney Heads Pass area indicate shortening and hence compression from the north. The contact between the Yelma and Frere Formations in the Mudan Hills and Lee Steere Range is faulted for much of its length, and a fault breccia is developed at the contact. This dislocation is subparallel to the bedding and is folded by the main deformation, but it is not clear whether the dislocation is due to an early thrust fault, or to slippage due to competency differences during folding.

STRUCTURAL DOMES IN THE STANLEY FOLD BELT

Considerable importance is attached to the granitoid domes that occur in the Stanley Fold Belt, as they all appear to have been emplaced into the deformed strata, yet no evidence of intrusive contacts with the sediments of the Nabberu Basin have been observed. The whole Nabberu Basin is singularly devoid of any granite, pegmatite or aplite dykes and veins. Undoubted unconformable contacts with the Yelma Formation are observed on the Malmac Dome and in the zone of interference domes and basins at the eastern end of the Marymia Dome.

Goodin Dome

The actual contact with this dome has not been observed but two lines of evidence point to an unconformable contact:

(a) the presence of the Finlayson Sandstone on the southern sides of the dome,

(b) the presence of arkose draped around the northern sides of the dome.

These observations further suggest that the granite, which is presumed to be Archaean, was a basement high during sedimentation.

Yarlarweelor Gneiss Belt

This is part of the basement that forms the western termination of the Nabberu Basin, and provides clues to the nature of the Marymia Dome. The belt consists of gneissic granitoid with abundant remnants of lineated quartzite, metamorphosed banded iron-formation, metasedimentary calc-silicate rocks, mafic and ultramafic pods of granulite or amphibolite facies metamorphism and quartz-muscovite schist. Elias and Williams (in prep.) consider this assemblage to be an older Archaean gneiss terrain, folding; however, on the actual dome and to the north, intruded by Proterozoic granites, and subsequently retrogressed by discrete mylonitic and cataclastic shear zones.

Intense shearing and mylonitization is a feature of the Padbury Group contact, and possibly about 5 km of sedimentary thickness is missing at the contact. Infolded wedges of Padbury Group also occur within retrogressed zones in the gneiss.

The Yarlarweelor Gneiss Belt is considered to be a bulbous segment of basement that has risen upwards and eastwards, possibly driven by rising Proterozoic granites well within the bulb, to become tectonically emplaced into the overlying sediments. It therefore has some features of a mantled gneiss dome.

Marymia Dome

This dome also contains the metamorphic rocks and gneissic granitoid that suggest an Archaean gneiss terrain, together with granulated granitoids of more magmatic appearance. These assemblages appear to be more prevalent in the southwestern half, whereas in the northeastern part granite-greenstone assemblages make an appearance.

Where it abuts the correlative of the Labouchere Formation along the western part of the southern margin, the contact is sinuous, but strictly concordant over a distance of 30 km. Along the length of this contact, no evidence of granitoid intruding sediment has been observed. Where observed, the actual contact is a shear zone, in places a mylonite, dipping steeply toward the granitoid. Penetrative cataclasis is prevalent in the granitoid, and shallow plunging fold mullions and phyllitic schistosity are developed in the adjacent quartz arenite and pelite. Here again, possibly in excess of 5 km of sedimentary sequence has been thrust out by movement on this contact.

The southwest part of the Marymia Dome is considered to represent the easterly continuation, beneath the Stanley Fold Belt, of the Yarlarweelor Gneiss Belt; and to be a tectonically activated basement segment that, in this area, moved upwards and to the south. By analogy with the gneiss belt, it is possible that intrusive Proterozoic granites occur in the dome. The northeast part of the dome displays few reworking effects and contains possible greenstone belt remnants.

SUMMARY OF TECTONIC EVOLUTION

TIMING OF EVENTS

The only geological constraints on the age of the basin are:—

1. the Earaheedy Group and the sequence in the Glengarry Sub-basin lie, with marked angular unconformity, on the Archaean Yilgarn Block, and

2. both sequences are folded and are overlain with angular unconformity by the Bangemall Group of about 1.1 b.y.

Further evidence is provided by K-Ar and Rb-Sr isotopic dates (Preiss and others, 1975; Horwitz, 1975) of around 1.6-1.7 b.y. for glauconite from sandstones of the Earaheedy Group.

The possibility of a correlation with the Hamersley Basin (about 2.2-2.0 b.y.) is immediately raised, when considering the gross regional symmetry between the Yilgarn and Pilbara Blocks, and by the collective similarity of the sequences. Indeed, this view has recently become popular (Horwitz, 1976; Hall and Goode, 1975), despite the difference in the ages quoted above.

Despite attempts to demonstrate similarities of thickness, lithology and sequence (Horwitz, 1976), we can see no basis for correlation, and are more impressed by the many differences between the Hamersley and Nabberu Basins, and the mounting evidence for regional unconformities in the pre-Bangemall sedimentary sequences across the northern margin of the Yilgarn Block. We believe that, at this stage of our knowledge, it is equally likely that the Nabberu Basin relates to the supracrustal rocks of the Gascoyne Province. The Nabberu Basin and particularly the Earaheedy Group could then be considerably younger than the Hamersley Basin, and we are inclined to accept the 1.7 b.y. K-Ar age as close to a true age.

There is, however, scope for extending the Padbury Group and the sequence in the Glengarry Sub-basin well back into the Lower Proterozoic. Although we prefer to interpret as Archaean the granites that are unconformably overlain by the Yelma Formation on the northeast of the Marymia Dome, the possibility that these are Proterozoic Gascoyne Province-type granites of about 1.6-1.7 b.y. (de Laeter, 1976) cannot be overlooked. This would demand that the Glengarry Sub-basin formed, was folded, intruded by granite and eroded before formation of the Earaheedy Group. The evaluation of this model, against the alternative facies change model, as presented in this paper, requires more detailed work in the critical, but poorly exposed areas, north and east of Thaduna.

BASEMENT CONTROL OF BASIN DEVELOPMENT

The primary location of the Nabberu Basin is the east-west trending junction of Archaean granite-greenstone terrains, and Archaean gneiss terrains. The influence of the respective north-northwest and east-northeast basement trends is apparent throughout sedimentation and deformation.

Initial downwarping occurred in the Glengarry Sub-basin and was even and gentle, allowing for the accumulation of 1 000 m of dominantly mature sandstone. Accelerated subsidence about active hinge lines and fractures was caused by fragmentation of basement. These fractures were related to the major crustal suture. Mafic volcanicity along parts of these fractures provided detritus for turbidity currents that fed into deep, probably fault-bounded, troughs.

As these troughs filled and basement activity relaxed, sedimentation again became widespread and of a stable shelf type. A new broad basin formed where the Padbury Group was deposited, consisting of a thick arenaceous blanket, followed by large thicknesses (about 4 km) of ferruginous chemical sediments.

According to the facies equivalent model, at the same time as Padbury Group sedimentation, a new gentle downwarp formed to the east on the eastern side of the Wiluna Arch to become the Earaheedy Sub-basin. A marine transgression deposited sandstones and clastic iron-formation in a much thinner and more shallow-water variant of the temporal equivalent, the Padbury Group. The succeeding sedimentation in the Earaheedy Sub-basin is younger than any other sequence in the Nabberu Basin.

All deformation in the Nabberu Basin is the result of basement block and fold movements, with a strong upthrust component from the north. The main synclinorium marks the boundary between mobile and cratonic basement, which in turn reflects a major suture within the Archaean crust.

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FOSSILIFEROUS TERTIARY DEPOSITS ON THE DARLING PLATEAU, WESTERN AUSTRALIA

by S. A. Wilde and J. Backhouse

ABSTRACT

Fossils are recorded from Muradup, 240 km southeast of Perth, and from Calingiri, 120 km northeast of Perth. They occur in sediments that form part of the Darling Plateau, a laterite-capped surface that overlies the southwestern part of the Precambrian Yilgarn Block. The plateau has been dissected by erosion and the sediments are preserved along drainage divides.

The fossiliferous deposits consist of silicified conglomerate, grit and sandstone, and are correlated with the Eocene Kojonup Sandstone on the basis of their preserved flora and geomorphic position. They indicate that the influence of the Eocene marine transgression was more widespread than is commonly recognized. Comparison with unfossiliferous deposits in a similar geomorphic setting in southwestern Australia suggests that these need not necessarily be of pre-Tertiary age.

INTRODUCTION

The Darling Plateau (Jutson, 1934) is the undulating, laterite-capped surface that forms the southwestern part of the Precambrian Yilgarn Block. It extends southward from near New Norcia almost to the south coast, a distance of about 460 km. It is separated from the Perth Basin to the west by the Darling Scarp and has been dissected by erosion (Finkl, 1971; Bettenay and Mulcahy, 1972).

Churchill (*in* McWhae and others, 1958) described Tertiary sediments containing plant fossils from near Kojonup, 150 km southeast of Perth. He defined these as the Kojonup Sandstone and made a tentative correlation, on the basis of similarities of the preserved flora, with the Eocene Plantagenet Group (Cockbain, 1968b) that occurs along the southwestern coast of Western Australia.

In the course of regional geological mapping in the southwestern Yilgarn Block, other localities with similar lithologies, and also containing plant remains, have been found (Fig. 25). The type section of the Kojonup Sandstone was visited in order that a detailed comparison could be made. The nature of these plant remains, the host lithology, and the distribution of the deposits in relation to the present geomorphology are of importance in elucidating the early Tertiary evolution of the Darling Plateau.

DISTRIBUTION

Plant remains were found near Muradup, 18 km west-southwest of Kojonup and at two localities near Calingiri, 120 km northeast of Perth. The fossils occur in sequences of silicified conglomerate, grit and sandstone and, in common with the Kojonup Sandstone, occur on present drainage divides (Fig. 25).

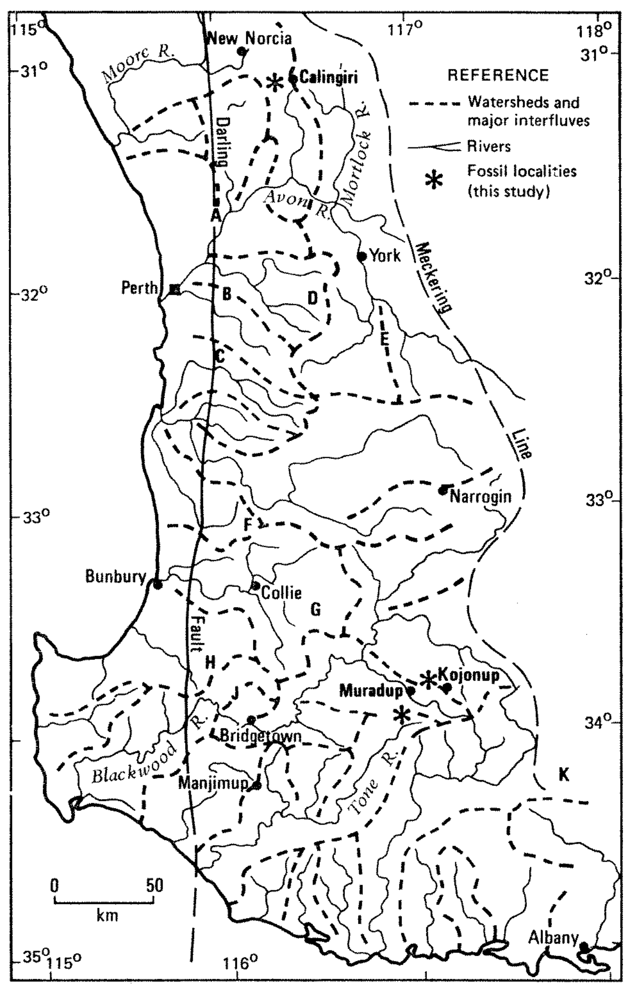
THE KOJONUP SANDSTONE

The type section of the Kojonup Sandstone (Churchill, *in* McWhae and others, 1958) is located on the property of "Half Moon", 7.2 km west-southwest of the Kojonup townsite. The rocks crop out in the headwaters of a north-flowing creek and upslope on the flanks of the divide separating Kojonup Brook and the Balgarup River (Fig. 26a), at a height of approximately 320 m above sea level.

The unit unconformably rests on Archaean migmatite and consists of a silicified basal conglomerate overlain by a sequence of grey to white silicified grit, orthoquartzite and sandstone. The strata appear to be flat lying and Churchill esimated the maximum thickness of the unit as 14.3 m. The upper part of the sequence is strongly lateritized. Churchill referred to other exposures of the formation, about 16 km south and southeast of Kojonup. These were not visited by the authors but are believed to be near Ngopitchup Swamp along the Kojonup/Balgarup/Gordon drainage divide.

At the type locality, the basal conglomerate consists of rounded pebbles of white quartz, up to 8 cm diameter, in a matrix of silicified, subrounded quartz grains. The sandstone is composed of fairly well-rounded grains of white quartz (0.4 mm average diameter) in a silica cement. Some ripple-marked surfaces are present. The grey orthoquartzite units are quite massive and boundaries between quartz grains and silica cement are not distinct.

Plant remains are locally abundant, particularly in the upper parts of the sequence. Specimens collected during this study, together with material housed in the Western Australian Museum, include species of *Nothofagus*, *Ficus*, *Apocynophyllum*, *Banksia* and *Grevillea*. In addition, the following species were recorded by Churchill (1961): *Araucaria derwentensis* Selling, *Phyllites yallournensis* Cookson and Duigan, *Agathis* sp., *Cyclosorus* sp., *Dacrydium* sp., *Livistonia* sp., *Lomatia* sp., and *Sterculia* sp. Rootlets and worm burrows are present and Churchill also recorded the tracks of a "two-toed animal of unknown affinities".



A Walyunga
B Roleystone
C Jarrahdale
D Darkin Swamp
E Mt. Kokeby
F Harvey
G Collie
H Kirup
J Greenbushes
K Stirling Range

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Figure 25. Major drainage features west of the 'Meckering Line' and localities mentioned in text.

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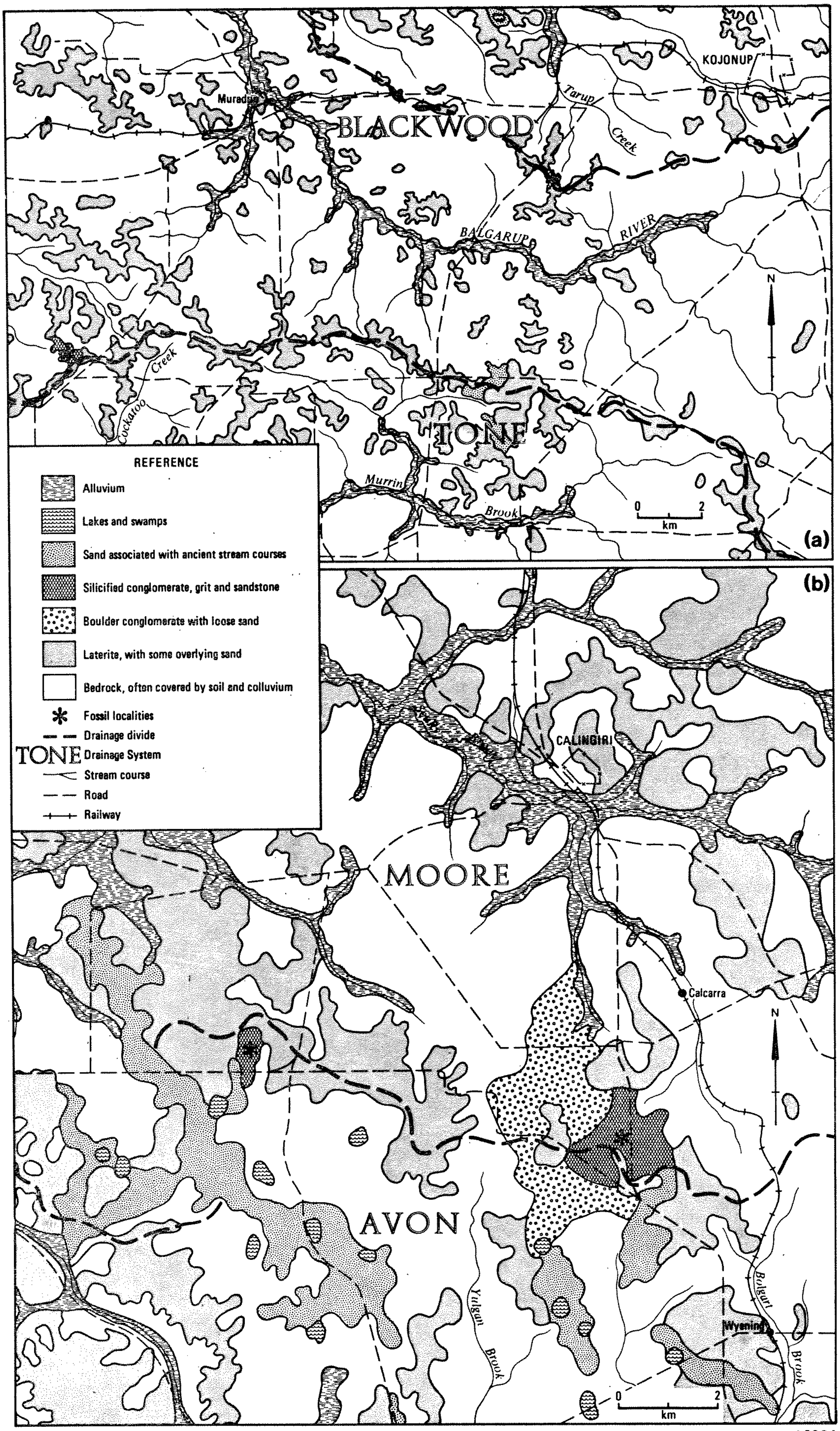

Figure 26. Location of fossiliferous deposits in (a) the Kojonup area and (b) the Calingiri area.

MURADUP LOCALITY

A small exposure of fossiliferous strata occurs on the property of "Na Laura", 10 km southwest of Muradup and 26 km west-southwest of Kojonup (Fig. 26a). A sequence of silicified grit and sandstone, about 3 m thick, directly overlies Archaean migmatite and is preserved on the drainage divide separating the Tone and Blackwood (Balgarup) river systems. The flat-lying strata crop out over an area of approximately 4 ha and are 310 m above sea level. The unit passes laterally into ferruginous duricrust, typical of the Darling Plateau.

The basal unit is a coarse-grained cemented grit that consists of angular to subangular grains of white quartz (3 mm average diameter) in a finer-grained matrix of subangular to subrounded quartz grains (0.2 mm average diameter) enclosed in a silica cement. A few larger fragments of feldspathic material are present. The rocks have a rather mottled appearance due to partial lateritization, which has mainly affected the matrix cement. A fine-grained, flaggy sandstone, identical to the main type at Kojonup, overlies the grit and is well exposed around it.

In contrast to the type section of the Kojonup Sandstone, abundant plant remains are preserved in the coarse-grained sediments at Muradup and are virtually absent in the sandstones. The flora consists of:—

Gymnospermae: *Araucaria* sp., *Podocarpus* sp., ?*Sequoia* sp. Monocotyledonae; ?*Typha* sp.

Dicotyledonae: *Nothofagus* sp., *Banksia* spp., ?*Lomatia* sp., ?*Eucalyptus* sp.

incerta sedis: *Phyllites yallournensis* Cookson and Duigan.

Several unidentified angiosperm leaves are also present, together with a number of fruiting bodies (Fig. 27). In addition, a nonmarine bivalve belonging to the family Unionidae occurs with the plant remains.

CALINGIRI LOCALITIES

Fossil plant remains were found at two localities near Calingiri (Fig. 26b). At 6 km due south of the townsite Wilde and Low (1975) described a "flaggy silcrete" deposit associated with sand rich in quartz cobbles. These deposits are 290 m above sea level and occur on the major drainage divide between the Moore, Avon and Mortlock river systems.

The deposits overlie metamorphic rocks of the Jimperding Metamorphic Belt (Wilde and Low, 1975). The boulder bed is presumed to underlie the subhorizontal "flaggy silcrete", since it occurs at a slightly lower topographic level. It contains well-rounded pebbles and boulders of white quartz and quartzite, up to 40 cm across, in a matrix of unconsolidated white sand. Rare pebbles of weathered dolerite are also present. The proportion of boulders to sand varies at the surface and there is some local cementation resulting from lateritization. The "flaggy silcrete" is essentially a silicified sandstone with units of silicified feldspathic grit. The deposit is poorly sorted and consists of rounded to angular fragments of quartz and altered feldspar up to 10 mm in diameter in a poorly sorted matrix of subrounded quartz grains (0.2 mm diameter) cemented with silica. Ripple-marked surfaces are present.

Plant remains occur within the flagstone, but are sparse. They consist of a few unidentified leaves scattered on the bedding surfaces and more numerous roots perpendicular to the bedding.

Fossil leaves are also present at Location 2807, 9 km southwest of Calingiri and 8 km west of the above locality (Fig. 26b). Specimens were previously deposited with the Western Australian Museum by Mr. A. J. Dean in 1967. The leaves are preserved in a fine-grained silicified sandstone, identical to deposits at Muradup and Kojonup. The sandstone crops out over 2 ha and is at the same height (290 m above sea level) as the adjacent laterite. The unit lies on the divide between the Moore and Avon drainage systems and the sandstone and laterite form part of the same surface that slopes rather steeply southward.

