GEOLOGICAL SURVEY
of
WESTERN AUSTRALIA

ANNUAL REPORT 1977

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REPORT

FOR THE YEAR

1977

EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

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

Under Secretary: B. M. Rogers

Director, Geological Survey: J. H. Lord

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DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1977

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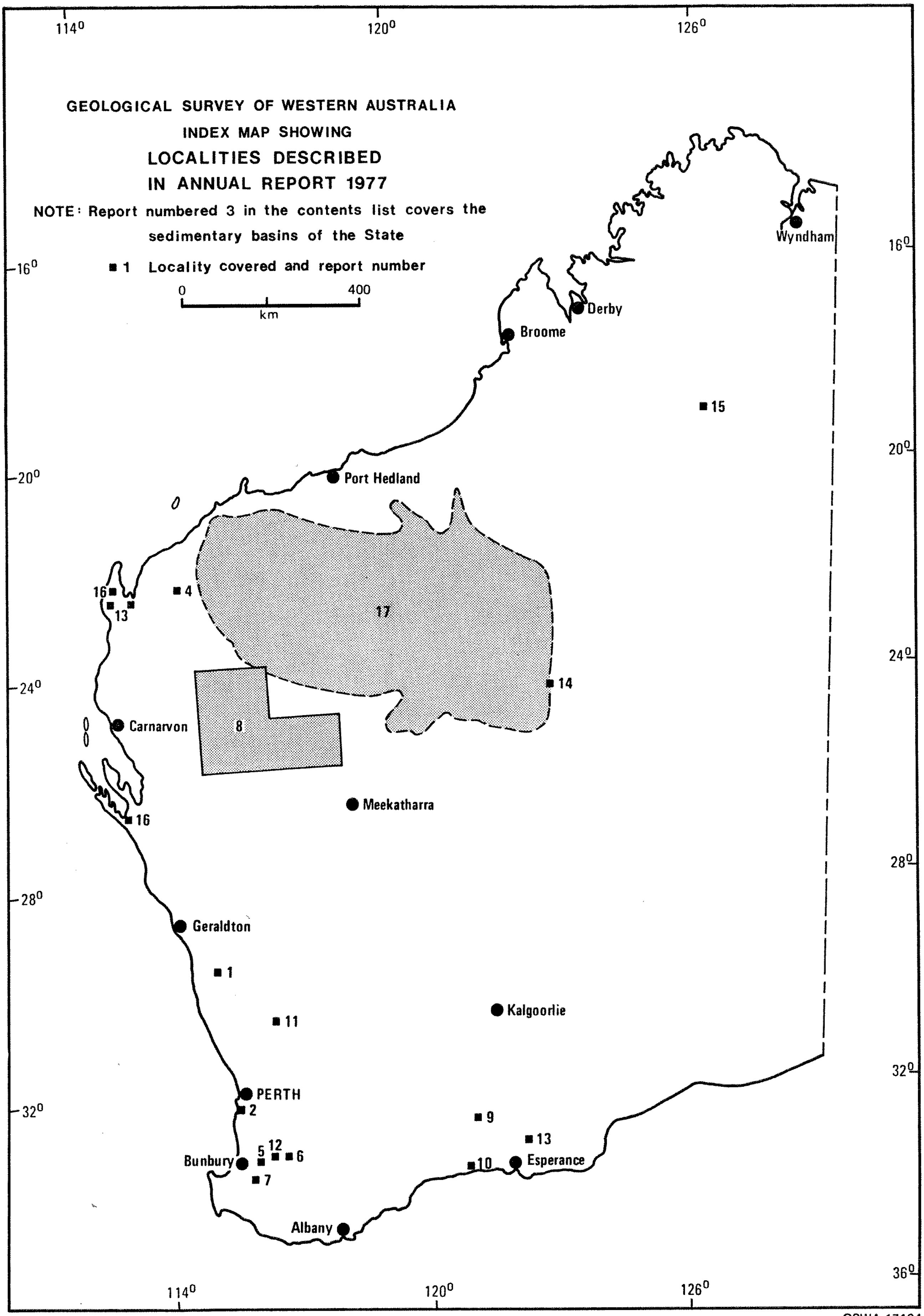

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DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1977

Under Secretary for Mines:

I herewith submit my report for 1977 on the activities of the Geological Survey of Western Australia for the information of the Honourable Minister for Mines, together with selected reports on investigations and studies made for Departmental purposes.

INTRODUCTION

The upward trend of exploration for minerals reported in 1976 levelled off during 1977, probably due to the depressed state of world prices for most metals. The main search was directed towards uranium with less interest than previously being shown in copper, zinc and nickel.

The applications or renewals for Temporary Reserves which may be taken as a guide to exploration activity, remained static.

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

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

Interest in petroleum exploration showed an increase both on and off-shore when new, such as Exmouth Plateau, and surrendered areas were taken up. A boom in oil exploration is commencing, as programmes costing hundreds of millions of dollars over the next 5 or 6 years have been approved.

There was a marked increase in the amount of drilling during 1977 and the length of marine seismic surveys more than doubled.

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
1977	8	35 339	Nil	5 994

No new oil or gas of commercial interest was found in the drilling done during 1977 but the extension test North Rankin No. 5 was successful.

No new noteworthy mineral prospect was reported during 1977. Exploration continued on most of the previously reported prospects but generally on a reduced scale.

Exploration for iron ore in the Hamersley and Nabberu Basins expanded in the 85 Temporary Reserves for iron granted late in 1976 and the 6 granted in 1977. There are 225 current Temporary Reserves for iron ore, some of which have been adequately tested for their iron ore potential.

The joint venture on a proposed alumina refinery near Wagerup was dissolved. Alcoa will continue with the refinery alone while Alwest is studying Worsley as the site for their own venture.

Uranium prospecting has spread throughout the State with the search being extended to all possible geological environments. Although new occurrences have been reported, none is known to be of possible economic significance.

Because of its importance in the present energy crisis, coal is another mineral which has attracted attention, and many companies have carried out reviews of the possible potential of the sedimentary basins. The area where most interest has been shown is in the Perth Basin in the vicinity of Eneabba. Here a deposit of low-grade coal was located a few years ago and there is the possibility of similar occurrences, but faulting is a major problem in this area.

With the rising price of gold, activity by prospectors and tributors (on the Golden Mile) has increased considerably. The new gold mine at Telfer, 220 km east-southeast of Marble Bar, has commenced production. Notice has been given that the small Blue Spec mine, east of Nullagine, will close early in 1978, having failed to locate more ore or to achieve the estimated extractable grade. If the gold price continues to rise and to stabilise consideration should be given to the feasibility of re-opening the mines on the Golden Mile.

The general level of mineral prospecting has continued without change in the Kimberley this year, but the search for diamond has expanded. As well as recovery of micro-diamonds, it has also been reported that kimberlite plugs have been located.

Due to the drought affecting most of the State, there has been a heavy call on the Hydrogeology Division to provide the public with assistance and to advise on the availability of underground water. This was particularly so in the Metropolitan area where water restrictions, imposed during the winter, have resulted in many home owners considering the establishment of their own water supply from underground. Inquiries for information of this nature have on occasions exceeded 100 per day. At the end of November two Information Pamphlets, No. 12 "Groundwater in Western Australia" and No. 13 "Drilling for Water", were issued. The demand was far in excess of any estimates. On the first day after the media announced their release, over 1 100 people called at this office to obtain a copy of each. Within 3 weeks 4 250 copies of each had been distributed.