A small pocket within the sandstone, only a few square metres in area, contains an abundance of fossil leaves. They are less well preserved than at Kojonup or Muradup and can only be tentatively assigned to the angiosperm genera *Eucalyptus, Lomatia* and *Apocynophyllum* (Fig. 27).

OTHER TERTIARY DEPOSITS IN SOUTHWESTERN AUSTRALIA

Tertiary fossils have been recorded from along the southwest coast of Australia and northward around the Stirling Range (the Plantagenet Group—Cockbain, 1968b), from Lake Cowan, near Norseman (the Eundynie Group—Cockbain, 1968a), from Coolgardie, 530 m east of Perth, (the Rollos Bore Beds—Balme and Churchill, 1959; Playford and others, 1975) and from Darkin Swamp, about 65 km east of Perth (Balme, pers. comm., 1976). Palaeontological evidence indicates an Eocene age for these deposits. The Kings Park Formation (Playford and others, 1975) is of Paleocene age and occurs near Perth in the subsurface of the Perth Basin.

The Eocene deposits consist of a variety of lithologies including sand, sandstone, siltstone, clay, lignite and spongolite, often overlying a basal conglomerate. The deposits at Coolgardie were laid down in a coastal lake or lagoon, whereas the sequences at Lake Cowan and near the present south coast are mainly beach and marine deposits. The foraminifers and nautiloids from the Plantagenet Group indicate warm, shallow seas with locally quiescent conditions to account for the spongolite and coastal lake or deltaic conditions for the formation of lignite. Fossil leaves are locally abundant, especially near the Stirling Range (Churchill, 1961; Western Australian Museum collection).

There are other deposits on the Darling Plateau of probable Tertiary age, but these are apparently devoid of fossils. The most extensive are the Nakina Formation, near Collie (Playford and others, 1975) formerly referred to as the "Collie Lake Beds" (Lord, 1952), and the "Old Alluvium" at Greenbushes (Hobson and Matheson, 1949). These deposits are lateritized and consist of clay, sand and grit horizons overlying a basal conglomerate. A number of conglomeratic deposits, also pre-dating laterite formation, occur on the Darling Plateau between Walyunga, 30 km northeast of Perth (Wilde and Low, 1975) and the south coast. Included in these are the deposits at Rolystone and Jarrahdale (Wilde, 1976), Harvey (Churchward and Bettenay, 1973) and Kirup (Finkl, 1971; Taylor, 1971) which have been considered either Tertiary (Playford and others, in press) or Mesozoic (Finkl, 1971; Churchward and Bettenay, 1973) in age.

GEOMORPHIC SETTING

The Darling Plateau has been extensively dissected by rejuvenation of the drainage. The "Meckering Line" (Mulcahy, 1967) represents the inland limit of rejuvenation, to the east of which is an ancient system of broad, sluggish drainage channels with salt lakes. Two stages of rejuvenation can be recognized west of the "Meckering Line" (Bettenay and Mulcahy, 1972); an early stage that resulted in the formation of broad, mature valley forms with well-developed, deep weathering profiles, and a later stage that produced more youthful valley forms, generally devoid of deep weathering profiles.

However, remnants of the old landscape, as recognized east of the "Meckering Line", are preserved locally along divides and major interfluves in the zone of rejuvenated drainage (Mulcahy and others, 1972; Bettenay and Mulcahy, 1972; Wilde, 1976). The oldest recognizable alluvial valley form is the Goonaping type valley (Mulcahy and others, 1972) which includes Darkin Swamp from which Eocene spores and pollen grains have been recorded (Balme, B. E., pers. comm., 1976). Fossil leaves were also reported from near Mount Kokeby (Feldtman, 1919) in another Goonaping type valley, although no specimens are available. These drainage deposits are thus of great antiquity and were laid down in channels that remained stable over a considerable period of time.

In several areas ribbons of reworked sands, accompanied by lakes and swamps, are associated with the Goonaping type valleys. These overlie, or form part of, the laterite plateau surface and appear to define old stream courses. In many remnant areas of the Darling Plateau, Goonaping type valleys are absent and only the ribbons of sand occur; this is true for the Calingiri localities (Fig. 26b). It is suggested that these sands may represent reworked Goonaping type material or, more likely, that they represent vestiges of an even older drainage system that may be equated with the sands occurring along divides and interfluves in the Bridgetown area and recognized as defining old stream courses (Finkl, 1971). The "Old Alluvium" at Greenbushes and most of the conglomeratic deposits on the Darling Plateau are also preserved along drainage divides.

CORRELATION AND PALAEOGEOGRAPHIC IMPLICATIONS

At least four species in the preserved flora from Muradup were also recorded by Churchill (1961) from the Kojonup Sandstone. The Muradup locality is 17 km west of the type section of the Kojonup Sandstone and both lie on the Blackwood watershed (Fig. 26a). The lithologies are also similar and the Muradup locality may be considered as part of the Kojonup Sandstone. Churchill (*in* McWhae and others, 1958) tentatively correlated the Kojonup Sandstone with the Eocene Plantagenet Group.

The fossil remains from Calingiri are less well preserved and cannot be identified with any certainty, partly due to the general lack of published information on Australian Tertiary floras. However, although they appear to differ somewhat from those in the Kojonup Sandstone, they occupy a similar geomorphic position, being preserved along a major watershed and forming part of the lateritized plateau surface. Local environmental differences and floral diversity in the Eocene (Churchill, 1973) similar to that in the present day Western Australian flora, could account for the differences at Calingiri. On the available evidence, the deposits at Calingiri are equated with the Kojonup Sandstone and are thus considered to be of Eocene age.

The discovery of a nonmarine unionid bivalve at Muradup confirms a fluviatile environment of deposition for the Kojonup Sandstone. The occurrence of Eocene deposits as far inland as Coolgardie and Calingiri indicates that the effects of the well-documented Eocene marine transgression were widespread over southwestern Australia. The change from freshwater coastal lake and fluviatile conditions at these localities to interdeveloped marine and non-marine sequences to the south suggests that there was an extensive drainage system developed on a land surface of low relief. This is also indicated by the shallow-water lithologies and fossil remains in the Plantagenet Group (Cockbain, 1968b). The Kojonup, Muradup and Calingiri localities are now about 300 m above present sea level and post-Eocene uplift of this order has been suggested (Churchill, 1973). Using the present 300 m contours, Churchill has shown that there would have been numerous islands bordering an irregular coastline with broad estuaries. Conditions were tropical, with possible development of mangrove swamps; mangrove pollen has been identified from the Plantagenet Group (Churchill, 1973).

It is significant that most of the Tertiary deposits in the southwestern Yilgarn Block are underlain by a basal conglomerate. Hobson and Matheson (1949) considered that the conglomerate at the base of the "Old Alluvium" at Greenbushes was a beach deposit. Although it cannot be proved at this stage that all the conglomerates represent beach deposits, it would seem likely that they formed as a result of the Eocene marine transgression.

Certain units that are older than the Goonaping type valleys, and which form part of the Darling Plateau, have previously been considered pre-Tertiary in age; these include the Harvey Beds (Churchward and Bettenay, 1973) and the Kirup Conglomerate (Finkl, 1971). However, the recognition of Eocene deposits in a similar geomorphic position at Muradup and Calingiri (and Kojonup) indicates that units forming part of the Darling Plateau are not necessarily pre-Tertiary.

ACKNOWLEDGEMENT

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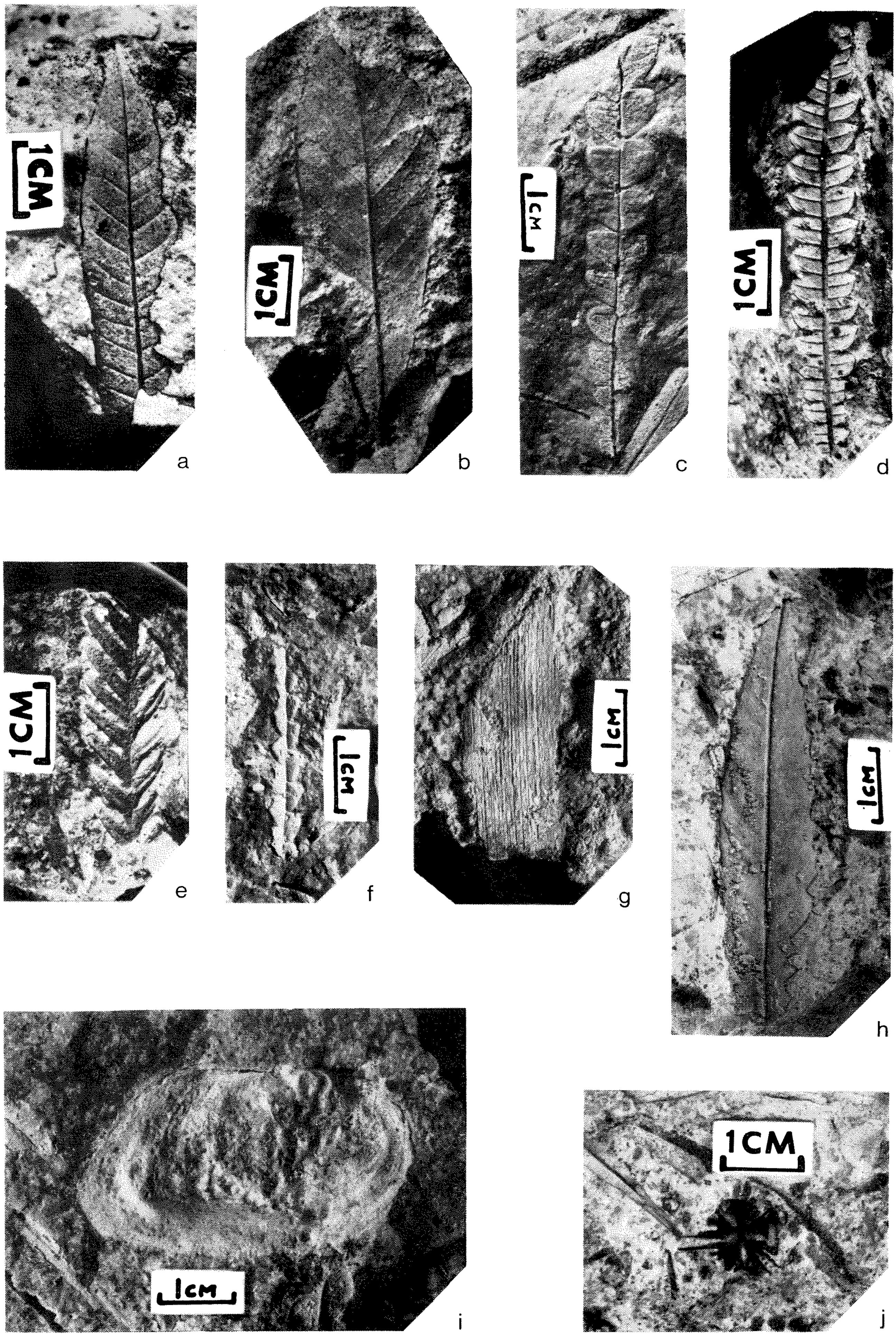
Figure 27. Fossils from Calingiri and Muradup. (a) *Apocynophyllum* sp., Calingiri, F 6420/b. (b) Angiosperm leaf, gen. and sp. indet., Calingiri, F 6420/a. (c) *Phyllites yallournensis* Cookson and Duigan, Muradup, F 9346/m. (d) *Banksia* sp., Muradup, F 9346/a. (e) ?*Sequoia* sp., Muradup, F 9346/2. (f) *Banksia* sp., Muradup, F 9346/v. (g) ?*Typha* sp., Muradup, F 9346/x. (h) Angiosperm leaf, gen. and sp. indet., Muradup, F 9346/q. (i) Unionid bivalve, Muradup, F 9346/w. (j) Fruiting body, Muradup, F 9346/l.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NEW AND REVISED DEFINITIONS OF ROCK UNITS IN THE WARRAWOONA GROUP, PILBARA BLOCK

by A. H. Hickman

ABSTRACT

Six Archaean formations, the North Star Basalt, the McPhee Formation, the Mount Ada Basalt, the Towers Formation, the Apex Basalt and the Euro Basalt are defined for the first time. The Marble Bar Chert Member is redefined as a member of the Towers Formation.

NEW ROCK UNITS

Table 8 compares the stratigraphic subdivision of the Warrawoona Group given by Lipple (1975, Table 9) with that now adopted. Table 9 presents formal definitions of the newly recognized rock units.

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TABLE 8. STRATIGRAPHIC SUBDIVISION OF THE WARRAWOONA GROUP: NEW AND REVISED ROCK UNITS

	Lipple, 1975	Present subdivision	
Salgash Subgroup	Wyman Formation	Wyman Formation	
	Pillow basalt and chert	Euro Basalt	
	Panorama Formation	Panorama Formation	
	Pillow basalt and chert	Apex Basalt	
		Towers Formation	basalt and chert
	Marble Bar Chert		Marble Bar Chert Member
	Pillow basalt		basalt and chert
	Duffer Formation	Duffer Formation	
Talga Talga Subgroup	Basalt with subordinate ultramafic and chert units	Mount Ada Basalt	
		McPhee Formation	
		North Star Basalt	

TABLE 9. DEFINITIONS OF NEWLY RECOGNIZED ROCK UNITS

Name	Derivation of name	Distribution	Type section	Thickness and lithology
North Star Basalt	North Star mine (lat. 21°00′50″S, long. 119°49′30″E)	50 km² S and E of McPhee Reward mine (lat. 21°00′10″S, long. 119° 49′30″E)	Along road from Great Northern Hwy to McPhee Reward mine	2 000 m. Massive and pillow basalt; local dolerite and gabbro; felsic lava (100 m) at top
McPhee Formation	McPhee Reward mine	Nimerry Creek (lat. 20°58′50″S, long. 119°58′10″E) to Pyramid Well (lat. 21°07′00″S, long. 119° 47′20″E)	Gorge at McPhee Reward mine	50–200 m. Carbonate-quartz (±chlorite) schist and metasediments
Mount Ada Basalt	Mount Ada mine (lat. 21°25′ 40″S, long. 119°36′40″E)	100 km² NE and SW of McPhee Reward mine	NW of McPhee Reward mine	2 000–2 500 m. Massive and pillow basalt; minor chert and dolerite
Towers Formation	Towers mine (lat. 21°16′20″S, long. 119°47′40″E)	2 km² at Salgash mining centre (lat. 121°16′45″S, long. 119°47′35″E)	Towers mine. Good exposures at Marble Bar Pool (lat. 20°11′00″S, long, 119°42′40″E)	500 m. Three chert members separated by basalt, felsic lava and minor ultramafic rock
Apex Basalt	Apex mine (lat. 21°16′20″S, long. 119°48′00″E)	25 km² S of Salgash mining centre	Chinaman Creek W from Marble Bar Pool	1 500–2 000m. Pillow basalt and local high-magnesia basalt
Euro Basalt	Euro mine (lat. 21°17′50″S, long. 119°48′15″E)	10 km² SW of Euro mine	SW of Euro mine	2 000 m. Pillow basalt; minor chert and felsic lava
Marble Bar Chert Member	The Marble Bar at Marble Bar Pool	The Marble Bar	Marble Bar Pool	100 m. Red and white, and grey and white banded chert

STRATIGRAPHIC RELATIONS OF ROCKS WITHIN THE WHIM CREEK BELT

by A. H. Hickman

ABSTRACT

The Whim Creek Group is a late Archaean succession of relatively undeformed volcanic and sedimentary rocks about 1 km in thickness. Two formations, the Mallina Formation and the Constantine Sandstone, included in the group by Fitton and others (1975), are now assigned to the Gorge Creek Group. The slate at Whim Creek copper mine overlies the Mons Cupri Volcanics whereas the Mallina Formation underlies this unit. A regional unconformity, said by Fitton and others to separate Upper from Lower Archaean rocks in the Pilbara Block, is not substantiated.

INTRODUCTION

Between the Sherlock River and Mount Negri in the western part of the Pilbara Block a northeast-trending belt of Archaean volcanic rocks flanks the southeastern margin of the Caines Well Granite (Fitton and others, 1975). These rocks occupy a synclinal structural unit, here referred to as the Whim Creek Belt, which is 80 km long and, over the greater part of this distance, about 5 to 10 km wide. Previous geological investigation of the area has been largely concentrated on mineralized rocks in the vicinity of Whim Creek copper mine. Accounts of this part of the belt are given by Blatchford (1921), Finucane and Sullivan (1939), Low (1963), Miller and Gair (1975) and Reynolds and others (1975).

The purpose of this paper is to examine the stratigraphic affinities of the rocks within the Whim Creek Belt. In this context, previous relevant publications are those by Woodward (1911), Low (1963), Ryan and Kriewaldt (1964), Ryan (1965), Fitton and others (1975) and Miller (1975).

Woodward (1911), on a geological sketch map of Western Australia, shows the Whim Creek Belt as composed of "metamorphic greenstones" older than the "Nullagine Series" (said to be Palaeozoic). Low (1963, p. 57) states that rocks in the Whim Creek area include sandstone, grit and slate with interbedded felsic lava, tuff and volcanic agglomerate, "rather strongly resembling Nullagine Rocks". Workers prior to Low had differed on the age of the succession: Blatchford (1921) favoured a correlation with rocks now termed Proterozoic, but Finucane and Sullivan (1939) thought the slate at Whim Creek was probably of "Mosquito Creek Series" age (Archaean).

Ryan and Kriewaldt (1964) describe facies changes in the Archaean of the west Pilbara. At Whim Creek a volcanic facies is said to pass laterally southeastwards into a sedimentary facies, the latter being deposited in a relatively unstable trough. In 1965 Ryan correlated rocks of the Whim Creek area with the "Warrawoona Succession" of the east Pilbara and regarded them as entirely older than the "Mosquito Creek Succession". Ryan adds, however, that "The sandstone succession at Mt. Constantine is overlain to the north by shale" (now correlated with Mosquito Creek Formation) "which is in turn overlain by volcanic rocks in the syncline southwest of Whim Creek".

Miller (1975) includes Ryan and Kriewaldt's trough of sedimentation within the "Pilbara eugeosyncline". The volcanic rocks of the west Pilbara are described as being of volcanic arc origin while the sediments are said to have been deposited in a trench. Whim Creek is positioned on the northern margin of the trench.

Fitton and others (1975) present a 1:250 000 stratigraphic map covering much of the west Pilbara and revise the area's stratigraphic succession. Earlier correlations between the western and eastern parts of the Pilbara Block (Ryan, 1965) are abandoned, chiefly because of Fitton's findings in the area around the Pilbara mining centre. Here, the "sedimentary succession" of Ryan's "Roebourne Group" is now mapped as *overlying* the "volcanic succession". This discovery dispenses with the need to envisage rapid lateral facies changes between the thick Archaean volcanic and sedimentary successions of the east and west Pilbara.

The recognition by Fitton and others (1975) that the Archaean stratigraphic succession of the west Pilbara is similar to that previously established in the east Pilbara (Hickman and Lipple, 1975) is an important contribution to our knowledge of Pilbara Block stratigraphy. The authors state, however, that the main purpose of their paper is "to describe a regional unconformity in the Archaean and to draw attention to a large complex of layered basic sills that essentially hugs the unconformity". Fitton and others (1975) interpret the regional unconformity as marking a major hiatus in deposition, and use it to separate "Lower" from "Upper" Archaean rocks. The rocks of the Whim Creek Belt belong entirely to their Upper Archaean and part of the evidence for the unconformity is drawn from this area.

STRATIGRAPHY

Most of the Archaean stratigraphic units named on Figure 28 were originally defined by Fitton and others (1975). The sequence indicated on the reference panel of the figure differs from that presented by Fitton in several important respects (Table 10). In particular, it will be noted that the present interpretation places the Mallina Formation and the Constantine Sandstone below the mid-Archaean "regional unconformity" of Fitton and others (1975) and assigns these formations to the Gorge Creek Group rather than the Whim Creek Group. The stratigraphic relationships of *Abu* (Fig. 28) are also discussed below.

TABLE 10. ARCHAEAN STRATIGRAPHIC SUCCESSION OF THE WHIM CREEK BELT

Fitton and others, 1975		This paper	
	Negri Volcanics: mainly terrestrial basic to acidic lavas including spinifex-textured basic rocks. Fine-grained sediments and local conglomerates towards top.		*Negri Volcanics:* variolitic and vesicular basalt. Includes sediments southwest of Mons Cupri.
			Unconformity
			Quench-textured basalt, high magnesia basalt, with gabbroic and ultramafic sills.
			Relations uncertain
			Silicified and epidotized basalt. Local felsic lava. Slate, 2 m thick, near base.
Local unconformity		Unconformity	
WHIM CREEK GROUP	*Mallina Formation*	WHIM CREEK GROUP	Slate Tuff, well-bedded Slate (e.g., at Whim Creek) Local conglomerate
	Constantine Sandstone		
	Mons Cupri Volcanics: Tuff and sediment. Agglomerate. Mount Brown Rhyolite Member. Felsic lava and tuff.		*Mons Cupri Volcanics:* Agglomerate and tuff. Mount Brown Rhyolite Member
	Warambie Basalt		*Warambie Basalt*
Regional unconformity		Unconformity	
GORGE CREEK GROUP	Banded iron-formation, chert, quartzite and shale.	GORGE CREEK GROUP	*Mallina Formation* *Constantine Sandstone* Banded iron-formation.

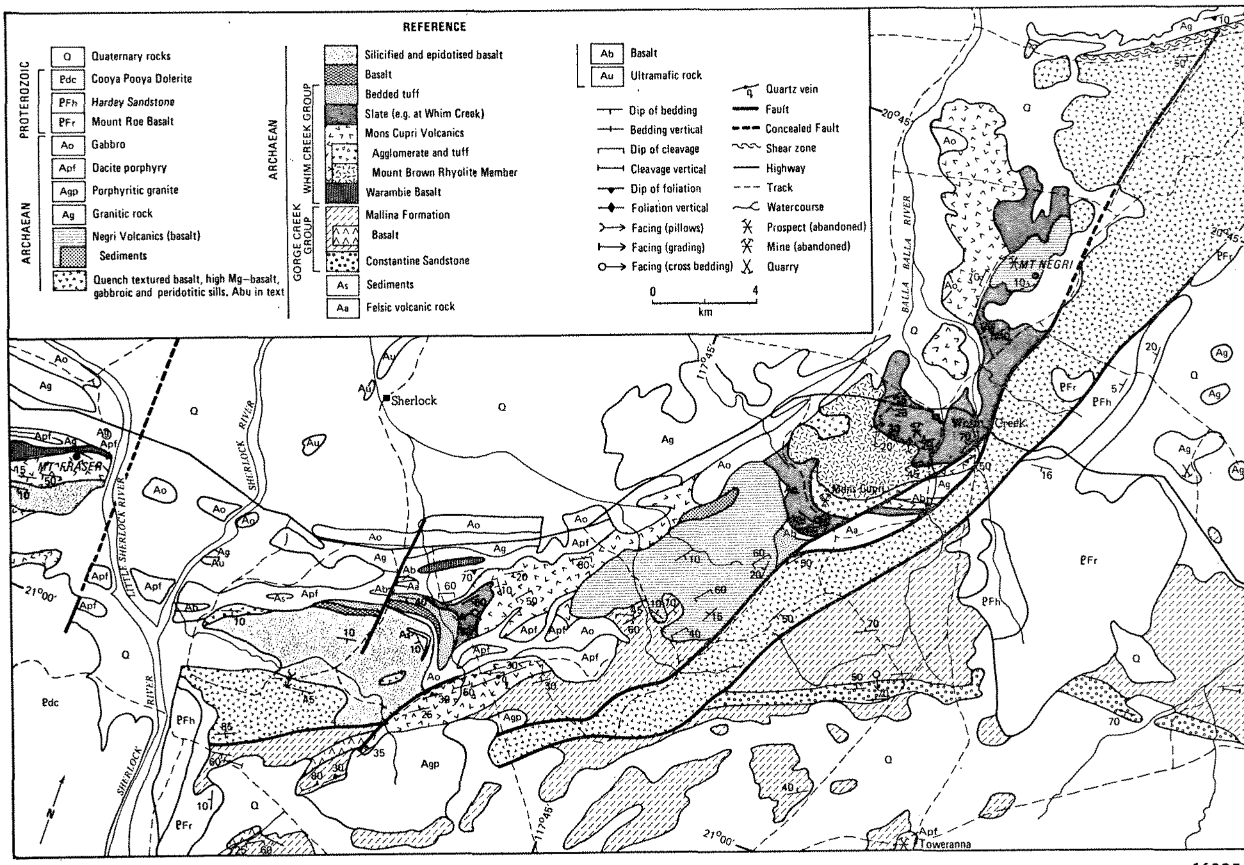

Figure 28. Geological map of the Whim Creek area.

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MALLINA FORMATION AND WHIM CREEK GROUP

The Mallina Formation (Fitton and others, 1975) is a thick succession of psammitic to pelitic rocks which are probably chiefly of turbiditic origin. As noted by various workers the unit is lithologically very similar to the Mosquito Creek Formation of the east Pilbara.

Fitton and others (1975) correlate the Mallina Formation with the slate at Whim Creek mine, but no reasons are given for this interpretation. Certainly the slate at Whim Creek lithologically resembles more pelitic parts of the Mallina Formation, but several stratigraphic problems are raised by the correlation. Firstly, the Constantine Sandstone is absent at Whim Creek, yet elsewhere in the Pilbara it is generally thickly developed below the Mallina Formation. Secondly, the Warambie Basalt and Mons Cupri Volcanics are absent beneath the Constantine Sandstone in other areas of the Pilbara. Thirdly, the slate at Whim Creek is only about 100 m thick, contains thin volcanic units and is overlain by tuff and lava, whereas the Mallina Formation is between 2.5 km (Fitton and others, 1975) and 15 km (Miller, 1975) thick and virtually devoid of volcanic intercalations.

The slate at Whim Creek *overlies* the Mons Cupri Volcanics, but the writer's mapping (Fig. 28) 15 km southeast of Sherlock indicates that the Mallina Formation *underlies* the Mons Cupri Volcanics, both formations dipping northwest at approximately 30°.

REGIONAL MID-ARCHAEAN UNCONFORMITY

One of the five localities in the Pilbara where Fitton and others state that the regional unconformity can be observed lies 2 km outside the western margin of Figure 28. Here, on a road from the North West Coastal Highway to Pyramid Station about 3 km south of the highway, the Warambie Basalt is said to unconformably overlie steeply inclined metabasalt of the Teichmans Group (equivalent to the Warrawoona Group).

An unconformity does exist at this point but its regional extent cannot be ascertained. Bedding attitudes within the Whim Creek Group range up to about 30° and, apart from being cleaved, the succession is relatively underformed. In view of the prevalence of dips greater than 45° in rocks of the Warrawoona and Gorge Creek Groups over most of the Pilbara, it seems probable that deposition of the Whim Creek Group followed a period in which the older Archaean rocks were considerably deformed. Thus an unconformity may be accepted between the Gorge Creek Group and the Whim Greek Group, but it is emphasized that the Constantine Sandstone and the Mallina Formation do not belong to the Whim Creek Group. Consequently the unconformity beneath the Warambie Basalt cannot be equated to unconformities beneath the Mallina Formation.

Whether or not a regional unconformity exists within the Gorge Greek Group or between this unit and the Warrawoona Group is a question beyond the scope of this paper. The writer expresses the opinion, however, that such a regional hiatus is not present. Local unconformities and disconformities exist at all levels of the Archaean layered succession but a single break, separating one group of older rocks from another group of younger, has not been recognized.

The succession of the Whim Creek Group is not repeated elsewhere in the Pilbara. Not only is its outcrop of small areal extent but its thickness is no more than 1 km (the average combined thickness of the Gorge Creek and Warrawoona Groups exceeds 20 km). Geochronology carried out by G. C. Sylvester (in press) indicates that intrusive rocks of the Mons Cupri area are between 2.7 and 2.4 b.y. old.

NEGRI VOLCANICS AND HIGH MAGNESIAN BASALT

As can be seen from Figure 28 the most extensive volcanic unit of the Whim Creek Belt is that labelled *Abu*. Fitton and others (1975) include this sequence of quench-textured mafic and ultramafic rocks within the Negri Volcanics. Mount Negri, situated about 6 km north of Whim Creek, is composed of subhorizontal flows of variolitic basalt. To the north and east of the hill are large outcrops of lithologically different basalt. Much of this basalt is extremely fine grained and fractures conchoidally. At first sight it appears siliceous, but the rock has a high specific gravity and commonly exhibits a fine spinifex texture. Other parts of the sequence include more coarsely spinifex-textured varieties, pillowed ultramafic flows and stratiform bodies (interpreted as sills) of gabbroic and ultramafic rocks. The rocks are typically massive, but pillowed units and spinifex zones show that dips are moderate south of Whim Creek and near the Sherlock River. The lithological differences between the variolitic basalt of Mount Negri and *Abu*, combined with the presence of consistently steeper dips in the latter, indicate that the two units are not conformable.

As can be seen from Figure 28, contacts between *Abu* and other rocks of the area are generally faulted. Near Sherlock River relations to *Ax* are uncertain because of incomplete exposure and a general absence of well-defined bedding planes. Approximately 20 km southwest of Roebourne rocks similar to *Abu* form part of the Teichmans Group, so that the unit may be older than the Whim Creek Group.

If *Abu* does not belong to the Negri Volcanics the relationship between the latter and the Fortescue Group cannot be directly demonstrated. Field evidence that the Whim Creek Group is Archaean rather that Proterozoic also becomes limited to an unconformable relationship between the Mount Roe Basalt and the Warambie Basalt near Warambie.

STRUCTURE

The Whim Creek Belt is bounded by major faults and, on the basis of stratigraphy, would appear to be a graben. Within the confines of these faults the Whim Creek Group is folded gently about northeast-trending axes. The folds plunge northeast and southwest, possibly because of open cross-folding, although this is uncertain. Miller and Gair (1975) recognize an east-trending anticline between Mons Cupri and Whim Creek.

A steep axial plane cleavage strikes northeast along the length of the belt, and affects all rocks, including the Negri Volcanics. At Whim Creek this cleavage is a true slaty cleavage inclined southeastwards at about 30° to 40° and is crenulated by a later nonpenetrative cleavage striking northwest. Kink bands which deform the slaty cleavage resemble D3 structures in the east Pilbara (Hickman, 1975).

CONCLUSIONS

The Whim Creek Group is a late Archaean volcanic sequence, relatively thin compared to the rest of the Archaean succession and of limited areal extent. The mid-Archaean regional unconformity recognized by Fitton and others (1975) has not been substantiated by regional geological mapping carried out by the Geological Survey of Western Australia. The Mallina Formation and Constantine Sandstone, placed by Fitton and others (1975) in the Whim Creek Group, belong to the Gorge Creek Group.

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GEOCHRONOLOGICAL DATA CONCERNING THE EASTERN EXTENT OF THE PILBARA BLOCK

by J. R. de Laeter,* A. H. Hickman, A. F. Trendall, and J. D. Lewis

ABSTRACT

The Pilbara Block, in the northwest part of Western Australia, is the smaller of the two major Archaean cratonic areas of the State. The bulk of its granitic rocks have Rb-Sr isochron ages of about 3.0 b.y., with initial $^{87}Sr/^{86}Sr$ ratios (R_i) of about 0.702. In the eastern part of the block post-tectonic "younger" granites, 2.7-2.6 b.y. old with an R_i about 0.73, intrude the older granites and are thought to be derived anatectically from them. Rb-Sr data are reported from three rock bodies spaced along an east-west transect across the largely obscured eastern edge of the block. At the eastern end of the transect the Mount Crofton Granite, which intrudes folded Proterozoic sediments of the Yeneena Group, has a concordant total-rock and biotite age close to 600 m.y.; the R_i of about 0.71 indicates that it cannot have been derived by melting of underlying Archaean granitic crust. At the western end of the transect the Cookes Creek Granite gives a broadly concordant total-rock and biotite age of 2.6 b.y. with an R_i of about 0.73; in both respects, and in other features, it belongs with other younger granites of the Pilbara Block. Between these, in the centre of the transect, granites with a pervasive cataclastic foliation in the southern part of the Gregory Granitic Complex, in the vicinity of Lookout Rocks, give a well-defined 2.65 b.y. total-rock isochron, with an R_i of about 0.71; discordant biotites give an age of 1.2 b.y. Geological and previous Rb-Sr evidence argue that the foliation cannot be older than 2.4-2.2 b.y., so that the total-rock age has survived its imposition. The biotite age may record either the age of the foliation or of a later event. The comparatively low R_i at Lookout Rocks suggests that between this area and the Cookes Creek Granite lies the eastern edge of the older granitic crust of the Pilbara Block.

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INTRODUCTION

The Pilbara Block is an area of Archaean rocks covering about 56 000 km² of the northwest part of Western Australia, between approximate latitudes 20° and 22°S and longitudes 116° and 121° E; it has a crudely triangular shape, with a short eastern side running north-south and longer north and south sides converging towards a western apex. The Archaean age of two generations of granite within it is established by Rb-Sr ages of 2 951 and 2 606 m.y., reported by de Laeter and others (1975) and by a similar range of Pb-Pb ages reported by Oversby (1976). Ages for the older granites, of 3 050 m.y. and 3 125 m.y., reported by Compston and Arriens (1968) and de Laeter and Blockley (1972) respectively, have wide uncertainty limits which include the more reliable ages already noted.

The northern boundary of the Pilbara Block is formed either by the Indian Ocean coastline or by overlying Phanerozoic sediments of the Canning Basin. The southern margin is defined by the unconformable base of the Proterozoic Fortescue Group, of the Hamersley Basin. On the most recent edition of the State geological map (G.S.W.A. 1973), and in a recent formal representation of Precambrian subdivisions (G.S.W.A., 1975, p. 29), the eastern edge of the Pilbara Block is shown as a continuation of the same unconformity, following an irregular north-south course within the rough longitude limits 120°20′-40′E. However, Hickman (1975a), after remapping of the Nullagine 1:250 000 Sheet area, which covers much of the relevant ground, shows a narrow north-south belt of Archaean and Proterozoic granitic rocks some 50-70 km farther east, and isolated from the main mass of the Pilbara Block by Fortescue Group and younger rocks. This roughly 10-km wide belt of granitic and related rocks, called by Hickman (1975a, b) the Gregory Granitic Complex, extends for nearly 100 km from the Yarrie Sheet area in the north to the Balfour Downs Sheet area in the south. On the earlier edition of the Nullagine Sheet (Noldart and Wyatt, 1962) this belt was included within the "Gregory Range Granite", and was regarded as Proterozoic. It was also mapped as Proterozoic on the Balfour Downs Sheet (de la Hunty, 1964).

Remapping of the Nullagine Sheet revealed that a large part of the "Gregory Range Granite" was composed of felsic lava, now named the Koongaling Volcanics, apparently belonging to the Fortescue Group. The remainder was found to include granophyre and several different types of granitic rock. Each of these various types is broadly restricted to a particular part of the belt, suggesting that either they represent distinct zones within a heterogeneous intrusion or they form individual plutons. Because mapping did not establish which of these alternative explanations was correct Hickman (1975a) introduced the term Gregory Granitic Complex to include the granophyre and all the granitic rocks.

The map appearing as Figure 29 illustrates the disposition of the rock units referred to above, and includes further information, dealt with subsequently. Blockley and de la Hunty's (1975, p. 115-6) account of the components of the "Gregory Range Granite", was compiled from the best information available in 1971, and is superseded by later parts of this paper.

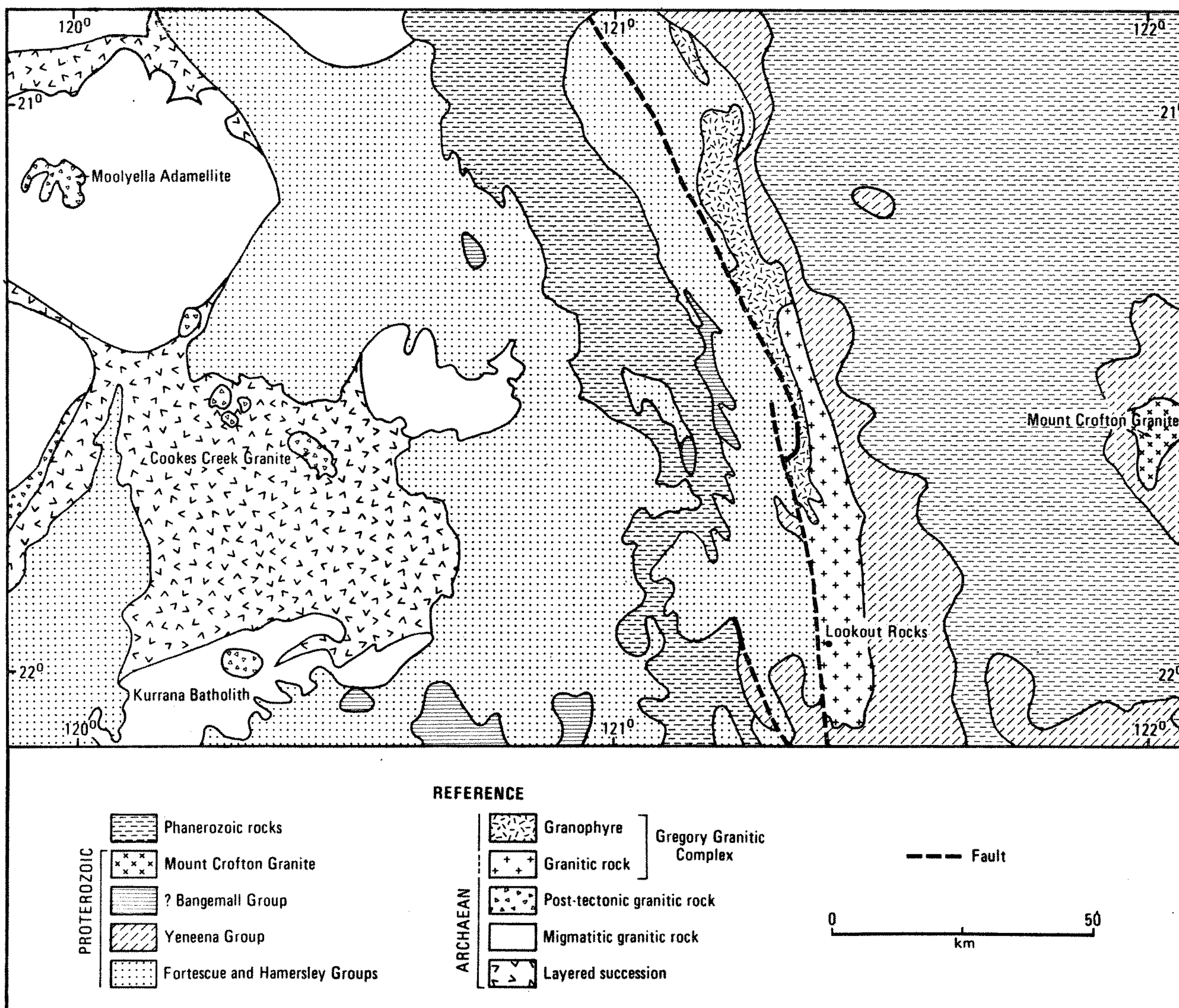

Figure 29. Simplified geological map of the eastern marginal area of the Pilbara Block.

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Hickman (1975a) did not provide explicit reasons for assigning an Archaean age to the granitic rocks of the complex, but gave the southern part the same lithological description as sheared granite and adamellite of the Kurrana Batholith (Fig. 29), a unit forming part of the Pilbara Block and known to be of Archaean age. Considerations not mentioned were the fact that the granophyre (regarded as a feeder of the Koongaling Volcanics) is generally far less deformed than the granitic rocks in the south, and also that the granitic rocks do not intrude or visibly metamorphose the Fortescue Group. He was also aware of the preliminary isotopic data mentioned by Blockley and de la Hunty (1975, p. 115) which, though of uncertain significance because of sampling problems, did indicate that at least part of the complex might be Archaean.

In 1975, as now, the only unequivocal geological evidence for the age of the rocks was that on the eastern side they are unconformably overlain by gently dipping sandstone of Lower or Middle Proterozoic age (Yeneena Group, Williams and others, 1976). On the western side, the contact between the complex and the Fortescue Group is tectonic in the south and tectonic or gradational (granophyre-Koongaling Volcanics contact) in the north.

The purposes of this paper are to record Rb-Sr whole-rock and mineral analyses of rocks from the southern part of the Gregory Granitic Complex which confirm their age as Archaean, to report additional Rb-Sr data from other rock units to the east and west, and to discuss the implications of all the data for regional geological history.

EXPERIMENTAL PROCEDURE

The experimental procedure for Rb-Sr analyses used in this laboratory are essentially the same as those described by Lewis and others (1975) and de Laeter and Abercrombie (1970).

The value of $^{87}Sr/^{86}Sr$ for the NBS 967 standard measure during this project was $0.710\,2 \pm 0.000\,1$, normalised to a $^{88}Sr/^{86}Sr$ value of 8.375 2. The value of 1.39×10^{-11} yr^{-1} was used for the decay constant of ^{87}Rb. The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios, as well as the calculated $^{87}Rb/^{86}Sr$ ratios are given in Tables 12-14. Errors accompanying the data are at the 95 per cent confidence level. Regression analyses of the data were carried out using the least squares programme of McIntyre and others (1966).

COOKES CREEK GRANITE

GEOLOGICAL RELATIONSHIPS

The position of the Cookes Creek Granite (Noldart, 1960, p. 141) is shown on Figure 29. It crops out over 40 km² at the junction of Cookes Creek with the Nullagine River, about 45 km northeast of Nullagine.