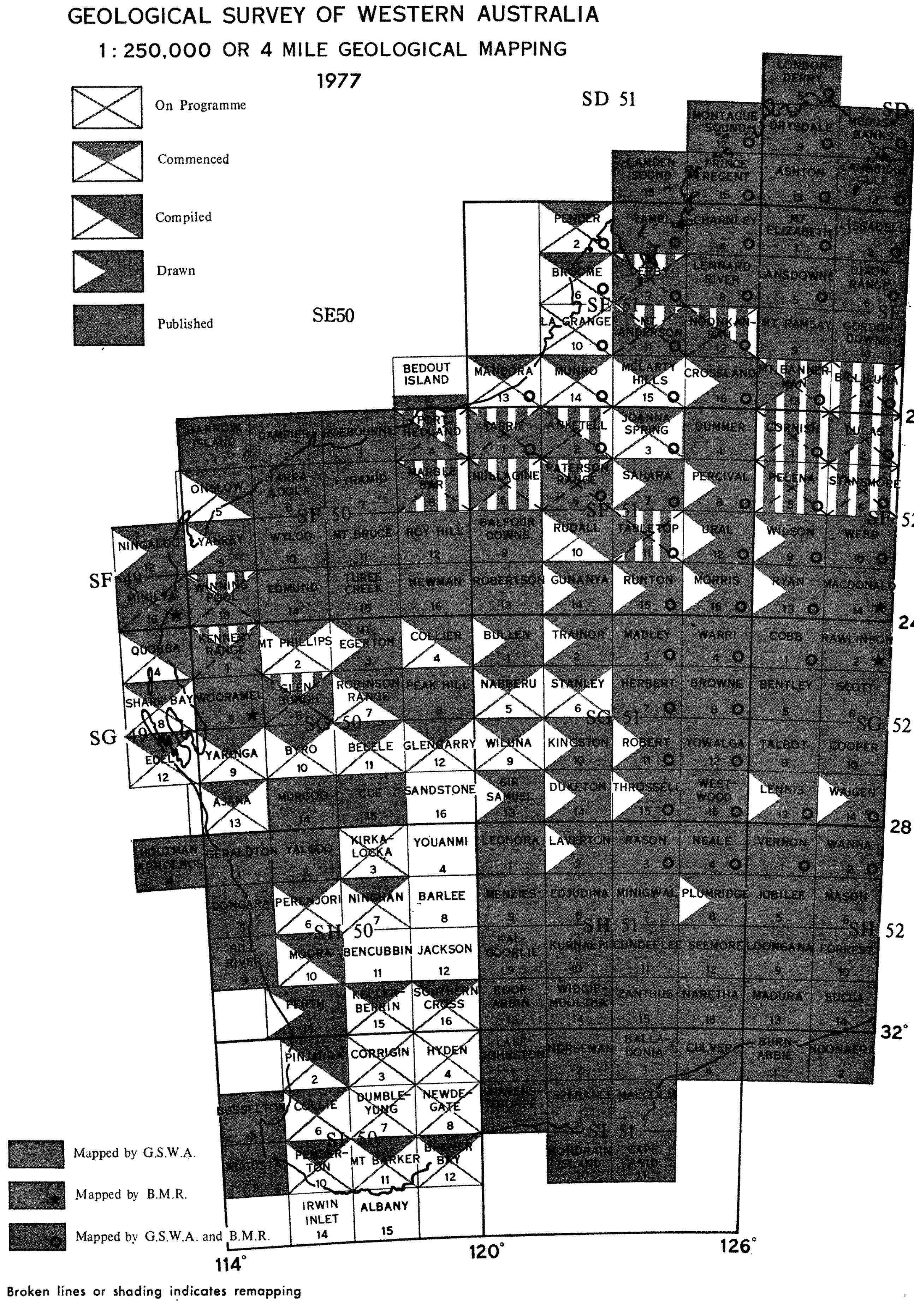


Figure 2 Progress of 1:250 000 or 4-mile geological mapping at the end of 1977

Regional geological mapping of the State continues (Fig. 2) with only 5 sheets not yet on the programme of work. Of the 175 sheets to be completed, only 95 have been printed, the remainder being in progress. There will be a slowing down of final production as the Bureau of Mineral Resources, who were committed to print all maps, has decided no longer to honour that agreement.

Public lectures: On April 15, 1977, a lecture series was inaugurated for those members of the public who are interested in geology. It consisted of nine lectures on aspects of geology emerging from projects on which the speakers were working. The maximum attendance at the morning session was 145 persons from mining and exploration companies, consultants, tertiary and research institutes.

From the results of a questionnaire completed by those who attended, there was an overwhelming opinion that similar lectures should be given each year and plans are being made to repeat the project in 1978.

Field excursion and lecture: A lecture was given at Meekatharra on the results of regional geological mapping on the Robinson Range 1:250 000 sheet, followed by a three day excursion to view the more interesting sites, which illustrate the geological interpretation proposed. Again such a venture proved popular with some 88 geologists attending.

Microfilm library: After many delays a microfilm library was established by the end of the year. It contains two 35 mm reader-printers, one 16 mm reader-printer and one 16 mm reader arranged for use by the public.

Available in the library are 16 mm cassette films of all Survey publications, 35 mm cassette film of reports on surrendered mining and petroleum tenements and microfiche of some reports. Additional film and microfiche will be added to the library as quickly as production permits.

The public may print out individual pages or maps in which they may be interested or purchase the complete roll of film.

Records: Each year since 1962 the Survey has issued Records containing reports requiring quick circulation or which are of insufficient general interest to warrant inclusion in the Annual Report. As Records were assembled internally the distribution was restricted, although a copy was always made available to anyone interested. It has always been debatable whether or not these Records could be regarded as publications as some numbers were classified as "restricted" or "confidential" and distribution was limited.

As from the beginning of 1978 the Record series will be produced on microfiche, will be freely available to those interested, and will not include classified reports. Under these circumstances Records should henceforth be regarded as a published series.

STAFF

There was one resignation and one retirement from the professional staff during 1977 with the number of movements in the general and clerical divisions being more than expected.

Dr Karl Berliat retired on February 25 after 26 years with this Branch. During this service he worked in most parts of the State from the Kimberley to the south coast. In the earlier years he handled all types of geological investigations, but in the later portion of his service he specialized in hydrogeological investigations and in particular property inspections for the general public and town water supply, in which he demonstrated his wide knowledge of the varied geological conditions in this State and their hydrogeological characteristics.

PROFESSIONAL

Appointments

Name	Position	Effective Date
Morrison, R. J., F.R.M.I.T., M.Sc., D.I.C., A.M.Aus.I.M.M.	Geologist L2	27/6/77
Laws, A. T., B.Sc. (Hons), M.Sc., M.Aus.I.M.M.	Geologist L3	4/7/77

Retirement

Berliat, K.	Geologist L3	25/2/77

Resignations

Crowe, R. W. A.	Geologist L1	4/11/77

CLERICAL AND GENERAL

Appointments

Willis, R.	Laboratory Assistant	18/2/77
Quinn, P.	Technical Assistant	14/3/77
Rowe, E. H.	Technical Assistant	16/3/77
Geste, P.	Geological Assistant	18/4/77
Wright, R.	Technical Assistant	21/3/77
Elms, B.	Typist	30/3/77
Kelly, D. F.	Technical Assistant	26/10/77

Promotion

Emery, L.	Laboratory Assistant	22/2/77

Transfer In

Fahmy, H.	Core Librarian	29/3/77

Transfer Out

Baints, R.	Technical Assistant	25/2/77

Resignations

Smith, P.	Typist	25/3/77
Rowe, E. H.	Technical Assistant	19/8/77
Pettigrew, D.	Geological Assistant	16/12/77

ACCOMMODATION

Rearrangement of space on the 6th floor, Mineral House, vacated by Hydrogeology Division in 1976 was completed to provide additional accommodation for the evaluation sections of the Mineral Resources and Sedimentary Geology Divisions. Space vacated on the 4th Floor by the Engineering Geology Division was used to relocate the Environmental Geology Section, two geologists of the Palaeontology Section, and provide space for relocation of plans from the 5th floor library area. A rearrangement of the library to provide needed additional stack space and to establish a public micro-form reading room was completed in readiness to open the reading room at the beginning of 1978.

Although there has been little increase in staff in recent years, the rapid influx of technical data has resulted in overcrowding in some areas, a situation that will require attention in the near future if efficiency is to be maintained.

OPERATIONS

HYDROGEOLOGY DIVISION

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

The aggregate depth of just under 4 000 metres which was drilled by the Department of Mines for groundwater resource evaluation in 1977 represents a reduction on that drilled during the preceding year. This was partly due to the effects of inflationary pressures and costs but also the diversion of effort into hydraulic testing for water resource assessments.

A further eleven bores have been drilled on five sites along the Moora line in the Perth Basin. One previously drilled borehole at Yoganup has been comprehensively test pumped. In the Perth region 23 deep bores have been drilled by the Metropolitan Water Board on 15 sites to depths of up to 838 metres. These provide important new stratigraphic and hydrologic data aiding the assessment of the deeper groundwater resources. The Board also drilled 16 shallow bores at Lake Thompson and Mirrabooka as aids to developmental planning and 31 bores at Lake Jandabup as the first stage of a detailed investigation of the hydrology and water balance of coastal plain lakes. Three bores were drilled at Lake Joondalup by the Survey to complete this shallow aquifer investigation.

One further bore was drilled in the West Canning Basin to a depth of 223 metres to complete the present programme of work in this area. Eighteen bores were comprehensively test pumped to provide hydraulic data for throughflow and storage assessments.

West of Millstream, in the Robe River catchment, seven bores were drilled in continuation of a long term programme of investigation of the complex aquifers of the West Pilbara. Two seismic traverses were completed to aid structural interpretation.

Further progress has been made with interdepartmental studies of the effects of the woodchip and bauxite mining industries on stream and groundwater hydrology. A novel test-pumping technique employed on bores in a pair of catchments at Yaraminup facilitated an assessment of water and salt balances based on groundwater flow and salinity data.

The demand for advisory facilities has been exceptionally high. Bore site inspections were carried out on 153 private properties and a further 23 were for various government departments. The imposition of water restrictions in the metropolitan area, because of drought conditions, was responsible for much enhanced interest by landholders in drilling for domestic irrigation supplies. In consequence of this telephone and other enquiries increased dramatically. To further assist landholders two information pamphlets were issued: No. 12 "Groundwater in W.A." and No. 13 "Drilling for Water".

ENGINEERING GEOLOGY DIVISION

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

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

Department of Public Works:

(a) Further investigations made where necessary and reports completed on the following Pilbara dam sites. Harding River (formerly Cooya Pooya), Robe River "D", Sherlock River and Fortescue 123.

(b) Geological reconnaissance made of Nunyerry proposed dam site.

(c) Report completed on Port Denison proposed quarry sites.

(d) Minor investigations carried out including foundation studies for a tank site at Derby and for basin extension to the inner harbour at Bunbury.

Metropolitan Water Board:

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

(b) Further studies on the South Canning and North Dandalup proposed dam sites.

(c) Studies made for the Beenyup and Burns Beach sewer tunnels and the Wungong proposed water tunnel.

Westrail:

Geological advice given on selection and development of quarry sites.

SEDIMENTARY DIVISION

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

The processing of data submitted by petroleum companies continued. There was an encouraging small increase in petroleum exploration during the year and many new exploration permits were issued, many of which were taken up by new companies entering the State for the first time. As a result of this, activity is expected to increase considerably in the near future.

Mapping continued in the Carnarvon Basin with the completion of compilation of the Phanerozoic portions of the Mount Phillips and Glenburgh 1:250 000 sheets. Field work has been completed on the Edel, Shark Bay, Yaringa and Ajana sheets, and a start has been made on the Wooramel sheet.

The study of the southern and central Carnarvon Basin has been completed and a study of the northern offshore part of this basin, between latitudes 19° and 23° has been commenced.

The Canning Basin mapping project, in conjunction with the Bureau of Mineral Resources, was completed during the year. The compilation of this Survey's contributions has been completed.

REGIONAL GEOLOGY DIVISION

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

Regional mapping for publication at a scale of 1:250 000 (Fig. 2) continued on the Precambrian portion of the State. Field mapping on Glenburgh, Mount Phillips and Glengarry was completed. Mapping on Belele, Bremer Bay and Newdegate commenced.

Work continued on the Bangemall Basin bulletin, which should be completed shortly.

Regional reappraisal of the Peak Hill-Nabberu-Stanley area was undertaken in preparation for a bulletin on the Nabberu Basin.

Compilation for a new, State geological map was completed.

MINERAL RESOURCES DIVISION

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

Mapping of the Precambrian portion of the Perenjori and Ajana 1:250 000 sheets was completed. Mapping continued on Pemberton and commenced on Ninghan. The map compilation and explanatory notes were completed for Moora and Port Hedland and continued on Collie.

The mineral resources bulletin on Copper was completed and one commenced on Nickel. A bulletin on the Pilbara Block is in preparation.

Sundry field work included a study of the Marra Mamba Iron Formation, inspections of Mount Mulgine molybdenum and wolfram, Golden Grove copper-zinc and Moolyella tin prospects. An inspection and estimation was made of the lime resources of the Boranup sand patch.

Microfilming of statutory mineral exploration reports on relinquished tenements commenced in 1977. 386 exploration projects were filmed ready to be placed on open file at the beginning of 1978.

During the year the Division answered about 260 verbal inquiries from the public and other Government agencies and dealt with some 200 requests for access to company reports on surrendered tenements. About 660 new accessions were added to the Survey's collection of mineral exploration reports, an increase of 160 on 1976.

COMMON SERVICES DIVISION

Petrology

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

A total of 81 petrological reports were completed during the year on a total of 1 964 rock samples. Further thin sections were studied for incorporation into the computer based petrological data system.

For most of the year J. D. Lewis was concerned with the production of the Meckering Earthquake bulletin which has been completed.

Two projects in the GSWA/WAIT co-operative geochronology programme were published during the year (Hardey Sandstone and East Pilbara), three have been prepared for publication early in 1978 (Greenbushes pegmatite, north margin Yilgarn Block, and Fitzgerald Peaks) and several other studies are nearing completion.

The laboratory prepared 2 700 thin sections of which 2 144 were petrological and 556 sedimentological. Thin sections stained for carbonate numbered 56. Polished mounts for petrological work totalled 49 and 336 rock slabs were polished. There were 32 heavy mineral separations and 11 sieve analyses. Samples crushed for chemical or geochronolgical analysis numbered 756 and 35 biotite separations for geochronological work were made.

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

Palaeontology

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

There was a slight increase in demand for palaeontological information during the year and 80 reports were written. The work of the section included studies on Devonian faunas from the Canning Basin, Cretaceous palynology of the Perth Basin, Precambrian fossils from the Bangemall Basin and various fossils from the Carnarvon Basin. Two manuscripts, one on Devonian atrypid brachiopods and one on Early Cretaceous palynomorphs, were completed.