The granite is a stock intruded into Archaean basaltic rocks of the Warrawoona Group (Hickman, 1975a). Its margins are irregular and discordant to the bedding of the greenstones, and appear to be intrusive on all sides. The enveloping greenstones are not visibly disrupted by the intrusion, indicating that emplacement was passive. At the southeastern contact of the mass, dykes of granitic rock intrude adjacent sandstone, gabbro and ultramafic rock. Sandstone near the contact is spotted and extensively recrystallized, apparently due to contact metamorphism. Granitic rock next to the contact contains about 70 per cent quartz and is rich in aluminous minerals. The main body of the stock is a poorly foliated or nonfoliated, coarse to medium-grained granite or adamellite. In places it is porphyritic and a cataclastic foliation is developed near minor faults. Faults and joints are a conspicuous feature of the stock, and, because the topography is rugged and the exposure good, these appear as well-defined lineaments on aerial photographs. Faults and joints trending north are offset by faults striking at 100°. Another set of lineaments, commonly intruded by quartz, trends north-northwest. Some of the quartz veins contain fluorite and barite, and at the Cookes Creek mining centre others have been worked for wolframite and scheelite.

Hickman (1975b) notes that the Cookes Creek Granite intrudes the core of a syncline, and interprets it as a post-tectonic intrusion, similar in many respects to the "tin granites" of the Pilbara Block. One of these, the Moolyella Adamellite (shown on Fig. 29), was dated by de Laeter and Blockley (1972) at 2 670 ± 95 m.y.

MATERIAL ANALYSED

Five samples (18415, 16, 17A, 17B, 18) collected from a restricted area near where the track from Mosquito Creek crosses Cookes Creek (lat. 21°37′52″S, long. 120°26′17″E) were analysed. Samples 18417A, 17B, and 18 were collected from the creek bed, no more than 30 m apart; 18415 and 16 come from an excavation close to the track about 150 m south of the crossing. They include equigranular and porphyritic varieties.

Sample 18417A is an equigranular coarse-grained adamellite containing masses of anhedral quartz up to 6 mm across, smaller subhedral to anhedral prisms of albite (An_5) and plentiful interstitial microcline. Minor biotite has been entirely chloritized and the albite is slightly sericitized. The chlorite is associated with accessory zircon and secondary sphene and fluorite. Fluorite also occurs, with a little carbonate, in minor fractures and shears within the rock. Specimen 18415 is a leucocratic variety with prominent mylonitic zones, apparent only in thin section, in which small masses of fluorite are developed. Sample 18417B is a medium-grained, leucocratic aplite similar in mineralogy to 18417A.

Sample 18418 is a porphyritic adamellite containing subhedral phenocrysts of perthitic microcline up to 2 cm long, subhedral to anhedral oligoclase (An_{25}) prisms, interstitial quartz and minor green biotite. Accessory apatite, zircon, sphene, epidote, and metamict allanite are present. The sphene contains metamict zones and is a pale brown low birefringence variety. Minor secondary fluorite is associated with the biotite.

Specimen 18416 was collected from a dyke-like pod and consists of a mass of pale bleached biotite with lesser microcline and fluorite. A little quartz is present, along with accessory zircon and secondary rutile.

Chemical compositions of the two main granite types are given in Table 11.

TABLE 11. CHEMICAL COMPOSITION OF THE COOKES CREEK GRANITE

	18417A	18418
SiO_2	76·3	71·2
Al_2O_3	12·1	13·9
Fe_2O_3	0·4	1·0
FeO	1·51	2·75
MgO	0·00	0·5
CaO	0·51	1·79
Na_2O	3·72	3·88
K_2O	4·3	4·4
H_2O^+	0·77	0·80
H_2O^-	0·10	0·13
CO_2	0·19	0·07
TiO_2	0·17	0·49
P_2O_5	0·02	0·11
MnO	0·04	0·06
Total	100·1	101·0

Trace elements (ppm)

Li	50	170
Ba	170	580
Rb	420	355
Sr	40	120
Sn	10	5
Zr	130	190
U	3	4
F....	2 240	1 880

Analyst: N. Marsh, West. Australia Government Chemical Laboratories

TABLE 12. ANALYTICAL DATA FOR FIVE TOTAL-ROCK SAMPLES AND TWO BIOTITE CONCENTRATES FROM THE COOKES CREEK GRANITE

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$Sr^{87}/^{86}Sr$
Total rocks					
18418	360	110	3·25 ± 0·03	9·7 ± 0·1	1·084 1 ± 0·001 1
18417A	418	31	13·5 ± 0·1	45·2 ± 0·5	2·341 1 ± 0·002 3
18415	495	23	21·1 ± 0·2	74·8 ± 0·7	3·017 2 ± 0·001 0
18417B	490	14	35·1 ± 0·3	161 ± 1	6·768 ± 0·008
18416	2 600	40	65·6 ± 0·6	561 ± 5	20·78 ± 0·04
Biotites					
18418	1 650	21	78 ± 2	526 ± 8	14·380 ± 0·014
18416	3 000	37	81 ± 2	1 640 ± 20	62·051 ± 0·062

RESULTS

The data from the five total rocks and from biotite fractions separated from two of them appear in Table 12, and are displayed in Figure 30. It is clear from inspection that 18415 falls below a line well defined by the remaining four total-rock samples. These yield a Model 1 isochron of 2 568 ± 37 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio (R_i) of 0.730 7 ± 0.009 7. This age and R_i are closely controlled by samples 18416 and 18418 respectively.

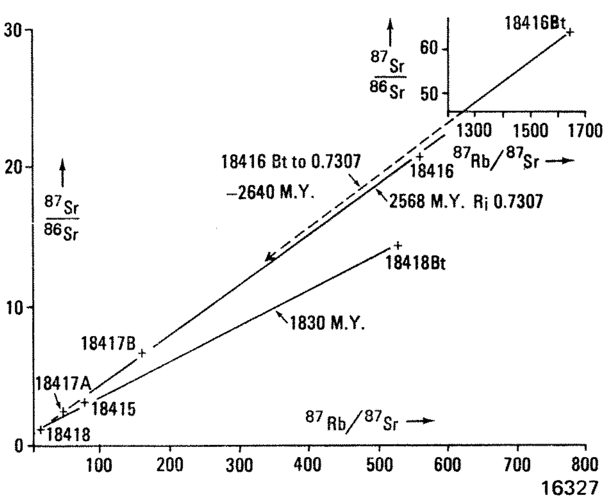

Figure 30. Isochron diagram of five total–rock samples from the Cookes Creek Granite and of biotites concentrated from two of them. The 1 830 m.y. line joins total rock 18418 with its separated biotite. The crosses marking analyses are symbolic only, and do *not* represent error limits.

The separated biotite 18416 yields an age of 2 700 m.y. when joined to its total-rock point, but this figure implies an impossible, negative, R_i. The biotite was separated from a different part of the sample from that used for the total-rock analysis, and this anomalous result can only be accounted for by slight inhomogeneity within the sample. We know of no mechanism whereby granite biotite can acquire an anomalously high Rb-Sr age, and conclude that the real age of the granite probably lies within both the error limits of the total-rock age and those of a model age for the biotite which accepts the computed R_i. These limits, an upper of 2 605 m.y. for the total-rock isochron, and a lower of 2 607 m.y. for the biotite, marginally fail to overlap, but this margin is trivial, and for purposes of later discussion we refer to this granite as showing a concordant total-rock and biotite age of about 2 600 m.y.

The green biotite in sample 18418 clearly records a discordant age of 1 830 m.y., and it may be that the position of the mylonitic rock 18415, which records a model age (R_i 0.73) of 2 170 m.y. reflects a partial response to this event.

GREGORY GRANITIC COMPLEX

GEOLOGICAL RELATIONSHIPS

The background to the introduction of the name Gregory Granitic Complex by Hickman (1975a) has already been given above; the complex includes both granophyre and granitic rocks and is shown in Figure 29. We are concerned here with the geological relationships only of that part of the complex in the Lookout Rocks area, from which the analysed samples were collected.

This part of the complex contains schistose to well-foliated granite and adamellite. On the west side these granitic rocks are separated from lava and sedimentary rocks of the Forescue Group by a major north-striking fault filled with quartz. On the east side they are unconformably overlain by gently east-dipping sandstone of the Yeneena Group, and to the north a foliated hornblende granite is exposed. In the field this rock is distinct from the foliated granite of the Lookout Rocks area; it is finer grained, more massive, and spotted with hornblende. The granite and adamellite of the Lookout Rocks area is locally flaggy, and in such cases primary igneous textures have been destroyed by shear. This tectonic foliation (S5) strikes north-northwest, and dips steeply southwestwards or northeastwards in the western part of the complex and gently westwards or sub-horizontally in the eastern part. A structural interpretation (Hickman, 1975a, Fig. 3) equates a north-northwest-trending anticlinal fold of S5 with folds of similar orientation which affect rocks of the Yeneena Group to the east. The S5 foliation in the granitic rocks is also correlated with an axial plane cleavage related to upright tight-to-isoclinal folds in the Fortescue Group immediately west of the complex. This correlation is based on similarity of orientation and on photo-interpretation. No locality affords a well-exposed, non-tectonic contact between the Fortescue Group and the granitic rocks.

The lithological similarity between the granite at Lookout Rocks and the granite and adamellite of the Kurrana Batholith has already been noted. Bouguer anomaly patterns (Hickman, 1975a, Fig. 6) do not rule out the possibility that the two masses are continuous at depth beneath the Fortescue Group. The strong tectonic foliation of the Kurrana Batholith is clearly Archaean in age, however; since it is unconformably overlain by the Fortescue Group.

MATERIAL ANALYSED

Twelve total-rock samples were analysed, together with separated biotites from two of these. Nine of these samples, collected by two of us in 1976 specifically for geochronology, came from two sampling points, situated respectively 1.8 km on a bearing of 328° from Lookout Rocks (45756A-E) and 1.6 km on a bearing of 342° from Lookout Rocks (45757A-D). The remaining three samples include one (13891) collected by H.W.B. Talbot (1920, pp. 129 and 187) in 1914 about 1 km due north of Lookout Rocks and two samples (16446, 7) collected by J. G. Blockley in 1969, respectively 9.0 and 10.6 km from Lookout Rocks on a bearing of 170°.

Samples 45756A-E were spaced at roughly equal intervals over an east-west distance of about 150 m along the crest of a low ridge. A, B, D, and E have an identical macroscopic appearance; they are fresh, coarse, pink, gneissic granites in which the thin dark streaks of biotite and hornblende which define the foliation enclose feldspars about 1 cm in diameter. Sample 45756C is a finer-grained and more massive, darker pink, rock in which the feldspars do not exceed a diameter of 2-3 mm. Samples 45757A-D come from about 1 km farther east, at the south foot of the same ridge, and have a maximum separation of 50 m. A and B are almost identical in appearance to 45756A, B, D and E, but more strongly foliated. Sample 45757C was taken from a very strongly sheared band about a metre wide within this granite, in which its components have apparently been ground to form a black streaky mylonite. Sample 45757D forms a halfway stage between C and the gneissic granite of A and B; it is an augen gneiss in which the dark streaks of mylonitised material enclose remnants of granitic material.

Along the whole ridge including the 45756 and 45757 sampling points, the foliation of the gneissic granite and of its mylonitic derivatives maintains a very consistent direction, striking 320-325° and dipping at about 80° eastwards.

In thin section this foliation, the S5 of Hickman (1975a, b), dominates the general appearance of the rocks. Mineralogically, and in initial texture, all these rocks were clearly granites, with patches of coarse quartz mosaic, and anhedral potassic feldspars and sodic plagioclases about 5 mm across forming the main components; less abundant biotite and hornblende were supplemented by accessory sphene, apatite, zircon, fluorite and opaques.

But the post-crystallization imposition of the strong foliation has been accompanied in all these rocks, including the more massive 45756C, by strong cataclastic deformation of all the major minerals. The quartz is streaked out into complex wisps and ribbons, and the feldspars are broken down into smaller grains, in which the twin laminae are kinked or bent. Even the biotite is strongly broken and twisted, and has not since recrystallized. It is clear that the development of the foliation has been associated with an intense and penetrative late cataclasis.

Samples 13891, 16446, and 16447 are coarse pink foliated granites closely similar to the 45756-7 samples in macroscopic appearance, mineralogy, and in the association, beneath the microscope, of the foliation with pervasive cataclasis.

RESULTS

The data from the 12 total-rock samples analysed, and from biotite fractions separated from two of them, appear in Table 13 and are also displayed in Figure 31. The total-rock data are well aligned on a Model 3 isochron of 2 651 ± 60 m.y.; the two biotites, when joined with their parent rocks, give closely similar ages with a mean near 1 200 m.y.

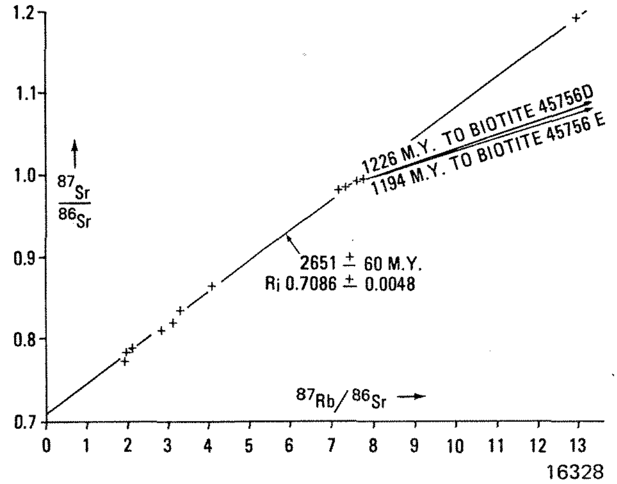

Figure 31. Isochron line of twelve total–rock samples from the southern (Lookout Rocks) area of the Gregory Granitic Complex and of biotites concentrated from two of them. Crosses marking analyses are symbolic only, and do *not* represent error limits.

MOUNT CROFTON GRANITE

GEOLOGICAL RELATIONSHIPS

The Mount Crofton Granite (Chin and Hickman, in prep.) underlies an area of approximately 150 km² in the Paterson Range 1:250 000 Sheet area (Fig. 29). The pluton is composed of medium to coarse-grained, unfoliated biotite granite with marginal pegmatitic and late aplitic phases. Its intrusive relationship to the Yeneena Group is visible 100 m south of the road linking Port Hedland and Telfer, about 15 km northwest of Mount Crofton. On a regional scale its contacts cut sharply across pre-existing fold structures in the neighbouring Proterozoic sedimentary rocks. Thus, the Mount Crofton Granite postdates the Yeneena Group and the main episode of deformation in the Paterson Province.

MATERIAL ANALYSED

The exact locations, and petrographic descriptions, of eight total-rock samples of the Mount Crofton Granite used for Rb-Sr isotopic analysis were given by Trendall (1974) and are not repeated here. Biotites were separated from four of the coarse granites among Trendall's samples.

RESULTS

Analytical results for the four biotite samples are given in Table 14. The ages given by projecting each biotite analysis to its parent total rock are, in the numerical order of the table, 568, 580, 592 and 580 m.y., so that there is little scatter about the mean of 580 m.y.

TABLE 13. ANALYTICAL DATA FOR TWELVE TOTAL-ROCK SAMPLES AND TWO BIOTITE CONCENTRATES FROM GRANITIC ROCKS OF THE LOOKOUT ROCKS AREA

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Total rocks					
45757C	115	176	0·65 ± 0·01	1·89 ± 0·03	0·774 31 ± 0·000 71
45757D	116	170	0·68 ± 0·01	1·97 ± 0·04	0·784 01 ± 0·000 74
45757B	111	105	1·06 ± 0·01	3·11 ± 0·04	0·821 45 ± 0·000 79
45757A	126	91	1·39 ± 0·02	4·08 ± 0·07	0·865 17 ± 0·000 64
45756B	172	71	2·41 ± 0·04	7·15 ± 0·08	0·984 14 ± 0·000 76
45756E	166	68	2·45 ± 0·04	7·30 ± 0·08	0·984 90 ± 0·000 83
45756A	168	66	2·54 ± 0·04	7·60 ± 0·09	0·991 71 ± 0·000 89
45756D	171	66	2·60 ± 0·04	7·69 ± 0·09	0·993 67 ± 0·000 83
45756C	171	40	4·28 ± 0·06	12·93 ± 0·15	1·191 5 ± 0·000 94
13891	....	....	0·70 ± 0·01	2·03 ± 0·02	0·788 51 ± 0·000 81
16447	....	....	0·96 ± 0·01	2·79 ± 0·03	0·810 52 ± 0·000 73
16446	....	....	1·13 ± 0·01	3·30 ± 0·03	0·834 32 ± 0·000 81
Biotites					
45756E	700	40	17·6 ± 0·4	56 ± 1·0	1·805 02 ± 0·001 2
45756D	615	42	14·6 ± 0·3	46 ± 1·0	1·653 61 ± 0·001 1

Note: In Tables 11, 12, and 13 the Rb and Sr concentrations have been determined by X-ray fluorescence spectrometry. We believe the values are accurate to ± 7 per cent. The Rb/Sr values do not correspond exactly with the ratios that would be derived from the separate Rb and Sr values listed.

TABLE 14. ANALYTICAL DATA FOR FOUR BIOTITE CONCENTRATES FROM THE MOUNT CROFTON GRANITE

Sample	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
30555	111 ± 2	427 ± 9	4·101 1 ± 0·005 1
30558	188 ± 4	953 ± 20	8·433 9 ± 0·008 4
30559	140 ± 3	601 ± 12	5·678 0 ± 0·004 8
30562	179 ± 4	876 ± 18	7·809 5 ± 0·007 3

DISCUSSION

The three rock bodies from which we report data are about equally spaced along a roughly east-west transect across the eastern margin of the Pilbara Block, and their Rb-Sr systematics thus have an important bearing on its history. The mean biotite age of 580 m.y. from the Mount Crofton Granite, the easternmost of the three, is slightly younger than the two alternative ages, 612 and 594 m.y., suggested by Trendall (1974) to be interpretable from his total-rock analyses from this body. The new data lend greater support to the second of these, with an interpretation of the younger biotite age as an expression of the delay in cooling to the biotite blocking temperature. However, the implied interval of 14 m.y. for this is notably longer than estimates for some eastern Australian granites with more precise Rb-Sr control (Williams and others, 1975; Roddick and Compston, 1976).

The intervals between all these interpretable ages are trivial within the broader time scale of this discussion, and Trendall's (1974) earlier conclusion that the Mount Crofton Granite is a diapiric granite emplaced about 600 m.y. ago, and that it had a prior crustal history no longer than 30-60 m.y., remains valid. This granite cannot have been anatectically derived from an underlying extension of the granitic crust of the Pilbara Block, if this bore any resemblance in Rb-Sr chemistry to Pilbara Block granites studied by de Laeter and Blockley (1972), de Laeter and others (1975), Oversby (1976), or by us in this paper. If the rising diapir penetrated such material it must have done so with minimal contamination by radiogenic strontium.

At the western end of the transect, the data from the Cookes Creek Granite indicate similar general concordance between total-rock and mineral ages; apart from biotite 18416 and total-rock 18415, to which this discussion returns later, the body has an undisturbed age of about 2 600 m.y. This is close to the previously reported ages of other "younger" granites from the eastern Pilbara Block, at Moolyella (de Laeter and Blockley, 1972) and Cooglegong (de Laeter and others, 1975). It is consistent also with Hickman's (1975b) designation of the Cookes Creek Granite, from field evidence, as an Archaen "post-tectonic granite". Like the other younger granites its R_i of 0.7307 is also consistent with a derivation from older granitic crust by partial melting.

With these two very different situations, both in age and origin, at each end of the transect the position in the centre is of critical significance. Here, in the Lookout Rocks area of the Gregory Granitic Complex, the total-rock isochron gives an age closely similar to that of the Cookes Creek Granite. There are, however, two important differences. Firstly, the R_i of 0.7086 is substantially lower than that of the Cookes Creek Granite or the other younger granites; this point is taken up in later discussion.

Secondly, the two Lookout Rocks biotites both give a much younger age, of 1 200 m.y., than the total rock isochron; the significance of these two ages needs assessment in the light of both the geological and other isotopic evidence.

The S5 foliation in the Lookout Rocks area equally affects both the granitic rocks and the adjacent Fortescue Group, the age of which thus sets an upper limit on the age of the granitic rocks. The lowermost lavas of the Fortescue Group were probably erupted about 2 330 m.y. ago (Lewis and others, 1975), although Trendall (1976), in a review of the evidence, has pointed out that the possible age limits imposed by the available data are about 2 700-2 200 m.y. Hickman and de Laeter (1977) have subsequently presented new evidence which can be interpreted as indicating deposition of the Fortescue Group at 2 650 m.y. However, if the Fortescue Group is younger than this, the age recorded by the total-rock samples from the Lookout Rocks area must be interpreted as a real emplacement age which has survived the imposition of the younger S5 foliation. The relative immobility of Rb and Sr during the presumably low-temperature development of this foliation appears consistent with its strongly cataclastic petrographic expression.