Geophysics

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

Seismic refraction surveys dominated geophysical activities in 1977 and encompassed various hydrogeology and engineering projects. The latter included a dam site on the Fortescue River, additional work at the Churchman Brook dam and an investigation of the inlet and outlet portals of the proposed Wungong Tunnel. Seismic sections were obtained across the Robe River in the Pilbara, in the Grasmere Valley for the Albany Town Water Supply and for the CSIRO at the Yallanbee Research Station. The Robe River work also involved resistivity profiling and magnetic measurements.

Magnetic surveys were used to delineate the margin of the Bunbury Basalt at Yoganup and to map a dolerite dyke at the Victoria dam.

Water-bore logging operations were carried out in 204 bores with an aggregate total depth of 43 710 m, matching the level of activity for 1976 when 191 bores were logged. The marked increase in aggregate depth is due to systematic temperature and differential temperature logging in some of the deeper cased bores such as the Eneabba line, and the demand for casing-collar locator and caliper completion logs.

Field salinity measurements exceeded 1 200 and the calibration of resistivity and temperature loggers used in various groundwater monitoring studies occupied considerable time. Transceiver and electronic servicing facilities were provided for Survey equipment as usual.

Environmental Geology

E. R. Biggs and R. H. Archer.

Work on the 1:50 000 Urban Geology map series was continued with the completion of 5 sheets (Pinjarra, Nickol Bay/Legendre, Karratha, Point Samson/Delambre and Dampier). Compilation is in progress on a further 4 sheets in the Roebourne and Dampier areas and fieldwork has been completed for two sheets around Port Hedland.

Geological information has been supplied for Karratha townsite development, Maida Vale Town Planning scheme, Joondalup sub-regional centre study, System 6 study, Rural Policy study and many other smaller projects. Committee and liaison meetings continue to occupy a large segment of the section's activities, both on major projects and on individual problems such as the supply of minerals in a specific area.

Appraisal continues on applications for mineral tenements in the Southwest Mineral Field with a view of lesssening adverse impacts of mining on the environment. Temporary excavations in the Perth area are examined to increase geological knowledge in the urban area.

Geochemistry

R. Davy.

Studies of low-grade zinc mineralization in the Bangemall Basin have continued. All investigative work has been carried out and reports are in preparation.

An investigation of the usefulness of B-Ga-Rb diagrams for determining the depositional conditions under which certain Proterozoic sedimentary rocks were formed has been concluded.

Reports on the silicate geochemistry of, and on orientation studies on sediments over, the Saddleback Greenstone Belt are in preparation for release as Records. Fieldwork for rock chip and stream sediment/soil geochemical surveys has been completed but analytical results are not yet available.

A geochemical study of the Mount McRae Shale has been initiated.

Samples of sulphides from various W.A. base metal mines and prospects have been submitted for analysis for mercury.

Technical Information

W. B. Hill, M. E. Wenham, J. F. Cameron, S. M. Fawcett.

The number of publications edited by this section continues to increase. One bulletin and one report were sent to press, and proof reading of these is in progress. At the end of the year editing was being carried out on one bulletin, three mineral resources bulletins and four reports. Twenty-two records have been edited and 17 maps with explanatory notes were published. Two new information pamphlets were prepared and issued.

The library storage facilities were expanded considerably by the addition of seven new compactus units. A room has been set aside for machines for viewing and reproducing microfilm material. This will be available for public use early in 1978.

Requisitions raised on the Surveys and Mapping Branch for drafting services and photography for the Survey totalled 1 157. Photocopying for the public of out-of-print publications numbered 762 requisitions; many of these contained several items.

During the year this section dealt with 702 requests for information including rock identification, and 1 696 members of the public visited the library for research purposes. Book loans to the staff totalled 4 933, and loans to other libraries 187.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

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

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

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

(iii) Analysis of rocks from the Pilbara Block in continuation of a joint geochemical project with this Survey.

(iv) Airborne magnetic and radiometric survey of Bremer Bay, Mount Barker, and part of Pemberton sheets.

(v) Completion of seismic and gravity observations for a crustal structure study between Mount Goldsworthy and Meekatharra.

PROGRAMME FOR 1978

HYDROGEOLOGY DIVISION

1. Continuation of the hydrogeological survey of the Perth Basin including deep drilling, test pumping and report on the Moora and Picton lines and at Irwin View.
2. Hydrogeological investigations and/or exploratory drilling for groundwater in the following areas:
   (a) West Canning Basin—completion of report.
   (b) Fortescue River area—further drilling and testing to assess the calcrete and other aquifers.
   (c) East Pilbara—further bore census, reconnaissance and report writing.
   (d) Reassessment, as required, of groundwater along the Yule, de Grey and Gascoyne rivers, Eneabba and Pinjarra.
3. Town water supply investigations and/or drilling for the following: Bunbury, Albany, Lancelin-Salvado, Australind, Dandaragan and others as required.
4. Hydrogeological investigations for the Metropolitan Water Supply Board:
   (a) Deep drilling at Mirrabooka East, Gnangara and Hamilton Hill.
   (b) Shallow drilling at Lake Jandabup, Lake Mariginiup and Lake Jandakot.
   (c) Continuation of pollution studies at Hertha Road/Jones Street; Gnangara liquid waste disposal and Alcoa red mud lake areas.
   (d) Study of water balance in coastal lakes.
5. Interdepartmental studies concerning groundwater salinity problems in the Darling Range bauxite and woodchip areas.
6. Continuation of bore census of selected areas, supervising of consultant work and State groundwater monitoring network.
7. Miscellaneous investigations and inspections as required by Government departments and the public.

ENGINEERING GEOLOGY DIVISION

1. Pilbara area—completion of reports on Fortescue and Sherlock Rivers and Nunyerry dam sites.
2. Darling Range area—continuing investigations on Wungong, South Canning, Victoria, North Dandalup, Marrinup Brook and Brunswick River dam sites, commencing reconnaissance investigations Brookman River, Wooroloo and Jane Brooks and safety reviews on existing dams.
3. Investigation of tunnel lines at Wungong, Burns Beach and Bibra Lake.
4. Miscellaneous investigations as required by Government departments including quarry sites for Westrail.

SEDIMENTARY GEOLOGY DIVISION

1. Maintain an active interest in the progress and assessment of oil exploration and potential in Western Australia including the checking and assessing of all company reports on exploration.
2. Continuation of the surface mapping and subsurface study of the Carnarvon Basin including the Minilya and Winning Pool 1:250 000 sheets.
3. Continuation of the compilation of a bulletin on stratigraphic studies of Devonian reef complexes in the Canning Basin.

4. Continuation of the investigation of coal resources of the Perth and Collie basins
5. Minor geological investigations as required.

REGIONAL GEOLOGY DIVISION

1. Continuation of the mapping of the Gascoyne Province, on the Byro, Kennedy Range and Winning Pool 1:250 000 sheets.
2. Completion of the mapping of the Belele 1:250 000 sheet.
3. Continuation of the mapping of the Bremer Bay, Mount Barker, Newdegate, Dumbleyung, Hyden and Corrigin 1:250 000 sheets.
4. Continuation and completion of the bulletin on the Nabberu Basin.

MINERAL RESOURCES DIVISION

1. Maintain records and assess mineral potential in Western Australia.
2. Completion of a bulletin on the regional and economic geology of the Pilbara Block.
3. Regional study of the nickel occurrences in Western Australia and commencement of a bulletin.
4. Complete the mapping of the Darling Range area and commence a bulletin on the geology and bauxite occurrence of this area.
5. Completion of the mapping of the Ninghan sheet to be followed by Kirkalocka sheet 1:250 000.
6. Continuation of assembling the ore reserves of known mineral deposits.
7. Undertake a surface assessment of iron ore reserves on Ministerial Reserves in the Hamersley Iron Province.
8. Miscellaneous minor mineral investigations as required.