If this interpretation is correct, it is not at present possible to assign a definite geological significance to the 1 200 m.y. biotite age, but some limitations can be suggested. The S5 foliation is truncated by, and is therefore older than, the Yeneena Group; it is also deformed by folding correlated with that of the Yeneena Group in the Paterson Province (Hickman, 1975a). Folds in the Yeneena Group are known to pre-date the Bangemall Group (Williams and others, 1976) which is dated at about 1 100 m.y. (Compston and Arriens, 1968; Gee and others, 1976). The Yeneena Group unconformably overlies the Rudall Metamorphic Complex (Williams and others, 1976; Chin and others, in prep.), provisionally dated by one of us (JRdeL) at about 1 500 m.y. (noted in Blockley, 1974). This figure must be treated with caution pending the results of further work in progress, but it suggests, in conjunction with the points already given, that deposition and deformation of the Yeneena Group occurred between 1 500 and 1 100 m.y.

Thus if the 1 200 m.y. biotite be assumed to be the age of the S5 foliation, which is the most immediately attractive hypothesis, it follows that both the deposition and folding of the Yeneena Group took place in a comparatively short, but not impossible, period between 1 200 and 1 100 m.y. Alternatively, our 1 200 m.y. age from Lookout Rocks may be related to the concurrent folding of S5 and the Yeneena Group. If this is so, there is no sign, in our data from the Lookout Rocks area, of any isotopic effect of S5 earlier than 1 200 m.y. but younger than the Fortescue Group.

The 18418 biotite age of 1 800 m.y. from the Cookes Creek Granite falls in this expected interval, but without further work we cannot do more than indicate the possibility of a relationship. Both that age, and the updating of the mylonitic total rock 18415 are clearly related to unknown regional events that only slightly affected this granite.

We return finally to the significance of the low R_i of the 2 650 m.y.-old granitic rocks of the Lookout Rocks area, which we see as an important result of this study. Arriens (1971) first focussed attention on the statistically sharp contrast between periods of largescale granite generation in the two major Archaean areas of Western Australia, the Pilbara and Yilgarn Blocks. In the Pilbara Block the greatest volume of granite is of approximately 3 000 m.y. age, with R_i of about 0.702. In the Yilgarn Block the greatest volume of granite has an age range about 2 700-2 600 m.y., with a similar R_i. In the eastern part of the Pilbara Block the post-tectonic younger granites have the same age, but have R_is close to 0.73, and occur in relatively small stocks cutting the older granites, from which they are presumed to be anatectically derived.

We suggest the possibility that this later granite-forming event was of vast extent and applied equally to areas of earlier-formed thick granitic crust, and to areas not so covered. In the latter, large volumes of low-R_i granites were generated, but in the former the main effects were the the generation of high-R_i material by partial crustal melting at low levels and its upward diapiric penetration in small volumes. In this concept the presence of a low-R_i granite with a 2 650 m.y. age in the Gregory Granitic Complex shows the real existence, between it and Cookes Creek, of an "edge" to the older granitic material of the Pilbara Block. In a petrogenetic, but not necessarily tectonic, sense we picture the granitic rocks in the Lookout Rocks area as more closely related to the Yilgarn Block than the Pilbara Block.

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THE DEPOSITIONAL ENVIRONMENT AND AGE OF A SHALE WITHIN THE HARDEY SANDSTONE OF THE FORTESCUE GROUP

by A. H. HICKMAN and J. R. de LAETER*

ABSTRACT

Boron, gallium and rubidium analyses support lithological and stratigraphic evidence that shale collected from the Hardey Sandstone, a formation of the Fortescue Group, was deposited in a fresh-water environment. Rb-Sr isotope analysis indicates that the age of the shale may be between 2 700 and 2 600 m.y., but whether or not this date is a true reflection of the unit's depositional age is uncertain. The possibility that the Hardey Sandstone is 2 600 m.y. old has important implications as to the age of the Proterozoic/Archaean unconformity in the Pilbara Block.

INTRODUCTION

The Hardey Sandstone (MacLeod and others, 1963) conformably overlies the oldest formation of the Lower Proterozoic Fortescue Group in the Pilbara, the Mount Roe Basalt (Kriewaldt, 1964). In many areas this basalt is absent and the sandstone rests directly on steeply inclined Archaean rock. The age of the formation therefore approximates to the age of the Proterozoic/Archaean unconformity, currently the subject of a regional investigation programme.

PREVIOUS GEOCHRONOLOGY

Previous geochronological work relevant to the age of the Hardey Sandstone indicates that it exceeds 2 200 m.y., the reported age of the Weeli Wolli Formation in the Hamersley Group (de Laeter and others, 1974), and that it is close to 2 329 ± 89 m.y., the age of the Black Range Dyke (Lewis and others, 1975), which may be a feeder to the Mount Roe Basalt. The younger age limit for the Hardey Sandstone is firmly established by the age of a major dacite sill which intrudes it. This sill, the Spinaway Porphyry, was dated by Trendall (1975) at 2 124 ± 195 m.y. The older age limit for the formation is far less well defined. South of Nullagine the Cajuput Dyke, a dolerite of the same orientation, composition and size as the Black Range Dyke, is unconformably over lain by shale, pisolitic tuff, sandstone and conglomerate of the Hardey Sandstone. The two dykes probably belong to the same intrusive suite; B. J. J. Embleton (pers. comm.) states that the two dykes are palaeomagnetically indistinguishable.

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PALAEOGEOGRAPHY

Deposition of the Fortescue Group commenced in a number of separate basins, the positions of which closely correspond to areas of Archaean greenstones (Hickman and Lipple, 1975; Hickman, 1975a). Where the Proterozoic/Archaean unconformity overlies granitic rocks, the Mount Roe Basalt and the Hardey Sandstone are almost invariably absent, some younger formation of the Fortescue Group resting on the surface of erosion. The thickness of the Mount Roe Basalt in the central parts of the basins is 300 m, and the Hardey Sandstone locally exceeds 1 000 m. Towards the basin margins both formations become thinner, the sandstone eventually overlapping the basalt before it too wedges out against the Archaean basement.

On a regional scale the Fortescue Group north of the Fortescue River exhibits a progressive onlap southwards across Archaean granitic rocks underlying the Chichester Range. Thus the overall palaeoslope during deposition of the Hardey Sandstone in this northern area was downwards towards the north, a conclusion supported by a limited number of palaeocurrent determinations from cross bedding and ripple marks. Poor sorting in much of the Hardey Sandstone, the common occurrence of lenticular conglomerate units, trough-type cross bedding and the absence of carbonate units suggest that the formation is of fluviatile rather than marine origin. At Nullagine a basal conglomerate (Beatons Creek Conglomerate Member) of the formation has been mined for gold. The gold occurs as fine flakes and rounded particles in the matrix of the conglomerate which contains large angular and subrounded clasts of Archaean sedimentary and granitic rocks. This conglomerate is almost certainly alluvial.

SHALE

The subject of this paper is a grey, fine-grained shale member of the Hardey Sandstone. The shale is about 20 m thick and extends 30 km acoss the Meentheena Basin (Fig. 32), a structural unit defined by Hickman (1975b). Similar rock occurs at the same stratigraphical position at Taylor Creek (60 km to the southwest) and Glenn Herring (100 km to the west), but it is uncertain as to whether or not these widely scattered outcrops represent remnants of a once continuous sheet. Obviously, the shale marks a temporary regional cessation in the influx of coarse detritus to the basins, but it has so far been impossible to determine if the deposit is of marine, estuarine or freshwater origin.

Fifty shale samples, each weighing 20 to 50 gm, were collected from the outcrop, the location of which is shown on Figure 32. Sampling was carried out over a distance along strike of 30 m and across a 2 m vertical section. Microscopic examination reveals the shale to be a recrystallized silty clay; micaceous minerals, strongly orientated in the plane of bedding, make up over 60 per cent of the rock. Quartz clasts, partly recrystallized, attain a maximum diameter of 0.05 mm but are generally 0.01 to 0.02 mm. No feldspar is visible. The size and abundance of quartz grains varies across bedding producing a weak banding. An X.R.D. examination of two samples revealed the presence of chlorite and muscovite, but no kaolin or montmorillonoid minerals. Illite was not detected, possibly due to the abundance of muscovite, but perhaps more probably because of the degree to which the rock has been recrystallized.

All the samples collected were flake-shaped, broken parallel to bedding so that no more than a 5 mm interval was normally represented. Some samples were consequently finer grained than others.

Each sample was powdered to below 200 mesh using a Tema mill.

PALAEOENVIRONMENTAL ANALYSIS

Degens and others (1975) constructed a triangular diagram to illustrate that fresh-water and marine shale

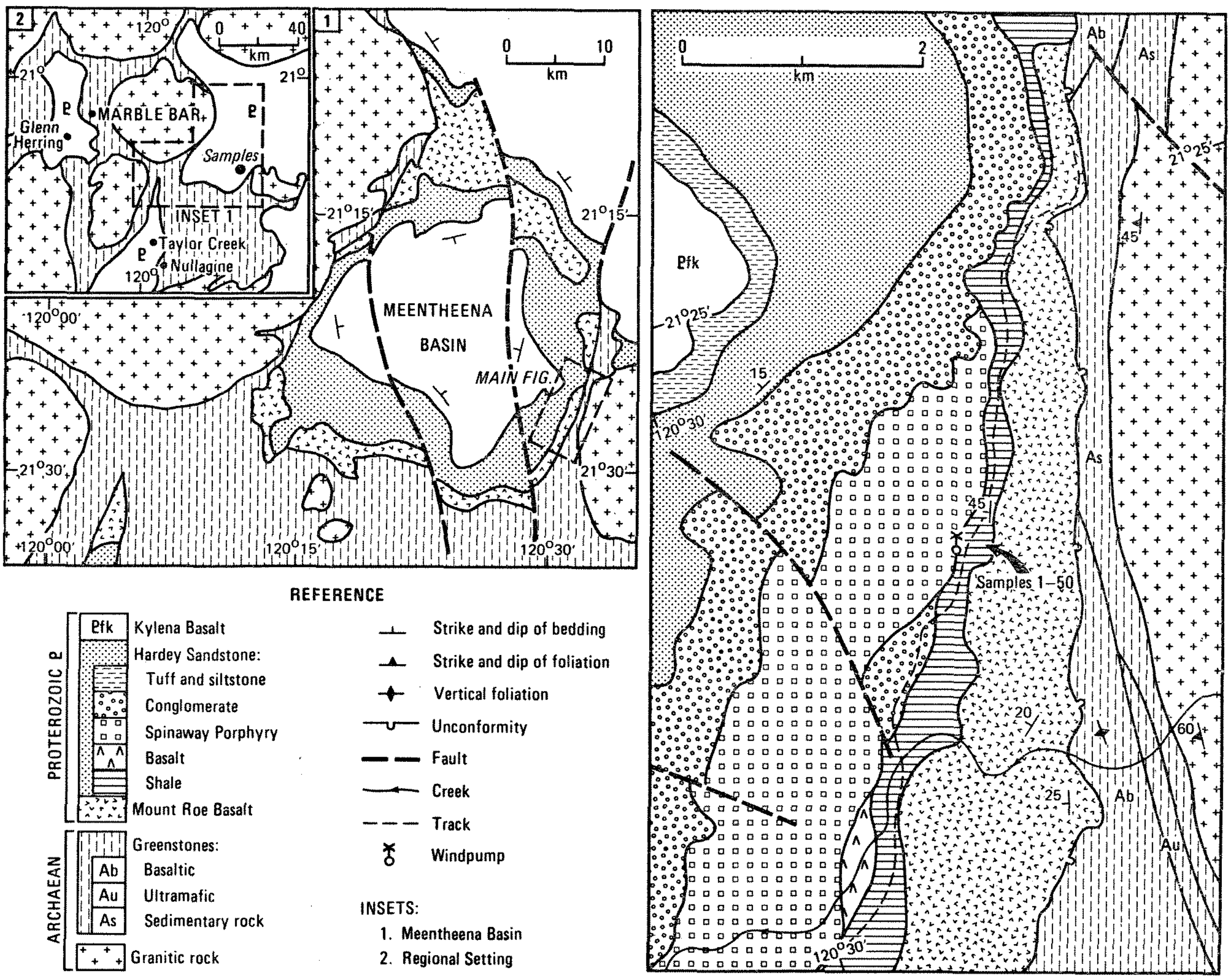

Figure 32. Geological setting and sample locality of a shale within the Hardey Sandstone.

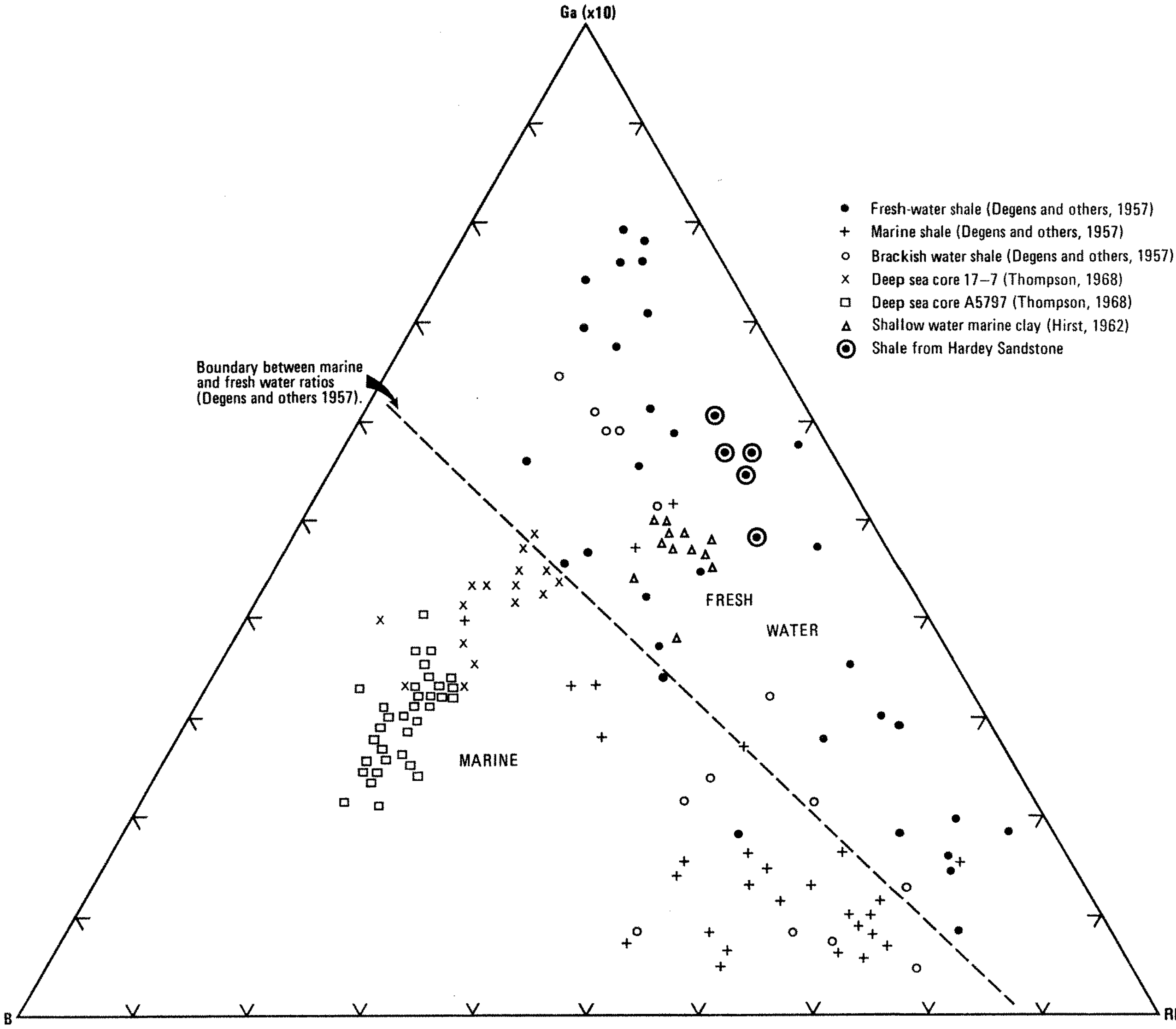

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Figure 33. Relative abundance of gallium, rubidium, and boron in shale from the Hardey Sandstone compared with marine and fresh–water shale.

samples can be distinguished on the basis of their relative gallium, rubidium and boron contents. This diagram has since been employed by other workers (Degens and others, 1958; Thompson, 1968; El-Askary and El-Mahdy, 1976) and is repeated, with the addition of new data, in Figure 33.

Boron was first used as an indicator of palaeosalinity by Goldschmidt and Peters (1932) who recognized a difference in the boron content of various marine and nonmarine sedimentary rocks. Landergren (1945, 1958) examined the usefulness of the element in distinguishing marine and fresh-water clay deposits. According to Ernst (1970) boron is present in sea water with a concentration of 4.8 mg/1 whereas its concentration in river water is only 0.01 mg/1. The boron contents of shales are far higher than those of igneous rocks. Concentration in the depositional environment is generally explained by incorporation of the element into illite, where it either substitutes for aluminium (Harder, 1961) or silicon (Walker and Price, 1963). Degens and others (1957) demonstrate that boron increases with the illite:Kaolinite ratio and that illite predominates in the marine environment. Walker and Price (1963) found that illite from freshwater shale contains only about one-third as much boron as illite from marine shale. Tourmaline also contributes boron to sediments but as Hirst (1962) points out, tourmaline contents are normally so low as to only account for up to about 3 ppm in most rocks.

Gallium substitutes for aluminium in clay minerals, and a strong positive correlation exists between the two elements in sedimentary rocks. Hickman (1972) examined over 300 inter-element correlations in 100 samples of Precambrian slate from the Scottish Highlands and found the correlation between gallium and aluminium to be second strongest after that between rubidium and potassium. Hirst (1962) states that the gallium:aluminium ratio is fairly constant through widely differing sedimentary facies and also in igneous rocks. He concludes that gallium enters depositional basins structurally combined within the lattices of degraded clay minerals and that there is little separation of gallium and aluminium during weathering and transportation. Degens and others (1957) explain their observation that fresh-water sediments contain more gallium than marine sediments as a consequence of the fact that kaolinite (relatively concentrated in the fresh-water environment) contains more aluminium than does illite.

Rubidium substitutes for potassium in feldspar, mica and illite. According to Ernst (1970) potassium is strongly adsorbed on clay minerals during diagenesis and is used in the reconstruction of micas. Degens and others (1957, Fig. 7) found that rubidium content increases as the illite: kaolinite ratio increases, the element thus being concentrated in marine sediments.

Table 15 presents average contents of boron, gallium and rubidium in various shale, clay and mud deposits known to be of either marine or fresh-water origin.

TABLE 15. MEAN B, Ga AND Rb CONCENTRATIONS (ppm) IN MARINE AND FRESH-WATER ARGILLACEOUS SEDIMENTS

Rock type	Age	B	Ga	Rb	Reference
Marine					
Shale	Carboniferous	115	8	281	Degens and others, 1957
Mud	Recent	140	....	....	Landergren, 1945°
Clay	Early Jurassic	75	....	....	Landergren, 1945°
Shale	Ordovician	75	....	....	Landergren, 1945°
Shale	Cambrian	100	....	....	Landergren, 1945°
Shale	Early Jurassic	115	....	....	Landergren, 1945°†
Shale	Carboniferous	130	....	....	Ostram, 1957†
Shale	Carboniferous	100–200	....	....	Ernst and others, 1958*
Deep water sediment	Recent	300	....	....	Goldberg and Arrhenius, 1958**
Clay	Recent	79	20	150	Hirst, 1962
Argillaceous sediment	Recent	90	20	....	Potter and others, 1963
Shale	Phanerozoic	124	25	....	Potter and others, 1963
Shale	Carboniferous	150	....	....	Porrenga, 1963*
Deep Water sediment	Recent	135	....	....	Landergren, 1964**
Shale	Carboniferous	96	....	....	Curtis, 1964
Deep water clay	Recent	320	18	110	Thompson, 1968
Deep water clay	Recent	180	19	104	Thompson, 1968
Argillaceous sediment	Camb.-Ord.	141	....	....	Shaw and Bugry, 1965
Argillaceous sediment	Devonian	278	....	....	Shaw and Bugry, 1965
Argillaceous sediment	Carboniferous	172	....	....	Shaw and Bugry, 1965
Argillaceous sediment	Jurassic	153	....	....	Shaw and Bugry, 1965
Brackish					
Shale	Carboniferous	92	14	186	Degens and others, 1957
Shale (or fresh-water)	Carboniferous	78	....	....	Eagar and Spears, 1966
Argillaceous sediment	Triassic	95	....	....	Shaw and Bugry, 1965
Shale	Cretaceous	110	....	....	Tourtelot, 1964†
Fresh-water					
Shale	Carboniferous	44	17	139	Degens and others, 1957
Underclay (or brackish)	Carboniferous	72	76	200	Degens and others, 1958
Shale	Carboniferous	15–45	....	....	Ernst and others, 1958*
Argillaceous sediment	Recent	46	14	....	Potter and others, 1963
Argillaceous sediment	Phanerozoic	40	16	....	Potter and others, 1963
Shale	Carboniferous	50	....	....	Porrenga, 1963*

* Harder, 1970; † Shaw and Bugry, 1966; ° Goldschmidt, 1958: ** Thompson, 1968.

CHEMISTRY OF THE SHALE

The powdered samples were first analyzed for rubidium and gallium (Table 16), then combined to form five composites (using equal weights of the initial samples) on the basis of rubidium:gallium ratio. These composites were analyzed for boron, gallium, rubidium and potassium (Table 17).