COMMON SERVICES DIVISION

Petrology

1. Carry out petrological investigations as required by other Divisions.
2. Further petrological study of the transition from the Yilgarn to the Gascoyne Block.
3. A study of the amphiboles from the Wongan Hills area and of the garnet-cordierite P-T conditions in the Southern Cross area.
4. Miscellaneous minor petrological studies.

Palaeontology

1. Carry out palaeontological investigations as required by other divisions.
2. Continuing a study of the Devonian stromatoporoids Lennard Shelf, Canning Basin.
3. Continuing a detailed palynological study on the Warnbro Group of the Perth Basin.
4. Completion of a study of stromatolites from the Nabberu Basin.
5. Determination of macrofossils from the Carnarvon Basin as required by the basin study group.

Geophysics

1. Well logging on groundwater drilling projects as required.
2. Seismic surveys for:
   (a) Dam sites in the Pilbara and Darling Range as required.
   (b) Tunnels for water supply and sewerage.
   (c) Groundwater supplies at Albany, Nullagine, Toolibin Lake, Norseman and East Fortescue.
3. Trial magnetic surveys over the southern portion of the Darling Fault.
4. Miscellaneous office studies as required.

Geochemistry

1. A study of the use of B-Ga-Rb diagrams as indicators of deposition in WA Phanerozoic rocks.
2. Statistical studies on gossans/ironstones with reference to the Yarri sheet.
3. A study of the Corunna Downs and Mount Edgar batholiths to identify further potential tin/tantalum-bearing rocks.
4. A comparative study of the Saddleback, Jimperding and Wongan Hills greenstone belts.
5. A preliminary study of favourable conditions for formation of chromite ore bodies.

Environmental Geology

1. Complete compilation of urban geology maps in the Roebourne and Port Hedland areas.
2. Complete study of Perth metropolitan sand resources.
3. Commence field work and compilation of urban geology maps in the Bunbury and Leeman areas.
4. Attend to miscellaneous environmental geological problems as required.

PUBLICATIONS AND RECORDS

Issued during 1977

Annual Report, 1976.

Mineral Resources Bulletin 10: Heavy mineral sands of Western Australia.

Report 6: Geology and hydrology of Rottnest Island.

Information pamphlet 12: Groundwater in Western Australia.

Information pamphlet 13: Drilling for water.

Geological map of Billiluna 1:250 000 sheet (SE/52-14 International Grid) with explanatory notes (Second edition).

Geological map of Cundeelee 1:250 000 sheet (SH/51-11 International Grid) with explanatory notes.

Geological map of Dummer 1:250 000 sheet (SF/51-4 International Grid) with explanatory notes.

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

Geological map of Helena 1:250 000 sheet (SF/52-5 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 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 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 Stansmore 1:250 000 sheet (SF/52-6 International Grid) with explanatory notes.

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

Geological map of Wanna 1:250 000 sheet (SH/52-2 International Grid) with explanatory notes.

Geological map of Webb 1:250 000 sheet (SF/52-10 International Grid) with explanatory notes.

Geological map of Westwood 1:250 000 sheet (SG/51-16 International Grid) with explanatory notes.

Geological map of Yalgoo 1:250 000 sheet (SH/50-2 International Grid) with explanatory notes.

Geological map of Yowalga 1:250 000 sheet (SG/51-12 International Grid) with explanatory notes.

Urban geological maps 1:50 000: Gingin, Moore River-Cape Leschenault.

In press

Bulletin 124: The geology of the Perth Basin.

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

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

Geological map of Bullen 1:250 000 sheets (SG/51-1 International Grid) with explanatory notes.

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

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

Geological map of Duketon 1:250 000 sheet (SG/51-14 International Grid) with explanatory notes.

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

Geological map of Lennis 1:250 000 sheet (SG/52-13 International Grid) with explanatory notes.

Geological map of Lucas: 1:250 000 sheet (SF/52-2 International Grid) with explanatory notes (Second edition).

Geological map of Morris 1:250 000 sheet (SF/51-16 International Grid) with explanatory notes.

Geological map of Mount Bannerman 1:250 000 sheet (SE/52-13 International Grid) with explanatory notes Second edition).

Geological map of Noonkanbah 1:250 000 sheet (SE/51-12 International Grid) with explanatory notes (Second edition).

Geological map of Percival 1:250 000 sheet (SF/51-8 International Grid) with explanatory notes.

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

Geological map of Robert 1.250 000 sheet (SG/51-11 International Grid) with explanatory notes.

Geological map of Runton 1:250 000 sheet (SF/5-15 International Grid) with explanatory notes.

Geological map of Ryan 1:250 000 sheet (SF/52-13 International Grid) with explanatory notes.

Geological map of Sahara: 1:250 000 sheet (SF/51-7 International Grid) with explanatory notes.

Geological map of Tabletop 1:250 000 sheet (SF/51-11 International Grid) with explanatory notes (Second edition).

Geological map of Throssell 1:250 000 sheet (SG/51-15 International Grid) with explanatory notes.

Geological map of Trainor 1:250 000 sheet (SG/51-2 International Grid) with explanatory notes.

Geological map of Ural 1:250 000 sheet (SF/51-12 International Grid) with explanatory notes.

Geological map of Waigen 1:250 000 sheet (SG/52-14 International Grid) with explanatory notes.

Geological map of Wilson 1:250 000 sheet (SF/52-9 International Grid) with expalantory notes.

Urban geological maps 1:50 000: Mandurah.

In preparation

Bulletin 126: The Meckering and Calingiri earthquakes, October 1968 and March 1970.

Mineral Resources Bulletins: Tin, Copper, Vanadium, Chromium, Molybdenum, and Tungsten.

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

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

Report 8: A study of laterite profiles in relation to bedrock in the Darling Range near Perth, W.A.

Report 9: Contributions to the geology of the Eastern Goldfields Province of the Yilgarn Block.

Geological maps 1:250 000 with explanatory notes, the field work having been completed: Ajana, Anketell, Broome, Collie, Collier, Derby, Glenburgh, Glengarry, Gunanya, Joanna Spring, Kingston, La Grange, Mandora, Marble Bar, McLarty Hills, Moora, Munro, Mount Anderson, Mount Egerton, Mount Phillips, Nabberu, Ningaloo-Yanrey, Nullagine, Onslow, Paterson Range, Pender, Perenjori, Perth, Pinjarra, Port Hedland, Quobba, Robinson Range, Rudall, Shark Bay-Edel, Sir Samuel, Southern Cross, Stanley, Wiluna, Yampi, Yaringa, Yarrie.

Urban geological maps 1:50 000: Baynton, Boodarrie, Dampier, Karratha, Nickol Bay-Legendre, Pinjarra, Point Samson-Delambre Island, Port Hedland, Roebourne, Warambie-Picard.

Records produced

1977/1 Wells drilled for petroleum exploration in W.A. to the end of 1976, by K. A. Crank.

1977/2 Explanatory notes on the Precambrian part of the Port Hedland-Bedout Island 1:250 000 geological sheets, Western Australia, by A. H. Hickman.

1977/3 Hydrogeology and drilling results of the 1969-1970 drought relief programme, by W. A. Davidson.

1977/4 Robe River proposed dam site "D"—seismic refraction survey, by I. R. Nowak (Restricted).

1977/5 Explanatory notes on the Kingston 1:250 000 geological sheet, Western Australia, by J. A. Bunting.

1977/6 Explanatory notes on the Robinson Range 1:250 000 geological sheet, Western Australia, by M. Elias and S. J. Williams.

1977/7 Explanatory notes on the Gunanya 1:250 000 geological sheet, Western Australia, by I. R. Williams and S. J. Williams.

1977/8 Outline of the geology and groundwater prospects in the Stirling Range area, by J. S. Moncrieff.

1977/9 Explanatory notes on the Ningaloo-Yanrey 1:250 000 geological sheet, Western Australia, by W. J. E. van de Graaff, P. D. Denman, R. M. Hocking, and J. L. Baxter.

1977/10 Fortescue dam site 123 (Booyeemala Creek dam site) geological reconnaissance, by R. P. Mather (Restricted).

1977/11 Proterozoic geology of the Paterson Range 1:250 000 sheet, Western Australia, by R. J. Chin and A. H. Hickman.

1977/12 Petrography and geochemistry of selected rocks from the Saddleback Greenstone Belt, by R. Davy.

1977/13 Explanatory notes on the Quobba 1:250 000 geological sheet, Western Australia, by P. D. Denman and W. J. E. van de Graaff.

1977/14 Mirrabooka area—predicted effects of pumping from shallow artesian bores, by W. A. Davidson (Restricted).

1977/15 Fortescue dam site 123—geological report, by G. Klenowski (Restricted).

1977/16 CSIRO Yallanbee Research Station—seismic refraction survey, by D. L. Rowston.

1977/17 Explanatory notes on the Runton 1:250 000 geological sheet, Western Australia, by R. W. A. Crowe and R. J. Chin.

1977/18 Burns Beach sewer tunnel—geological report, by I. H. Lewis (Restricted).

1977/19 Harding River (Cooya Pooya) dam site—geological report, by G. Klenowski (Restricted).

1977/20 An orientation investigation of sediments from the Saddleback Greenstone Belt, by R. Davy.

1977/21 Robe River dam site "D"—geological report, by G. Klenowski (Restricted).

1977/22 Sherlock River dam site—geological report, by G. Klenowski (Restricted).

Reports in other publications

Barrett, F. M., Binns, R. A., Groves, D. I., Marston, R. J., and McQueen, K. G., 1977, Structural history and metamorphic modification of Archean volcanic-type nickel deposits, Yilgarn Block, Western Australia: Econ. Geol., v. 72, No. 7, p. 1195-1223.

Bestow, T. T., 1977, The movement and changes in concentration of contaminants below a sanitary land-fill, Perth, W. A., *in* Effects of urbanization and industrialization on the hydrological regime and on water quality: Procs of Amsterdam Symposium Oct., 1977, convened by UNESCO, organized by UNESCO and the Netherlands National Committee for the I. H. P. in co-operation with I. A. H. S. UNESCO Publication No. 123, p. 370-379.

Groves, D. I., Barrett, F. M., Binns, R. A., Marston, R. J., and McQueen, K. G., 1976, A possible volcanic-exhalative origin for lenticular nickel sulfide deposits of volcanic association, with special reference to those in Western Australia: Discussion: Canadian Jour. of Earth Sciences, v. 13, no. 11, p. 1646-1650.

Marston, R. J., and Travis, G. A., 1976, Stratigraphic implications of heterogeneous deformation in the Jones Creek Conglomerate (Archaean), Kathleen Valley Western Australia: Geol. Soc. Aust. Jour., v. 23, pt. 2, p. 141-156.

Playford, P. E., 1977, Fossil fuels, uranium, and the energy crisis: Oil and Gas, v. 23, no. 8, p. 9-12, 19.

Playford, P. E., and Cockbain, A. E., 1977, Modern algae stromatolites at Hamelin Pool, a hypersaline barred basin in Shark Bay, Western Australia: Stromatolites, chapter 8.2, p. 389-411.

Playford, P. E., Cockbain, A. E., Druce, E. C., and Wray, J. L., 1977, Devonian stromatolites from the Canning Basin, Western Australia: Stromatolites, Chapter 10.4, p. 543-563.

Van de Graaff, W. J. E., Crowe, R. W. A., Bunting, J. A., and Jackson, M. J., 1977, Relict Early Cainozoic drainages in arid Western Australia: Zeitschrift fur Geomorphologie N.F., v. 21, pt. 4, p. 379-400.

Contributions from staff members of the Survey to Monograph 8 of The Australian Institute of Mining and Metallurgy (Economic geology of Australia and Papua New Guinea, Industrial minerals and rocks, edited by C. L. Knight, 1976) covered the following commodities in Western Australia: Asbestos; barite; bentonite; ceramic clay; construction materials; corundum; diamond; diatomite; dolomite; emerald; expanded aggregate, raw materials (vermiculite); fluorite; garnet; graphite; gypsum; kaolin; limestone; magnesite; pegmatite minerals (mica, beryl, lithium, feldspar); phosphate; pigments (mineral); potassium; precious opal; rare earths; salt; semi-precious stones; silica; sillimanite, kyanite, andalusite; sulphur; talc.

1st February, 1978.

J. H. LORD,
Director.

HYDROGEOLOGY OF THE ENEABBA BOREHOLE LINE

by D. P. Commander

ABSTRACT

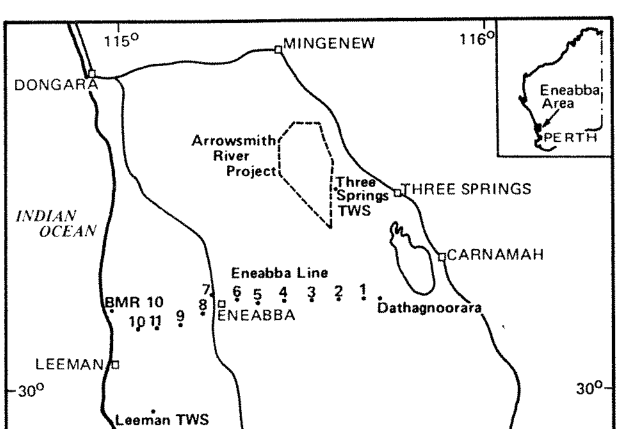
The Eneabba Line consists of twenty-eight boreholes drilled to a maximum depth of 800 m in an east-west line across the Perth Basin. These have been left cased for observation. The drilling encountered sediments ranging in age from Triassic to Lower Cretaceous and forming a synclinal structure with a faulted west limb and a very shallow dipping east limb.

Limited testing indicates very large groundwater resources in the upper Yarragadee Formation (Lower Cretaceous) about 350 m thick and in the lower Yarragadee Formation (Upper Jurassic) about 2 500 m thick. Groundwater salinity is in the 200-1 200 mg/l range and low salinity water extends below the depths drilled. The Otorowiri Siltstone acts as an aquiclude between the two groups of aquifers and maintains a head difference of 140 m.

In the west of the area the Cockleshell Gully Formation and the Lesueur Sandstone both contain large reserves of fresh to brackish water.

Groundwater movement in all aquifers is northerly; Triassic sediments near the coast are a barrier to westward movement and are not themselves groundwater sources. The Tamala Limestone in the area contains only limited quantities of brackish water.

Temperature logging shows a high geothermal gradient in the west of up to 5.5°C per 100 m but lower gradients in the east.



GSWA 17106

Figure 3 Location map, Eneabba Line

INTRODUCTION

The Eneabba Line of bores was drilled as part of a continuing programme of deep exploratory drilling to assess the hydrogeology of the Perth Basin by providing a stratigraphic and hydrogeological cross section to depths of about 800 m.