TABLE 16. Ga, Rb CONTENTS (ppm) AND Rb: Ga RATIOS OF THE FIFTY SHALE SAMPLES

GSWA No. (32656)	Lab. No. (1974)	Ga	Rb	Rb: Ga
1	7416	18	133	7·4
2	7417	18	134	7·4
3	7418	24	162	6·8
4	7419	16	138	8·6
5	7420	20	139	7·0
6	7421	19	136	7·2
7	7422	21	146	7·0
8	7423	18	165	9·2
9	7424	18	158	8·8
10	7425	17	127	7·5
11	7426	17	140	8·2
12	7427	16	147	9·2
13	7428	42	155	3·7
14	7429	29	143	4·9
15	7430	22	157	7·1
16	7431	21	148	7·0
17	7432	20	146	7·3
18	7433	26	159	6·1
19	7434	23	148	6·4
20	7435	25	140	5·6
21	7436	25	128	5·1
22	7437	26	141	5·4
23	7438	25	138	5·5
24	7439	28	147	5·2
25	7440	26	142	5·5
26	7441	27	137	5·1
27	7442	20	149	7·5
28	7443	27	149	5·5
29	7444	24	141	5·9
30	7445	18	135	7·5
31	7446	25	143	5·7
32	7447	21	123	5·9
33	7448	16	158	9·9
34	7449	19	150	7·9
35	7450	18	125	6·9
36	7451	20	169	8·5
37	7452	26	148	5·7
38	7453	19	142	7·5
39	7454	23	172	7·5
40	7455	22	127	5·8
41	7456	21	150	7·1
42	7457	25	146	5·8
43	7458	19	123	6·5
44	7459	17	133	7·8
45	7460	21	120	5·7
46	7461	16	151	9·4
47	7462	15	139	9·3
48	7463	16	137	8·6
49	7464	18	142	7·9
50	7465	17	138	8·1

Analysts: R. W. Lindsey and J. Gamble, West. Australia Government Chemical Laboratories.

TABLE 17. B, Ga, Rb and K_2O CONTENTS OF FIVE COMPOSITE SAMPLES

Composite sample	B	Ga	Rb	K_2O
	ppm	ppm	ppm	per cent
A(7)	28	22	139	3·34
B(13)	40	28	144	3·41
C(15)	39	25	149	3·47
D(7)	37	24	157	3·62
E(8)	42	19	160	3·72
Mean	37	24	150	3·51

Note: Figures in parentheses refer to number of samples in each composite.
Analysts: R. W. Lindsey and J. Gamble, West. Australia Government Chemical Laboratories.

Methods of analysis

A part of each shale sample was decomposed using a mixture of hydrofluoric, nitric and perchloric acids and fumed to dryness. The resulting salts were dissolved in hydrochloric acid and made to volume so that they contained 2 000 mg/1 of potassium as potassium chloride. The determination of rubidium was performed on a Varion-Techtron (No. 5) atomic absorption spectrophotometer. Gallium was determined photometrically using rhodomine B.

Boron was determined using the following procedure. The samples were attacked by fritting with a sodium carbonate-zinc oxide mixture. A water extract of the frit was acidified and complexed with a zirconium salt to avoid interference from fluoride. Boron was then extracted into a solution of 2-ethylhexane-1, 3-diol in chloroform. The chloroform was evaporated off at low temperature and the remaining solution treated with a solution of Curcumin in glacial acetic acid followed by 1:1 v/v sulphuric acid-acetic acid mixture. After 1 hour reaction time the solution was diluted to 100 ml with alcohol and the boron content determined spectrophotometrically.

Potassium was determined by the following method. Samples were treated with a mixture of hydrofluoric, nitric, perchloric and hydrochloric acids, fumed to dryness, taken up in 5 ml 1:1 sulphuric, 5 ml hydrochloric and 5 ml hydrofluoric acids, again evaporated and fumed to dryness. The resulting contents were dissolved in a small volume of water and three drops of hydrochloric acid, and made to a standard volume. An aliquot was taken, and after the addition of a radiation buffer solution, potassium was determined using a flame emission spectrophotometer.

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Results

When the results presented in Table 17 are plotted onto Figure 33 it is clear that the shale member of the Hardey Sandstone falls well within the fresh-water field. The same result occurs when the data are plotted on alternative palaeosalinity diagrams such as presented by Degens and others (1957, Ga:B) and Walker and Price (1963, K_2O: adjusted B). Thus, on the basis of element ratios and observed boron content (comparison with data presented in Table 15) the shale appears to be of fresh-water origin. This interpretation agrees with that reached on stratigraphic and lithological grounds (noted above).

GEOCHRONOLOGY

The experimental procedures of Rb-Sr isotopic analysis are essentially the same as those described by Lewis and others (1975). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured in this laboratory is 0.7102 ± 0.0001, normalized to a $^{88}Sr/^{86}Sr$ value of 8.3752. The value of 1.39 x 10^{-11} yr^{-1} was used for the decay constant of ^{87}Rb. The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios, as well as the calculated $^{87}Rb/^{86}Sr$ ratios are given in Table 18. Errors accompanying the data are at the 95 per cent confidence level. The data are plotted in Figure 34.

TABLE 19. VARIATION OF ISOCHRON AGE WITH INITIAL $^{87}Sr/^{86}Sr$ RATIO

	Initial $^{87}Sr/^{86}Sr$ ratio	Age (m.y.)
MODEL 3 Derived Ri*	0·694 95 ± 0·012 93	2 765 ± 151
MODEL 2 Assumed Ri*	0·697 5	2 736 ± 9
	0·700 0	2 708 ± 9
	0·702 5	2 680 ± 10
	0·705 0	2 652 ± 11
	0·707 5	2 624 ± 12
	0·710 0	2 595 ± 13

* *Initial ratio*

It can be seen that increasing the initial ratio reduces the slope of the isochron to give successively younger ages. An increase of 0.0025 initial ratio gives an approximate decrease of 28 m.y. in the age. The error limits calculated from the isotopic data give an upper limit in initial ratio of 0.708 and a lower limit in the age of 2 615 m.y. The isotopic age of 2 765 ± 151 m.y. is realistic and meaningful, although the experimental data give only a rough assessment of the true initial ratio, and hence no isotopic evidence as to the origin of the shale.

TABLE 18. ANALYTICAL DATA FOR THE SHALE MEMBER WITHIN THE HARDEY SANDSTONE

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
7439	148	78	1·91 ± 0·02	5·63 ± 0·06	0·916 70 ± 0·000 91
7448	147	75	1·96 ± 0·02	5·78 ± 0·06	0·920 61 ± 0·000 86
7416	133	66	2·02 ± 0·02	5·96 ± 0·06	0·928 87 ± 0·000 73
7427	142	69	2·05 ± 0·02	6·01 ± 0·06	0·929 41 ± 0·000 68
7432	152	70	2·16 ± 0·02	6·38 ± 0·06	0·945 02 ± 0·000 97
7455	122	55	2·23 ± 0·02	6·59 ± 0·07	0·953 31 ± 0·000 48
7421	140	62	2·26 ± 0·02	6·68 ± 0·06	0·956 97 ± 0·000 88

Note: The Rb and Sr concentrations have been determined by X-ray fluorescence spectrometry. We believe the values are accurate to about ± 7 per cent. The Rb/Sr ratios do not correspond exactly with the ratios that would be derived from the separate Rb and Sr values listed.

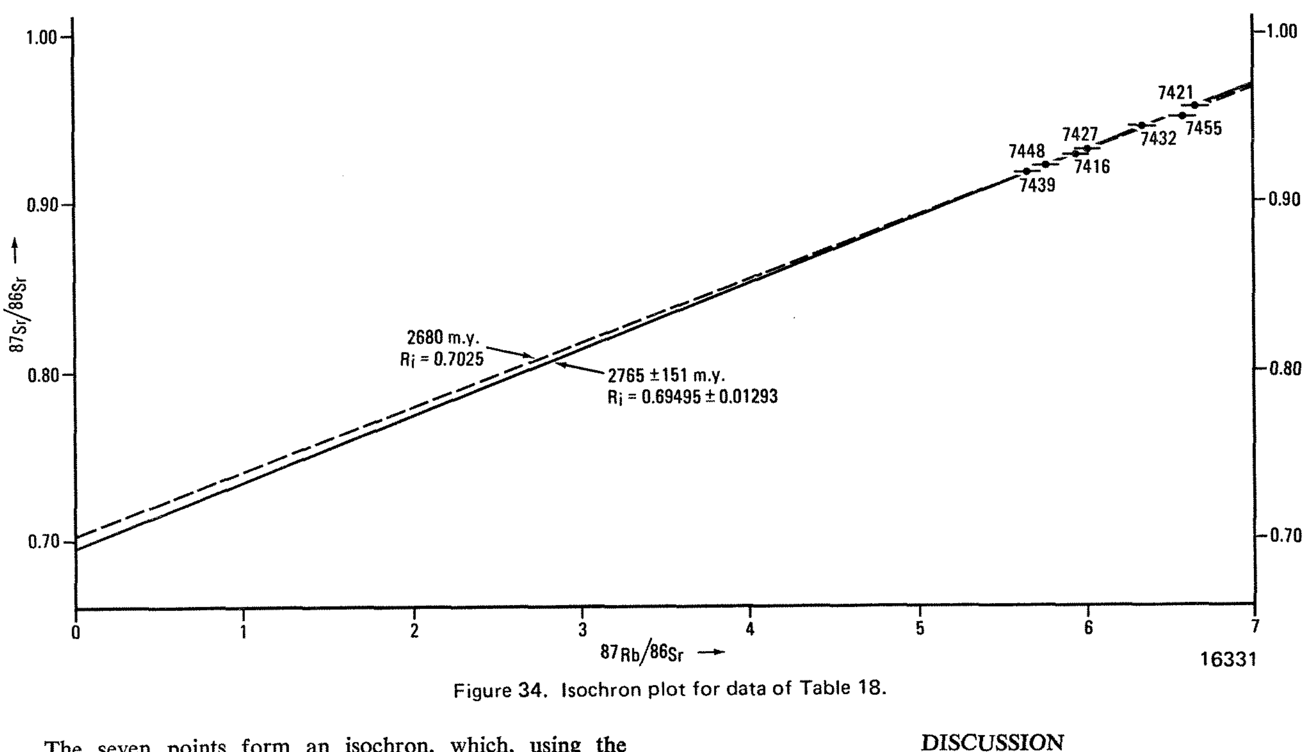

Figure 34. Isochron plot for data of Table 18.

The seven points form an isochron, which, using the regression analysis of McIntyre and others (1966), give a Model 3 isochron of 2 765 ± 151 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0.69495 ± 0.01293. An initial ratio of 0.69495 is geologically and theoretically untenable (Faure and Powell, 1972, p. 45). To illustrate the effect of forcing the isochron to pass through an assumed initial ratio, 0.0025 increments have been added to the calculated initial ratio of 0.69495 as given in Table 19.

DISCUSSION

The fresh-water origin of the shale is reasonably well established, but the age computed for the rock raises several interesting problems.

Veizer and Compston (1976) present evidence to show that the primary Sr isotopic composition of sedimentary carbonate rocks has varied through geological time. At about 2 500 m.y. the $^{87}Sr/^{86}Sr$ ratio of carbonate rocks was similar to that of the contemporaneous upper mantle, and approximately 0.7025. Assuming this initial ratio, an age of 2 680 m.y. is calculated for the shale.

It will be appreciated from earlier references to previous geochronological work in the Pilbara that such an old age for the Hardey Sandstone is unexpected, yet even assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.710 (the highest common value noted by Veizer and Compston (1976) for Phanerozoic rocks) the age of the shale is computed at 2 595 m.y. The question therefore arises as to whether 2 700-2 600 m.y. is the true age of the Hardey Sandstone or whether the result merely testifies to a substantial component of Archaean detritus.

The "post-tectonic granites" (Hickman, 1975b) or "tin granites" (Blockley, 1970; de Laeter and Blockley, 1972) of the Pilbara Block range in age from 2 700-2 600 m.y., and have always been regarded as Archaean. Unfortunately, there are no contacts between dated plutons of this type and the Fortescue Group. The only granitic rocks observed to intrude the Fortescue Group are small stocks of hornblende adamellite which appear to be unrelated to the post-tectonic granites (Hickman, 1975a). In view of the large area of outcrop of the Fortescue Group (approximately 40 000 km^2) in the Pilbara this negative evidence suggests that the Fortescue Group probably post-dates the 2 700-2 600 m.y. granites. The Cooglegong Adamellite (dated by de Laeter and others (1975) at 2 606 $\pm$ 128 m.y.) is intruded by the Black Range Dyke, so that if the latter belongs to the same suite as the Cajuput Dyke (see above) the Hardey Sandstone must be younger than these granites. The presence of detrital cassiterite (almost certainly derived from the post-tectonic granites) in the Beaton Creek Conglomerate Member of the Hardey Sandstone lends further support to this relationship.

As noted above microscopic examination of the shale reveals no identifiable clastic component, but the rock is recrystallized. It is possible that the samples contain mica derived from an Archaean source region. Palaeogeographical evidence indicates that such a source region lay to the south of the Meentheena Basin. The closest principal source of mica in this direction is the Mosquito Creek Formation, a relatively late Archaean succession of metamorphosed turbidite sediments.

If mica derived from Archaean rocks is obscuring the true age of the shale, the fact that the resulting isochron is a straight line demands acceptance of thorough mixing of this material with authigenic clay. The initial $^{87}Sr/^{86}Sr$ ratio of such a mixture would be higher than that of the water in the depositional basin. If the true age of the shale is 2 400 m.y., for example, this initial ratio would probably have been about 0.73. However, the error limits computed from the raw data indicate that the minimum age of the rock is about 2 600 m.y., a figure which imposes a maximum initial ratio of 0.71. A variable initial $^{87}Sr/^{86}Sr$ ratio through the shale, perhaps resulting from sedimentary differentiation, might conceivably result in a straight isochron giving an erroneously old age, but no other examples of such a process are known.

It is concluded that the true age of the Hardey Sandstone may be about 2 600 m.y., but this figure must be treated with caution. In particular, it is hard to reconcile such an old age with that of 2 329 m.y. obtained on the Black Range Dyke (Lewis and others, 1975), previously considered to be slightly older than the formation.

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REVIEW OF THE REPORTED OCCURRENCE OF FAMENNIAN (LATE DEVONIAN) ATRYPID BRACHIOPODS IN WESTERN AUSTRALIA

by K. Grey

ABSTRACT

The anomalous occurrence of Famennian (late Late Devonian) atrypid brachiopods recorded by Veevers (1959a) is discussed. Considerable doubt now exists that atrypids occur in any locality of undoubted Famennian age in Western Australia. This provides further evidence for the world-wide extinction of atrypids at the end of the Frasnian (early Late Devonian).

INTRODUCTION

With the exception of two doubtful occurrences, members of the brachiopod order Atrypida are believed to have undergone world-wide extinction at the end of the Frasnian (early Late Devonian). Boucot, Johnson and others (1965), in the Treatise on Invertebrate Paleontology, give the range of the atrypids as Middle Ordovician to Late Devonian. Ager, Copper and others (1967), give the oldest occurrence as being Llanvirnian, the youngest as late Frasnian. Two doubtful Famennian records are also mentioned, one by Mansuy (1912) from Indo-China, and one by Veevers (1959a) from the Canning Basin of Western Australia. Copper (1973), in a synopsis of atrypid relationships and their ranges, does not extend the group beyond the Frasnian.

ATRYPIDS IN WESTERN AUSTRALIA

The first major systematic publication on the atrypid brachiopods of Western Australia was that of Coleman (1951, 1952). Veevers (1959a, 1959b) made a comprehensive systematic study of the brachiopod faunas of the Canning Basin, and revised the atrypid species described by Coleman. The species were further discussed by Roberts (1971) in work on the brachiopod faunas from the Bonaparte Gulf Basin. Two of the species *Spinatrypa prideri* (Coleman) and *Desquamatia (Synatrypa) kimberleyensis* (Coleman) were recorded from samples of Famennian age by Veevers, implying a longer range for the atrypids in Western Australia than is known in the rest of the world—with the exception of the record from Indo-China.

Recent work in Russia, Europe, and North America, has shown the need for a re-appraisal of atrypid taxonomy. As part of the revision of Western Australian atrypids (Grey, in preparation), six critical samples described by Veevers (1959a) were borrowed from the Bureau of Mineral Resources.

Veevers (1959a) recorded atrypids from 3 samples which he considered to be Famennian in age. These were K289 and K503 from the *proteus* zone, and Ld29 from the *scopimus* zone. Three other atrypid-bearing samples (Ld8, Ld31 and 0/73) from the northern end of the Oscar Range have also been examined. These samples were considered to be Frasnian in age by Veevers (1959a), but occur in areas where the rocks are now regarded as Famennian.

SAMPLE K 289

B.M.R. registered fossil number F18632, described as "DF2 Al South of Burramundi Range (Base of Fairfield Beds in section DF2)—*proteus* zone". Veevers (1959a) recorded the following species:

Camarotoechia lucida = *Ptychomaletoechia lucida*
Atrypa desquamata kimberleyensis = *Desquamatia (Synatrypa) kimberleyensis*
Athyris oscarensis
Schizophoria sp. cf. *S.stainbrooki*

The sample locality can be shown to lie within the Nullara Limestone which is of Famennian age (Playford and Cockbain, 1976). However, the lithology of the portion of the sample which was examined is typical of the Sadler Limestone, showing the type of silicification known only from that formation. Although *Ptychomaletoechia lucida* is restricted to the Famennian, (Roberts 1971, p. 150), *Athyris oscarensis* occurs in both the *proteus* and the *saltica* zone. *Schizophoria* sp. cf. *S. stainbrooki* cannot be regarded as definitive of any zone. Finally, the portion of the sample examined contains the stromatoporoid *Amphipora*, which is not known to occur above the Frasnian in the Canning Basin.

There is conflicting evidence for the age of this sample, and it seems reasonable to suppose that it has become contaminated by material from the Sadler Limestone. Roberts and others (1972, p. 472) also comment on the probable mixing of material from this locality. This sample cannot, therefore, be regarded as an authentic record of Famennian atrypids.

Of the atrypids present, only one can be identified as *Desquamatia (Synatrypa) kimberleyensis*. The remainder are either *Spinatrypa prideri*, or are too poorly preserved for identification.

SAMPLE K 503

B.M.R. registered fossil number F18641, described as "Geikie Gap area (?Fairfield Beds)—*proteus* zone". Veevers (1959a) recorded the following species:

?Spinatrypa aspera prideri = *Spinatrypa prideri*
Schizophoria pierrensis

Approximately 40 specimens from this sample were examined and were identified as *Spinatrpya prideri*. An undescribed spiriferid is also present, and the same form has been observed in material of Frasnian age (Grey, 1974).

The locality lies in an area mapped as Pillara Limestone, which is now restricted to the Frasnian (Playford and Cockbain, 1976).

SAMPLE Ld 29

B.M.R. registered fossil number F18560, from Wire Spring, described as "(Napier Formation)—*?scopimus* zone". The following species were recorded by Veevers (1959a):

Pugnax hullensis
Atrypa desquamata kimberleyensis = *Desquamatia (Synatrypa) kimberleyensis*

Pugnax hullensis, regarded by Veevers as being restricted to the Famennian, has also been recorded from the Frasnian by Grey (1974); and the faunal evidence which previously supported a Famennian age must now be regarded as inconclusive.

The main problem in accepting this sample as an authentic record of Famennian atrypids lies in the fact that the precise locality is not known. No air-photo data were supplied, and, therefore, although Wire Spring itself lies within the Napier Formation, and nearby outcrops are of Famennian age, it is not certain that the sample in question came from the immediate vicinity of Wire Spring. Until atrypids are collected from this part of the Napier Formation, the validity of this sample must be questioned.

SAMPLE Ld8

B.M.R. registered fossil number F18546, from Morown Yard, described as "(Oscar Formation)—*saltica* or *torrida* zone". The following species were recorded by Veevers:

Atrypa desquamata kimberleyensis = *Desquamatia (Synatrypa) kimberleyensis*
Uncinulus wolmericus = *Flabellulirostrum wolmericum*

This sample was re-examined because the description of the locality as Morown Yard suggested a possible origin from the Famennian. There is, however, no evidence to suggest a Famennian age. The locality is mapped as Pillara Limestone, and the faunal evidence indicates that the outcrop is of Frasnian age.

SAMPLE Ld31

B.M.R. registered fossil number F18564, from Elimberrie Spring described as "(Napier Formation)—*apena* zone". The following fossils were recorded by Veevers (1959a):

Crurithyris apena
Hypothyridina margarita
Pugnax sp. cf. *P. pugnus*
?Atrypa desquamata kimberleyensis = *Desquamatia (Synatrypa) kimberleyensis* cf. *Schizophoria stainbrooki*

This sample was re-examined because of its proximity to material known to be of Famennian age. The locality is in the core of a bioherm within the Famennian part of the Napier Formation. However, on the basis of the fauna, there is no reason to doubt that the sample is of Frasnian age.