Ground water is used extensively in the mineral sands industry at Eneabba, and is also important for town and farm water supplies. The area lies within the North Coastal proclaimed groundwater area.

Exploratory drilling had been carried out in neighbouring areas (Fig. 3) at Arrowsmith River (Barnett, 1969), and at Agaton (Balleau and Passmore, 1972) and Watheroo (Harley, 1975). Drilling on the Eneabba Line commenced in 1972 and was completed at the end of 1976. The line consists of twenty-eight boreholes on eleven sites; all bores but two were drilled by the Mines Department Drilling Section. The bores range in depth from 66 to 797 m and the aggregate depth is 12 745 m. All the bores are cased for observation of water levels.

The Dathagnoorara bore, drilled for Carnamah town water supply, and the Bureau of Mineral Resources stratigraphic bore (BMR 10A), lie on each end of the drilling line, and information from these bores is included.

A more detailed account of the geology and hydrogeology including water level trends is issued as a G.S.W.A. Record (Commander, 1978).

DRILLING AND TESTING PROCEDURES

Strata samples were collected at 3 m intervals from the deep bore on each site and conventional cores were cut in three bores. On completion of drilling, gamma ray and normals resistivity logs were run and sidewall cores were cut. Temperature logs were run in the cased bores in 1977.

At eight sites (1 to 7 and 11) a deep 152 mm diameter bore was drilled to about 760 m and cased with 76 mm casing; subsequently two shallower bores were drilled at each site to test different intervals. Screens or perforations were used and development was by airlifting.

The procedure used on bores 8A and 9A was somewhat different: these bores were drilled by a contractor and cased with 169 and 143 mm casing respectively. The casing was perforated at several intervals and each one tested by an inner casing string of 76 mm pipe with movable rubber packers, which was subsequently left in the bore.

Eneabba Line (EL) bore 10A was not drilled to the planned depth because the Kockatea Shale was encountered; this bore was finished with slotted casing.

The main drilling problems were the presence of squeezing clays in the Otorowiri Siltstone and loss of circulation in parts of the Yarragadee Formation and the Tamala Limestone.

Water samples were chemically analyzed by the Government Chemical Laboratories and the bores were levelled in to Australian Height Datum by the Surveys and Mapping Branch of the Mines Department.

Table 1 summarizes the bore construction; further details are available in the form of composite logs which are available on application to the Geological Survey.

TABLE 1. SUMMARY OF BORE DATA

Bore name	Latitude S	Longitude E	Date drilled	Total depth m bns	Depth cased m bns	Observation		Elevation	
						Interval m bns	Method *	Nat. Surf. m above AHD	Top casing m above AHD
Dathagnoorara	29°48′07″	115°42′15″	Mar 71	305	178	155–178	S	....	276·04
EL1A	29°48′00″	115°39′40″	Feb 74	751	687	675–681	S	256·6	256·900
EL1B	....	....	Apr 74	444	443	422–428	P	....	256·710
EL1C	....	....	May 74	250	242	230–236	P	....	256·685
EL2A	29°48′00″	115°35′30″	Oct 73	762	671	646–658	S	264·3	264·628
EL2B	....	....	Jan 74	250	242	224–236	S	....	264·826
EL2C	....	....	Feb 74	70	68	43–61	S	....	265·334
EL3A	29°48′00″	115°31′30″	July 73	762	687	662–674	S	295·0	295·374
EL3B	....	....	Sept 73	491	484	472–478	S	....	295·396
EL3C	....	....	Oct 73	110	90	71–77	S	....	295·266
EL4	29°48′10″	115°27′10″	May 73	762	627	607–613	S	254·2	254·508
EL4A	....	....	May 73	66	53	35–41	S	....	254·493
EL4B	....	....	June 73	487	477	459–465	S	....	254·526
EL5	29°48′17″	115°23′09″	Mar 73	718	562	543–549	S	201·3	201·675
EL5A	....	....	Mar 73	216	183	171–177	S	....	200·987
EL5B	....	....	Apr 73	402	399	387–393	S	....	201·389
EL6	29°47′45″	115°19′30″	Feb 73	763	635	616–622	S	138·4	138·766
EL6A	....	....	Feb 73	270	269	250–256	S	....	138·446
EL6B	....	....	Mar 73	167	164	145–151	S	....	138·563
EL7	29°45′08″	115°15′45″	Oct 72	765	756	737–743	S	95·5	95·809
EL7A	....	....	Nov 72	598	526	408–414	P	....	95·859
EL7B	....	....	Nov 72	159	157	144–150	S	....	96·074
EL8A	29°50′10″	115°13′40″	July 74	758	730	673–684	P	68·9	69·291
EL8A annulus	....	....	....	....	....	508–518 321–327	B P	....	69·021
EL8B	....	....	Oct 74	177	174	157–162	P	....	68·795
EL9A	29°51′10″	115°10′30″	Oct 74	797	797	785–794	P	50·8	52·472
EL9A annulus	....	....	....	....	....	60–66 276–282 558–567	P P P	....	....
EL10A	29°52′	115°03′	May 74	159	42	24–36	SL	11·3	11·937
EL11A	29°52′	115°06′	June 74	102	97	84–90	P	....	66·813
EL11C	....	....	July 74	762	752	672–678	P	66·8	67·361
EL11D	....	....	Sept 74	458	452	438–444	P	....	68·238

* S Screen   SL Slots   P Perforation   B Break in casing

PHYSIOGRAPHY

The Dandaragan Plateau and the Arrowsmith Region are the most extensive physiographic units in the area (Fig. 4). Both of these are remnants of a laterite-capped plateau with an elevation of about 300 m. The Arrowsmith Region is now subject to dissection by ephemeral streams having their headwaters in the outcrop of the Otorowiri Siltstone, which has given rise to the Dandaragan Scarp. On the Dandaragan Plateau itself drainages are now inactive and the valleys are infilled with sand.

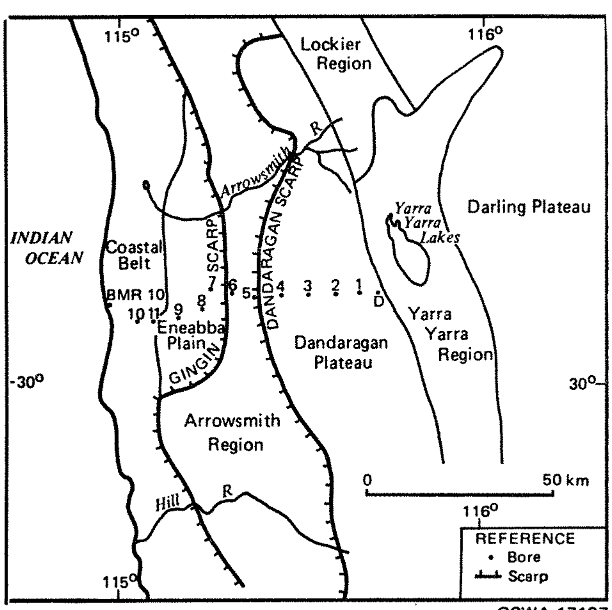


Figure 4 Physiographic regions

The Yarra Yarra Region lies to the east of the Dandaragan Plateau and is an area of low relief, being occupied by the Yarra Yarra Lakes and the upper part of the Moore River system. The region has been formed by erosion along the Darling Fault.