SAMPLE 0/73

B.M.R. registered fossil number F18573, from Palm Spring, described as "(Oscar Formation)—*apena* or *saltica* zone" and containing the following fossils (Veevers, 1959a):

Hypothyridina margarita
Nervostrophia bunapica
Pugnax sp. cf. *P. pugnus*
P. sp. cf. *P. acuminatus*
Atrypa desquamata kimberleyensis = *Desquamatia (Synatrypa) kimberleyensis*
?Crurithyris apena

This sample was examined because of its proximity to known Famennian material. It is regarded as being part of the Pillara Limestone, and there is no reason to doubt the Frasnian age indicated by the fauna.

OTHER RECORDS OF FAMENNIAN ATRYPIDS FROM WESTERN AUSTRALIA

Teichert (1949, p. 23) records *Atrypa* ?sp. ind. from the *Productella* zone (Veevers' *proteus* zone). This specimen has not been located, and no locality details are given. The identification is tentative and in view of the lack of information it is impossible to assess the significance of the record.

A specimen of *Atrypa reticularis teicherti* Coleman, from the type collection of the Geology Department of the University of Western Australia, is described in the catalogue, but not in the literature, as being from rocks of Famennian age. The specimen was illustrated by Coleman (1951, Pl. 100, Figs. 6-10) but incorrectly numbered as 26893a. The correct number is 26273e (not 25893 as indicated in the catalogue) and the specimen is from the type locality. Lithological and other evidence confirm a Frasnian age for this sample (Grey, in preparation).

ATRYPIDS FROM INDO-CHINA

Mansuy (1912) describes atrypids from the Frasnian and Famennian of Yunnan. These atrypids, in particular *Atrypa bodini* Mansuy (Pl. 8, Fig. 10, Pl. 9, Fig. 11) show a close similarity to specimens from Western Australa (Grey, in preparation). Specimens from Ta-Hi-Ti (now in North Vietnam) are described as Famennian in age (Mansuy 1912) though the fossil evidence for this would now appear doubtful, as both Grabau (1931) and Alekseeva (1962) have commented. Russian specimens of *Spinatrypa bodini* (Mansuy) are known only from the Frasnian. Fontaine (1967) in a review of the stratigraphy of Cambodia, Laos and Vietnam, states that the Famennian has never been described with certainty from North Vietnam. Therefore, the Indo-Chinese record of Famennian atrypids must be regarded as a doubtful occurrence.

CONCLUSIONS

Of the six atrypid samples examined, it seems unlikely that any can be regarded as of Famennian age. The faunas described from localities Ld8, Ld31, and 0/73, all indicate a Frasnian age, and there is no stratigraphical evidence to suggest that these could be Famennian.

The three remaining samples were all described as Famennian by Veevers, but there is now considerable doubt regarding the authenticity of these samples. K289 presents conflicting evidence, and must be regarded as contaminated. K503 is Frasnian. The dating of Ld29 is equivocal; however, the complete lack of locality data prevents this being considered as a valid record of the occurrence of Famennian atrypids. The other Western Australian records of Famennian atrypids cannot be confirmed.

This study shows that the presence of Famennian atrypids in the Canning Basin has not been proved. The factors suggesting a Famennian age for the localities under consideration are ambiguous. On such slender evidence, the occurrence cannot be regarded as valid.

There is no evidence elsewhere, with the exception of the very doubtful record from Indo-China (Mansuy, 1912), to suggest that the atrypids extended into the Famennian, and it seems reasonable to conclude that in Australia, as in the rest of the world, the atrypids became extinct at the end of the Frasnian.

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PRECAMBRIAN STROMATOLITES AS PROVENANCE INDICATORS IN THE PERMIAN LYONS FORMATION, CARNARVON BASIN

by K. Grey, W. J. E. van de Graaff, and R. M. Hocking

ABSTRACT

Proterozoic stromatolites occur as erratics in the Lower Permian Lyons Formation of the east-central Carnarvon Basin, and in two cases have been matched with stromatolites from localities in the Henry River area of the Middle Proterozoic Bangemall Basin. The pin-pointing of the source areas of the erratics indicates a north to south movement of ice across the Bangemall Basin to the Gascoyne River area. This direction of ice movement is consistent with that indicated by striated glacial pavements.

INTRODUCTION

During the Early Permian, large areas of Australia were subjected to glaciation. In Western Australia, continental and marine glacial sediments indicate that Early Permian ice-centres were located on the Yilgarn, Pilbara, and Kimberley Blocks (Crowell and Frakes, 1971), and on the Musgrave Block (Jackson and van de Graaff, in prep.).

The Permian glacial deposits of the Carnarvon Basin are mapped as the Lyons Formation ("Lyons Group" of Teichert, 1950; Condon, 1954, 1967; amended van de Graaff and others, 1977). It was described by Condon (1967, p. 12) as a sequence ". . . related genetically to glaciation and consisting of siltstone, quartzwacke and boulder beds". The earlier authors considered the Lyons Formation to be mainly a marine glacial deposit, with lesser amounts of glacio-lacustrine and fluvioglacial sediments. Our recent field work supports these interpretations.

Crowell and Frakes (1971) in their review of the Early Permian glaciation in Australia claimed that direct evidence for glaciation in the Carnarvon Basin is scanty, but considered that important ice-rafting in a marine environment took place. They postulated a glacial centre on the Yilgarn Block, to the east of the central Perth Basin, with glacial imprint lessening northwards as distance from this source increased.

In contrast to this, erratic boulders collected in 1976 indicate that a derivation from a northerly direction is more probable for at least some of the ice-rafted material. The boulders consist of stromatolite fragments which are similar to forms occurring in the Irregully Formation (Middle Proterozoic, 1 100 m.y. old) in the Bangemall Basin. This basin lies northeast of the Lyons Formation outcrop-area, and extends in a northwest direction (Fig. 35, inset). Several forms of stromatolite are present in the basin, and lithologies show a fairly wide variation and restricted distribution. As a result, the provenance of the erratics can be determined with considerable confidence.

DESCRIPTION OF GLACIAL ERRATICS

Sample F9477, collected from locality 44517 is a large boulder of *Baicalia capricornia* Walter. The lithology consists of a dark blue-grey limestone which weathers to a light brown along the edges of the laminae. Sample F9478 from locality 30122, is a laminate or cumulate form which cannot be given a specific name because it does not show column development. It is probably the basal part of *Baicalia capricornia* and has a similar lithology to F9477.

Samples F9479 and F9480 also from locality 30122, are extremely well-preserved specimens of a small form of *Conophyton*. The samples contain a series of discrete, steep-sided cones with occasional bridges. The cones are approximately 15 to 20 cm high, and at least one is curved near the tip. The specimens are almost completely replaced by silica.

PROVENANCE

Stromatolite localities in the Bangemall Basin have been recorded by Daniels (1968, 1969 and 1970) and Walter (1972). Recent field work in the basin has shown the presence of previously undescribed forms; from these studies it is evident that both stromatolite-form and lithology vary widely, and show restricted distributions within the basin. This is an important factor in determining the provenance of the glacial erratics.

The stratigraphy and facies variation in the basin have been described by Brakel and Muhling (1976) and Williams and others (1976). Stromatolites are rare in the more arenaceous facies of the eastern and central areas of the basin. Where they do occur, laminate and cumulate forms predominate. Large forms of *Conophyton* and some *Baicalia capricornia* are present; lithologies are either pink or cream dolomite, or light-grey or dark-grey limestone, and show minor silicification. On the basis of known localities, an origin east of Long. 116° seems unlikely.

West of Long. 116° stromatolite localities are more abundant. Stromatolites at localities in the Parry Range and adjacent areas are heavily slicified, elsewhere lithologies are varied but consist of dark-grey limestones and cream dolomites. Small specimens of *Conophyton* occur in a north-south band extending from the Parry Range to Milly Spring. *Baicalia capricornia* is found near the Henry River East Branch. From this it is evident that the most probable source for the glacial erratics lies along the western margin of the Bangemall Basin.

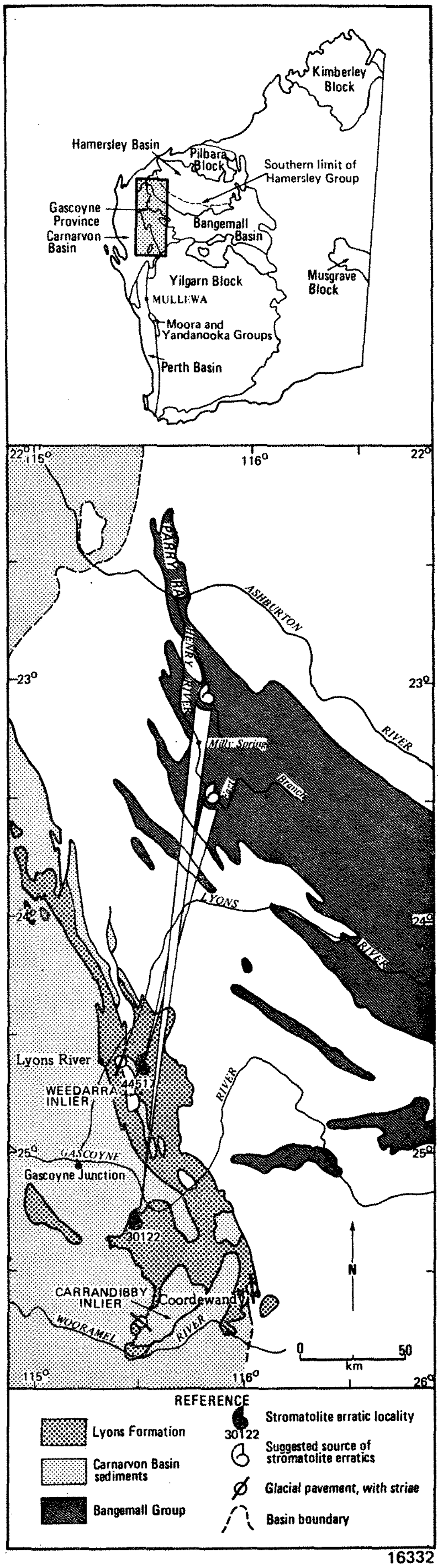

Figure 35. Location of glacial—provenance indicators in the eastern Carnarvon Basin, and suggested source of stromatolite erratics from the Bangemall Basin.

Within the north-south band of *Conophyton* localities, considerable variation of form, size and lithology occurs. Discrete cones are most common to the south of the Ashburton River in the Wongida Creek area, and cones of approximately 15 to 20 cm were observed to the west of the track which crosses Wongida Creek. The lithology at this locality is very similar to that observed in samples F9479 and F9480, and many of the cones have curved tips which may be either tectonic in origin or a growth characteristic. To the north and south of this locality, the cones are usually of a different size and are frequently laterally linked. *Conophyton* is extensively exposed at Milly Spring, where it shows considerable variation in size and also has curved tips. Frequently, the cones are not discrete at this locality. The *Conophyton* cones which are present in the glacial erratics, are sufficiently distinctive for an origin from the Wongida Creek-Milly Spring area to be considered as most probable.

Well preserved specimens of *Baicalia capricornia* are found in a dark blue-grey limestone at the type locality near the Henry River East Branch (Walter, 1972). Elsewhere, preservation is poor, and the lithology is variable; replacement by a green carbonate occurs at some localities. The area around the type locality is therefore regarded as the most probable origin for the glacial erratics containing *Baicalia capricornia.*

DIRECTION OF ICE MOVEMENT

On the basis of both stromatolite form and lithology, the glacial erratics collected from the Lyons Formation have been derived from the Henry River area to the north-northeast. It is unlikely that material could have been derived from areas further east because of the differences in form and lithology. The remarkable resemblance to stromatolites from known localities is good evidence for movement of ice from north to south in the Gascoyne River area.

Scarce pebbles and cobbles of banded iron-formation containing bright red jasper occur in some Lyons Formation boulder beds. One of these, collected from locality 44517, originated from either the Boolgeeda Iron Formation or the Weeli Wolli Formation in the Hamersley Group (Dr. A. F. Trendall, pers. comm. 1977), indicating transport from the north to northeast (Fig. 35, inset). This supports the northerly derivation deduced from the stromatolite erratics.

Glacial pavements at the base of the Lyons Formation are known from three localities. The pavements on the west side of the Carrandibby Inlier and to the east of Coordewandy homestead, which were described by Konecki and others (1958), have striations tending 315° and 352° respectively. The third pavement, which is on the western side of the Weedarra Inlier (approximately 7 km east of Lyons River homestead and 650 m south of the track to Deathtrap Outcamp) has striations trending 030°. The Lyons River and Coordewandy striated pavements are consistent with the north-south movement of ice indicated by the stromatolite erratics. The north-westerly trend of the Carrandibby Inlier pavement may be due to local factors, as the Carrandibby Inlier was a positive area during the Early Permian.

Further south, in the Perth Basin northeast of Mullewa, there is evidence for the northward movement of ice. In tillite of the Permian Nangetty Formation, Playford and others (in press) record boulders from every known formation of the Proterozoic Yandanooka Group, which crops out near the Darling Fault between Carnamah and Mingenew (Fig. 35). Stromatolites derived from the Coomberdale Chert in the Proterozoic Moora Group also occur as glacial erratics in the Nangetty Formation (Logan and Chase, 1961). It is difficult to account for this disparity in the direction of movement unless converging ice sheets were present.

CONCLUSIONS

Likely source areas for erratics, and the trends of striations on the two northernmost pavements are strongly indicative of a north to south direction of ice movement in the Gascoyne River area, with established transport distances of about 250 km. The direction of ice movement indicates that this part of the Carnarvon Basin was covered by an ice cap and/or ice shelf, which moved south from the Hamersley Basin/Pilbara Block region. Between the Wooramel River and Mullewa, about 400 km to the south, no evidence to indicate ice-transport directions is known. South of Mullewa, however, a northward movement of ice has been proved.

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A PRELIMINARY EVALUATION OF THE USE OF SULPHUR DIOXIDE AS A PROSPECTING TOOL IN W.A.

by R. Davy and M. Stokes*

ABSTRACT

Preliminary sampling for sulphur dioxide in drillhole air (soil air) over sulphide bodies has been inconclusive. Sulphur dioxide was readily detectable, though at a low concentration (4 $\mu g\ SO_2/m^3$ air), in traverses over a sulphide body (at Golden Grove), and the highest values outlined the mineralized zone on one traverse. Using the same technique, sulphur dioxide was detected in one hole out of sixteen at two other areas, Burbidge and Forrestania. However, extended time sampling at Forrestania showed that very small amounts of sulphur dioxide (1.5 $\mu g\ SO_2/m^3$ air) could be detected.

It is concluded that the method shows some promise, but that the parameters of sulphur dioxide evolution and detection are not yet fully worked out. Much additional test work is needed.

INTRODUCTION

Sulphur dioxide is used as a prospecting tool for sulphide ore bodies in parts of Europe and in North America. Kahma (1965), Nilsson (1971), and Kahma and others (1975) report on the use of dogs to detect sulphur dioxide released by oxidizing ore minerals. Kahma commented that a dog located 1 330 sulphide-bearing boulders in a test field, whereas a prospector only managed to find 270, ". . . even though the man knew he was taking part in a test in competition with a dog" (Kahma and others, 1975, p. 3).

The present interest in sulphur dioxide lies in its use for the identification of concealed sulphide-bodies. It was hoped that the testing of shallow boreholes over geophysical anomalies might, if sulphur dioxide proved absent, obviate the need for diamond drilling. Restriction of diamond drilling to areas with known sulphide would be a major saving during exploration programmes.

Literature on the scientific detection of sulphur dioxide generated by concealed ore-bodies is still sparse. A comprehensive paper by Rouse and Stevens (1971) evaluates the method, and gives case studies over various vein, porphyry-type disseminated sulphides, and sandstone-type disseminated sulphides which were buried to depths of up to 30 m in Canada and the U.S.A. Other case histories have been given by Meyer and Peters (1973) for Newfoundland, and Fisher (1976) for Colorado.

In Western Australia, testing at Mount Keith (approximately 75 km south-southeast of Wiluna), and at Nepean (26 km south of Coolgardie) was a failure, possibly because of inadequate analytical methods (detection limit 10 ppb) and, particularly at Mount Keith, unfavourable geological conditions (C.R.M. Butt, pers. comm.).

This paper reports on preliminary tests carried out over buried sulphides at three locations on the Yilgarn Block: Golden Grove, Burbidge, and Forrestania (Fig. 36).

*Public Health Department

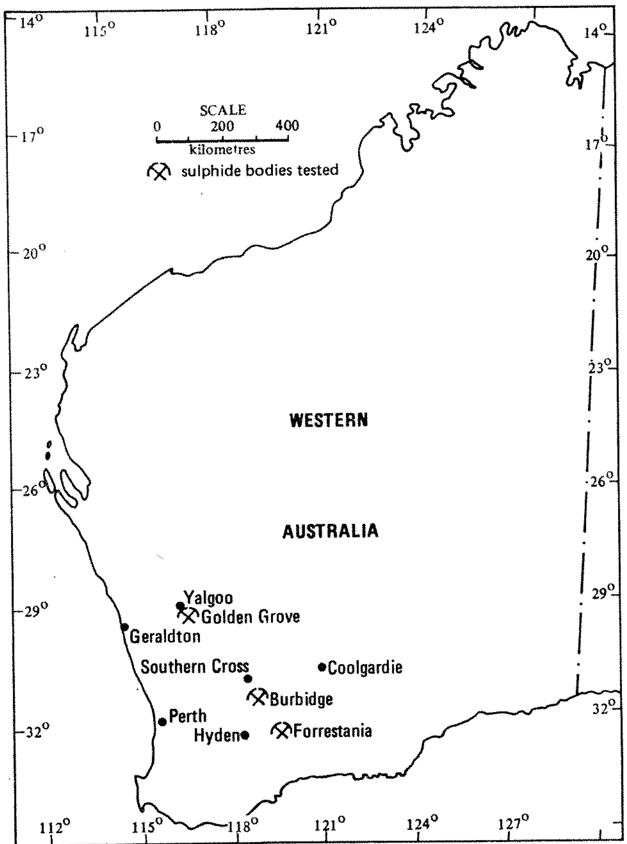

Figure 36. Locations sampled for sulphur dioxide concentration.

At each locality the dominant sulphide is pyrite or pyrrhotite, but varying proportions of base-metal-iron sulphides are also present. The ore bodies do not reach the surface, though, in each area, gossanous ironstone capping has been a surface indicator of buried sulphides. No mining has taken place at Golden Grove or Forrestania, but the site chosen at Burbidge included the floor of a shallow open-pit left after the removal of the ironstone capping ("laterite") during previous gold mining.

Drilling at Golden Grove and Forrestania had been carried out previously for companies holding the present tenements. Rotary holes at Burbidge were drilled in 1972, and diamond drilling has been carried out by the present operators.

Holes were drilled through laterite and clay at Burbidge, weathered bedrock and very shallow residual soils at Golden Grove, and colluvium and residual soils at Forrestania.

METHODS

The method used for collection and detection of SO_2 is that used by the Public Health Department of Western Australia. A diagrammatic sketch of the apparatus used is given in Figure 37.

Most sampling was carried out in rotary air-blast drillholes of various depths; three samples were taken from diamond drillholes which extended to greater depths.

Plastic tubing was fed to the bottom of the hole or 5 m (whichever was reached first), and the hole sealed from atmospheric air with a plastic plate and packed soil. Air was drawn from the holes through a filter to a gas absorber by means of a suction pump. The volume passed was measured using a combination of gas meters and flow meters. Depending on the capacity of pumping 1 to 2 m^3 air were collected in the 24 hour period. The power sources were 6V or 12V batteries.

The initial runs were carried out for a standard 24 hour sampling time. An extended run of 4 days sampling time was later carried out at Forrestania. Samples were stored in a refrigerator, and brought to Perth for analysis.

The method of analysis used is a modified West-Gaeke method, itself modified from Scaringelli and others (1974).

Sulphur dioxide from the soil air is tapped by absorption in a solution of sodium (or potassium) tetrachloromercurate (II), with the production of a non-volatile dichlorosulphito-mercurate complex. This complex resists direct oxidation, but is temperature dependent, and decomposes slowly at temperatures above 15°C. Interference from oxides of nitrogen and from heavy metals is eliminated by addition of sulphamic acid, ethylene-diamine-tetracetic acid (in the form of the disodium salt) and phosphoric acid; determination of the isolated sulphur dioxide is based on a red-violet colour, produced by addition of para-rosaniline methyl sulphonic acid (this colour is also temperature dependent). The absorbance of the solution is read at 548 nm using a spectrophotometer with an effective band width of 15 nm.

Detection is an absolute 2 μg in 50 ml reagent. The detection limit can be lowered with an increase in sampling time—with passage of a larger volume of air.

RESULTS

Sixteen samples were taken at each site during the initial sampling.

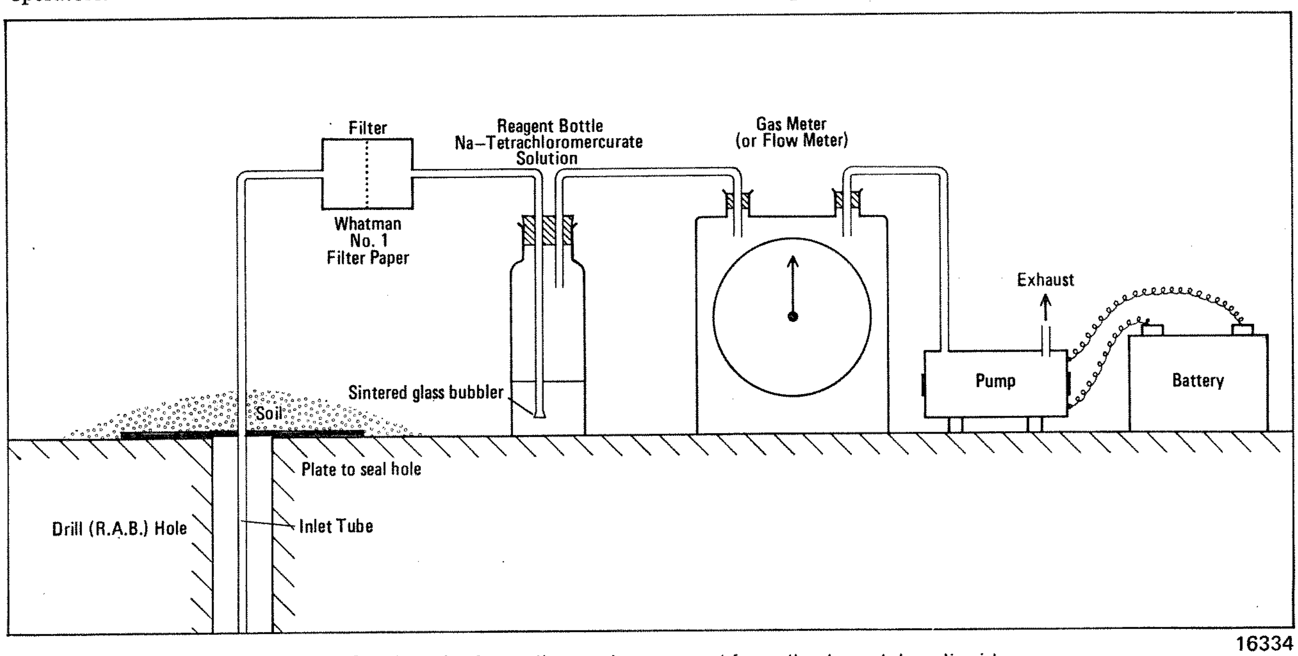

Figure 37. Sketch of sampling equipment used for collecting sulphur dioxide.

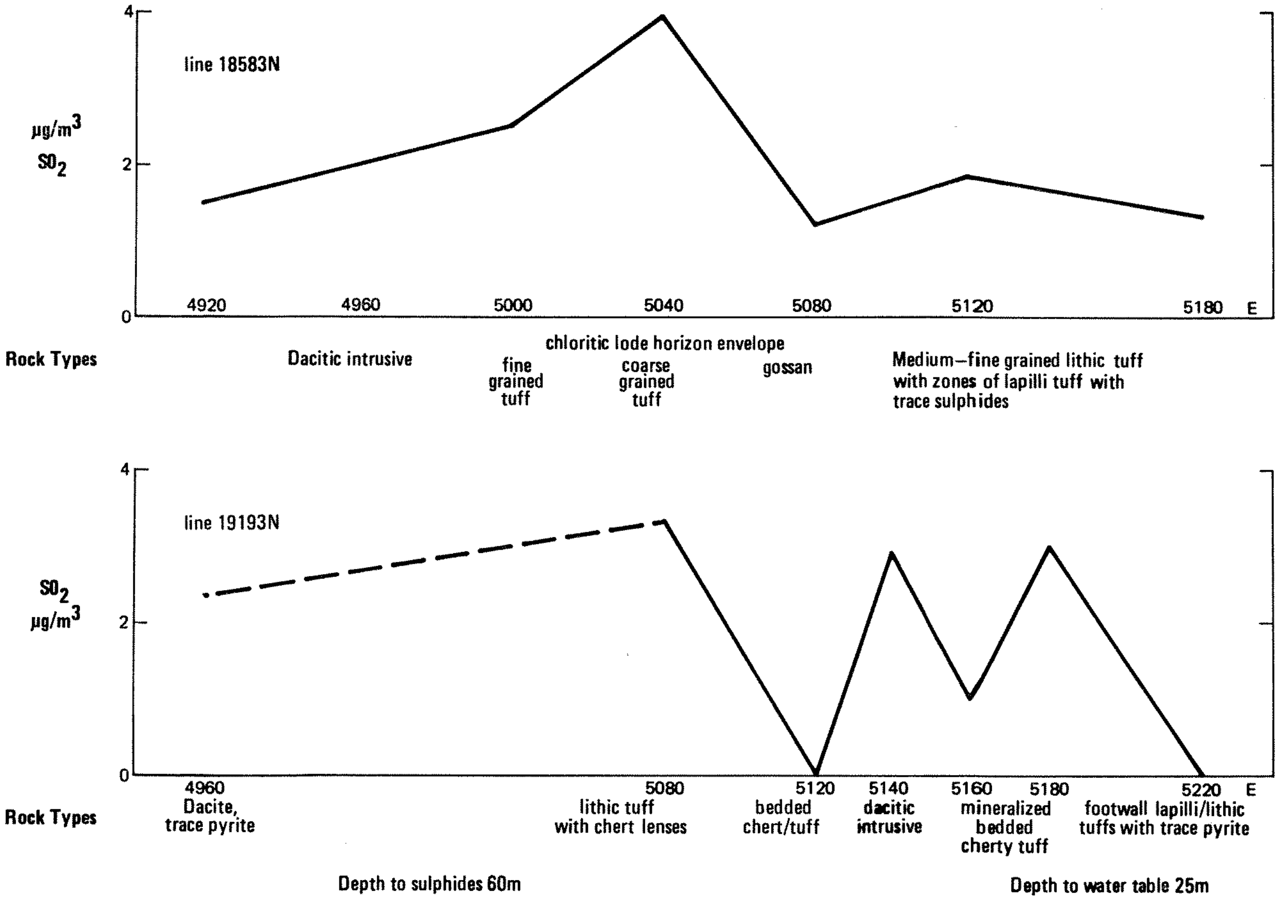

Figure 38. Sulphur dioxide profiles at Golden Grove.

Golden Grove

Golden Grove lies approximately 70 km southeast of Yalgoo. The project is currently operated by the Electrolytic Zinc Co. of Australasia Ltd.

Pyrite-magnetite-chalcopyrite lenses occur within a sequence of acid tuffs; the lithology along the traverse lines is given in Figure 38.

Samples were taken from shallow, rotary air-blast holes which had been drilled into weathered bedrock. Residual soil sulphides are absent at the surface, but occur about 60 m from the surface. The water table is approximately 25 m below ground level.

Samples were taken in May 1976 during a spell of fine calm weather with warm days (20-25°C) and cool to cold nights (0-10°C). Rain (17.5 mm) fell the night before sampling commenced.

The results of the two traverses are given in Table 20, and are presented diagrammatically in Figure 38.

TABLE 20. RESULTS AT GOLDEN GROVE

Sample Site Grid location	Depth of hole (m)	$SO_2 (\mu g/m^3)$	Remarks
18583N 4920E	3·5	1·5	hanging wall, trace pyrite
4960	3·3	2·0	
5000	1·5	2·5	lode horizon envelope
5040	1·6	3·9	
5080	3·5	1·2	
5120	2·2	1·8	footwall
5180	3·1	1·3	
19193N 4960E	2·0	2·4	hanging wall, traces pyrite
5080	3·0	3·3	
5120	1·5	0·0	
5140	2·0	2·9	
5160	2·3	1·0	lode horizon
5180	2·2	3·0	footwall, traces pyrite
5220	1·75	0·0	
19319N 4600E	3·2	0·0	alluvium over unmineralized acid intrusive
19600N 5100E	....	0·0	atmospheric sample

The traverse along line 19193N was carried out on the two days immediately following the rain (four samples per day). Results along this traverse (the lower profile in Figure 38) are ambiguous; the ore zone itself is low, but it is flanked by high values. The results along line 18583N (610 m to the south) reach a maximum over the known lode (and suggest a subsidiary peak in the footwall zone).

No sulphur dioxide was obtained from a hole drilled in alluvium over a barren acid intrusive (19310N, 4600E) and no sulphur dioxide was detected in a sample of atmospheric air.

Burbidge

The old Great Victoria gold mine at Burbidge lies about 42 km southeast of Southern Cross. The property is currently under investigation by the Minerals Department of Esso Australia Ltd.

At Burbidge a massive pyrrhotite-pyrite body occurs between footwall amphibolites, and overlying "spotted schists" and other metasediments. The metasediments contain disseminated pyrite. A massive ironstone capping ("laterite") has been worked for gold, and the "laterite" had been removed from part of the zone leaving a shallow open cut 2 to 3 m deep.

Percussion holes had been drilled to 180 m on behalf of previous operators in 1972. A few diamond holes have been drilled on behalf of the current operators.

Sampling of soil air was on a grid patern, mainly in the air-blast holes, and included lode, and both footwall and hanging wall sites. Most samples were collected from a depth of 5 m. Sampling was carried out in July 1976 under calm dry conditions. Day temperatures were 10-15°C, overnight —2 to +5°C.

The water table is lower than at Golden Grove—an estimated 60-90 m—and sulphides are present at depths varying from 60 to 100 m. Massive sulphides were identified in five deep percussion holes in the hanging wall and over the lode, at depths of 90 to 140 m. Disseminated sulphides occurred at 70 to 90 m.

The only hole from which sulphur dioxide was recorded was B22, which was sunk to a depth of 7.6 m from a site in the hanging wall. The SO_2 value was 2.2 $\mu g/m^3$.

One hole, B3, near the lode-hanging wall contact, had been expected to show sulphur dioxide, since a pungent acrid smell was noticeable, but showed none. Possibly mercaptans or even hydrogen sulphide were present.

A sample drawn from the atmosphere showed no sulphur dioxide.

Forrestania

The camp at Forrestania lies approximately 85 km east-southeast of Hyden, and 160 km south-southeast of Southern Cross. Samples were collected on leases currently operated by Amax Exploration (Australia) Inc. Sampling was carried out in August 1976 in dry weather with day temperatures 10 to 18°C and night temperatures of 0 to 5°C.

Apart from the hills of banded iron-formation known as "Ironcaps", outcrop is rare, and considerably weathered when it does occur. Amax Exploration have systematically tested the area using rotary air-blast drilling to bedrock, supplemented by limited diamond drilling. Near the surface most holes pass through residual soils, or colluvium; a few penetrate the badly weathered rock.

Initially, samples were taken on four short traverses over mineralized and unmineralized contacts. These traverses were at:

(a) "New Morning" where thin zones of massive sulphide separate serpentinite from metasediments.

(b) "North Ironcap" where mineralization occurs as disseminated sulphides, and thin zones of massive sulphide in a thin zone of chert associated with a contact between ultramafic rocks ("high-magnesian basalts") and metasediments.

(c) "Western Belt" where no sulphide mineralisation was known, but where there was a surface geochemical anomaly in cap rock over weathered dunite.

(d) "Seagull" where mineralization consists of disseminated sulphide in the basal zones of an ultrabasic rock near, but apparently unrelated to, its contact with a barren "high magnesian basalt".

Five holes were sampled at New Morning, four at North Ironcap, three in the Western Belt and four at Seagull.

Sulphides were present at approximately 60 m at New Morning, at 165 m at North Ironcap, and at approximately 70 m at Seagull.

One hole only, at line 396N, 1244.OE, at Seagull, showed sulphur dioxide—a value of 3 $\mu g SO_2/m^3$.

In view of these results, it was decided to carry out extended sampling in holes over mineralization at Forrestania. Tests were carried out at two of the sites originally chosen, New Morning and Seagull, and over two other mineralized areas, Digger Rocks and Flying Fox. Digger Rocks was chosen because fresh sulphide, as stringers locked in quartz and other, secondary, silica, had been identified at the surface.

At Digger Rocks, ferruginous cap rock extends to 20 to 30 m from the surface. Sulphides occur immediately below this cap rock. The water table is at 20 m. At Flying Fox, the depth to sulphides is 80 m, to the water table at least 120 m.

The sampling time was extended to four days. This meant that 3 to 12 m^3 of air passed through the sampling bottles (the actual volume depending on the suction of the pumps and the "running down" of the batteries). Flow meters were used to monitor the flow at 12 hour intervals, and the total volume passed was estimated to about 15% accuracy. Results are given in Table 21.

TABLE 21. RESULTS OF EXTENDED TIME TESTS UNDERTAKEN AT FORRESTANIA

Area	Grid location	Volume air passed (m^3)	SO_2($\mu g/m^3$)
Digger Rocks	490N 307·0E	8	1·4
	492N 307·5E	2	1·0
Seagulle	396N 1242·75E	8	....
	1243·75E	8	....
New Morning	186N 1071·0E	8	....
	1071·5E	3	....
	1072·0E	3	....
Flying Fox	932N 1106·5E	6	0·5
	1107·0E	6	0·4

Depth of sampling: 5m
Air Blast holes.

The repeat tests over the sites used initially showed no sulphur dioxide (that is the concentration of sulphur dioxide was less than 0.2 to 0.5 $\mu g/m^3$ depending on the volume of air passed). However small but detectable amounts of SO_2 were obtained from the other two zones. Two samples from Digger Rocks gave values of 1.4 and 1.0 $\mu g/m^3$ SO_2. Two samples from the other mineralized zone gave 0.5 and 0.4 $\mu g/m^3$ SO_2 respectively.

DISCUSSION

The results presented above demonstrate that this method, like any other remote sensing technique, is not infallible, but that, given the right conditions, it could be helpful in exploration.

Readily detectable sulphur dioxide was found at Golden Grove, but levels at Burbidge and Forrestania were so low that the use of SO_2 detectors is not likely to be economic. The results do show, however, that, despite the highly oxidized state of the near surface rocks and soils, despite the considerable depth to fresh sulphide, and despite the fact that the bulk of the fresh sulphide is known to occur only below the water table, some sulphur dioxide is present.

Rouse and Stevens (1971) discuss qualitatively the solubility of sulphur dioxide in water, but consider that a fluctuating water table with some "seasonal" drying out of the rock may release sulphur dioxide and allow it to migrate upwards. As part of their general comments, they prefer to see some part of the sulphide deposit in a moist area above the water table to ensure that oxidation is taking place. In the areas tested here, as far as is known from diamond drill data, the sulphides occur below the water table. As sulphur dioxide is measurable over sulphides, and not in barren areas, particularly at Golden Grove, there is the inference that some oxidation is still taking place. The low levels shown at Forrestania by the extended trial imply that oxidation is presently occurring in this area at a very slow rate. The same possibly applies at Burbidge, though extended time sampling was not attempted there.

In the tests carried out for this report there was no attempt to measure or compare seasonal variations, though the holes at Golden Grove were sampled in warmer weather than at the other two places. Diurnal variations in temperature and pressure were noted at both Golden Grove and Burbidge, but there were no striking differences to explain the sulphur dioxide found in one case but not in the other. Extended trials, at different times of year should be used to test the influence of the weather.

A possible, though doubtful, reason for the lack of sulphur dioxide at Burbidge and Forrestania may be the poor permeability of the overlying weathered material. At Forrestania relict sulphide does occur in at least two gossans with the sulphide totally enclosed in silica. Where fractures or cavities exist there is no near surface sulphide, and it is the lack of access for water and air which has allowed retention of the sulphide.

Comparisons with other published data

Of the three papers cited earlier, Fisher (1976) is the least instructive. He gives no absolute values but expresses maximum readings as up to three times background. He does comment that ventilation of the sulphide-rich area by drillholes may have caused the release of additional sulphur dioxide.

Meyer and Peters (1973) report values up to 3.2 ppb (9 $\mu g/m^3$) at two sites over shallow sulphides in Newfoundland. They obtained much higher values in the vicinity of tailings dumps, but noticed that the actual values they obtained varied by factors up to 25 depending on the weather. High values were found on warm sunny days, low values on cool, overcast days.

Rouse and Stevens (1971) sampled both air and soil air, the latter commonly at 15 cm (6 in.) depth. At Central City, Colorado, over a sulphide vein buried at 3 to 5 m (10-15 ft) values of just over 40 ppb (114 $\mu g/m^3$) were reported. Similar readings were obtained at the New Orphan Boy mines, Alma, Colorado, but background readings were 1-15 ppb (28-42 $\mu g/m^3$). The anomaly:background ratio was 3:6.

Over disseminated sulphides in igneous rocks, at depths up to a maximum of approximately 30 m (100 ft), values of 25 ppb (72 $\mu g/m^3$) were obtained at various sites in Colorado and New Mexico compared with a background of 8 ppb (23 $\mu g/m^3$). At the Lornex orebody, covered by more than 60 m (200 ft) of glacial till soil—gas values reached 18 ppb (51 $\mu g/m^3$).

Rouse and Stevens also investigated uraniferous pyritiferous sandstone (with disseminated sulphides) with similar values. No depths are mentioned.

The results reported here are very much lower with a highest value of 4 $\mu g/m^3$ (1.4 ppb). This appears to be a function of deeper ore bodies covered by water, and the fact that oxidation is proceeding very slowly at the present time. It would be interesting to compare the values obtained in winter for this study with the results of repeat samples taken in the height of summer. If Meyer and Peters (1973) findings are correct, values in Western Australia may also increase in summer.

Sulphur dioxide in the atmosphere

Sulphur dioxide is monitored on a weekly basis in the Perth area by the Public Health Department. Readings for central Perth range from 5-100 $\mu g/m^3$ with an average of 14 $\mu g/m^3$ over the year. Near the coast, at Wembley Downs, the annual average is 2 $\mu g/m^3$ for the year; inland at the W.A. Institute of Technology it is 9 $\mu g/m^3$ per year.

The atmosphere was sampled at Golden Grove and at Burbidge, but no sulphur dioxide was recorded in a 24 hour period.

The low values obtained for soil gas, however, demonstrate the necessity of determining the concentration in the atmosphere near the sampling points. Very little human activity can produce amounts which could, in Western Australian conditions at least, give apparent major anomalies.

Oxidizing vegetable matter

No attempt has been made to determine the sulphur dioxide producing potential of decaying plants. The lack of sulphur dioxide in many areas, mineralized as well as non-mineralized, suggests that vegetation cannot be a major factor in the production of unusual sulphur doixide values.

Prospects for the method

Now that outcrop areas in most of Australia have been prospected attention has turned to the identification of concealed ore bodies.

This method is not selective for base metals, but, if sulphur dioxide can be shown to be present, may help identification of the location of sulphide bodies. Wildcat sulphur dioxide prospecting is not considered economically feasible, but the method is considered to be most applicable when geophysics has shown the presence of electromagnetic, induced potential, or self potential anomalies. These geophysical techniques do not discriminate between anomalies caused by sulphides, magnetite or graphite. The ideal situation for the sulphur dioxide prospecting technique is to have a sulphide body oxidizing above the water table, and buried under 10 to 15 m of sand or alluvium.

For the method to be effective, the geophysical anomalies need to be accessible for testing by sampling from shallow auger holes preferably at depths no greater than 3 m. The inference is that, in the Golden Grove area this may be possible, at Burbidge and Forrestania it is not.

One limiting factor is the time taken for sampling. Once the method appears viable, however, it is anticipated that more rapid collecting techniques, or agents which absorb sulphur dioxide more rapidly, will be developed.

Much additional test work is needed to establish the parameters of the method and its applicability in other parts of Western Australia.

CONCLUSIONS

Preliminary sampling for sulphur dioxide in drillhole air (soil air) over sulphide bodies has been inconclusve. Sulphur dioxide has been readily detectable, though at a low concentration, in traverses over a sulphide body at Golden Grove, and the highest values outlined the mineralized zone on one traverse. Using the same technique, sulphur dioxide was recognised in one hole out of sixteen at both Burbidge and Forrestania. However extended-time sampling showed that very small amounts of sulphur dioxide could be detected at Forrestania.

It is concluded that the method shows some promise, but that the parameters of sulphur dioxide evolution and detection are not yet fully worked out. Much additional test work is needed.

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Analyses for sulphur dioxide were carried out by the Public Health Department in Perth.

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APPENDIX

SAMPLE SITES AT BURBIDGE AND FORRESTANIA

BURBIDGE

The following percussion holes were sampled:
B1, 3, 4, 5, 7, 14, 15, 17, 20, 21, 22, 23, 38, 39.

One diamond drill hole was sampled:
GV1, located 10 m north-northwest of B18.

An atmospheric sample was also taken near hole B11.

FORRESTANIA

Sample sites were as follows:

New Morning Line 816N
Air Blast holes 1071.OE, 1071.5E, 1071.75E, 1072.OE
Diamond Drill hole NMD 4 (started at 1072.6E)

North Ironcap Line 22N
Air Blast holes 112.1E, 112.3E, 112.5E, 112.7E

Western Belt Line 516N
Air Blast holes 1058.5E, 1059.25E, 1059.5E

Seagull Line 396N
Air Blast holes 1242.75E, 1243.75E, 1244.OE, 1245.75E

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