The Gingin Scarp, formed by Tertiary marine erosion, forms the western boundary of the Arrowsmith Region. The alluvial fans, colluvium and former strandlines at the base of the scarp form the Eneabba Plain. To the west of this a series of calcarenite dunes and beach ridges, termed the Coastal Belt, run parallel to the coast. These have the effect of ponding back streams on their east side and drainage then takes place through cave systems. The Coastal Belt includes shallow salt pans a few kilometres from the coast.

CLIMATE

The climate of the area is mediterranean, with hot, dry summers and mild, wet winters. Average annual rainfall decreases inland from 590 mm at Eneabba to 400 mm at Carnamah, and falls mainly between April and October. Mean daily temperatures exceed 30°C from December to March and potential evaporation is three times as great as the annual rainfall. Rainfall only exceeds evaporation in June, July and August.

GEOLOGY

The general geology of the area has been described by Playford and others (1976) and the detailed geology of the sediments encountered by the drilling is described by Commander (1978).

The area lies within the Perth Basin and has been subdivided into three structural units (Fig. 5): the Irwin sub-Basin, the Dandaragan Trough and the Beagle Ridge.

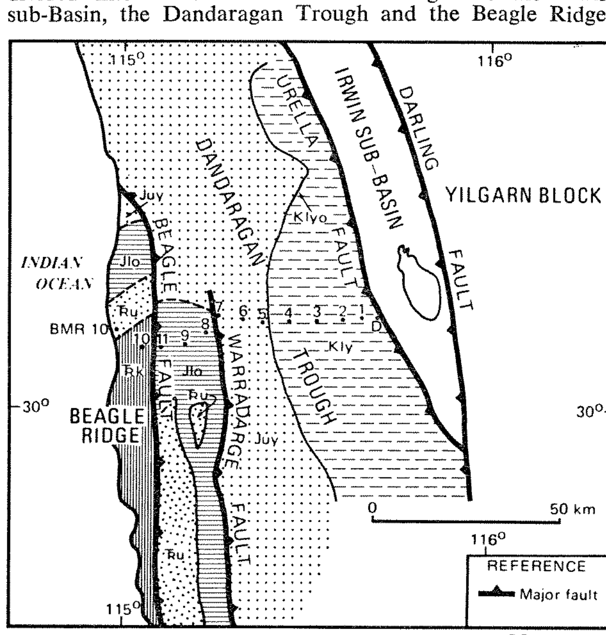


Figure 5 Geology (for symbols see Table 2)

The Irwin sub-Basin is an area of shallow Proterozoic rocks contained between the Darling and Urella Faults on the eastern margin of the basin. The Proterozoic rocks are covered in places by Permian and Quaternary sediments.

The centre of the onshore part of the basin is the Dandaragan Trough. This is occupied by a shallow synclinal structure, with shallow dips on the east and a faulted western limb. The sediments in the trough range in age from Permian to Cretaceous, and the thickness exceeds 8 km.

The Beagle Ridge lies to the west of the Dandaragan Trough and is separated from it by the Beagle Fault. Here the Precambrian basement is shallower, and covered by Permian and Triassic sediments.

Table 2 summarizes the Mesozoic and Cainozoic stratigraphy. The Permian and Lower to Middle Triassic formations are predominantly shaley. The Upper Triassic to Lower Cretaceous sequence is mainly sandy with some shaley sections, and it is in these formations that the major aquifers occur.

TABLE 2. SUMMARY STRATIGRAPHY IN THE ENEABBA AREA

Age	Formation	Symbol	Thickness (approx.) (m)
Quaternary	Safety Bay Sand, Tamala Limestone	Q	80
	unconformity		
Tertiary	Unnamed Channel Sand	Cz	153
	unconformity		
Lower Cretaceous	Yarragadee Formation (upper)	Kly	437
	Otorowiri Siltstone Member	Klyo	99
Upper Jurassic	Yarragadee Formation (lower)	Juy	2 500
Middle Jurassic	Cadda Formation	....	80
Lower Jurassic	Cockleshell Gully Formation	Jlo	....
	Cattamarra Coal Measures Member	Jloc	500
	Eneabba Member	Jloe	700
Upper Triassic	Lesueur Sandstone	TRu	600
Middle Triassic	Woodada Formation	TRk	1 100
Lower Triassic	Kockatea Shale		

Cainozoic sediments are thickest near the coast, west of the Gingin Scarp. In one bore, EL6, a channel sand was encountered extending to 15 m below sea level. The channel is probably associated with the palaeo-drainage system on the Dandaragan Plateau and the sand itself may be of marine origin, similar to other deposits in the Perth Basin (Allen, 1977).

A cross section showing the geology of the bore-hole line is shown in Figure 6.

HYDROGEOLOGY

The Dandaragan Trough contains all the major aquifers, and all the bores except EL10A were drilled into it. The trough is bounded both on the east and the west by impermeable barriers, the Urella and Beagle Faults, which impose a regional south-north groundwater flow on the contained aquifers. Head information from surrounding bores indicates that the flow direction is south to north.

The hydrogeology of the Irwin sub-Basin and the Beagle Ridge are briefly dealt with, and the occurrence of groundwater in the aquifers in the Dandaragan Trough is described in the order of declining potentiometric heads. Generally this is downwards, and the relationship is shown in Figure 6b.

IRWIN SUB-BASIN

Quaternary aquifer

Quaternary sands which overlie Proterozoic rocks and Phanerozoic sediments on both sides of the Urella Fault adjacent to the Eneabba Line, have a shallow water table developed only on the east side of the fault. The water table is several metres below surface and is about 270 m above sea level. Groundwater is recharged directly from rainfall and flows eastwards to be discharged at the surface near the Yarra Yarra Lakes (Fig. 7). Groundwater salinity in the western part of the aquifer is low, only several hundred milligrams per litre.

Proterozoic aquifer

Groundwater occurs in fractured Proterozoic crystalline and sedimentary rocks and in the clayey weathering products. The salinity ranges from 1 500 mg/l to just over 4 000 mg/l. The potentiometric surface is below that of the overlying Quaternary aquifer, but to the north where the Quaternary aquifer is absent it is 290 m above sea level. The amount of water in storage is probably very small, and the rates of groundwater movement very slow. There is a potential for leakage westwards across the Urella Fault, but the quantity is probably not significant.

DANDARAGAN TROUGH

Upper Yarragadee Formation aquifer

This aquifer occurs between the Dandaragan Scarp and the Urella Fault, and includes all the Yarragadee Formation stratigraphically higher than the Otorowiri Siltstone. Harley (1975) uses the term "Agaton groundwater system" to include both the upper Yarragadee Formation and the overlying Warnbro and Coolyena Groups which are absent in the Eneabba area.

The aquifer has a maximum saturated thickness of 300 m, and a salinity range of 160 mg/l to just over 2 000 mg/l, although it is generally less than 1 000 mg/l. The areas of fresher water (less than 500 mg/l) seem to coincide with the lower parts of the palaeodrainage systems where absence of laterite may facilitate recharge.

The water table occurs at a maximum depth of 90 m below surface (about 220 m AHD) and has a very small apparent east to west gradient. The westerly movement gives rise to spring flow along the Dandaragan Scarp. The drilling line lies near the groundwater divide between water flowing north towards the Arrowsmith River discharge area (Barnett, 1969) and southerly flowing groundwater at Agaton (Balleau and Passmore, 1972).

The potentiometric head in the Dathagnoorara bore is 183 m AHD which is significantly lower than heads elsewhere in the aquifer. It is possibly situated in a fault block with a different potentiometric head, and may indicate downward leakage into the lower Yarragadee Formation aquifer.

The base of the aquifer is the Otorowiri Siltstone, which is effectively impermeable and maintains a head difference of 140 m between the upper Yarragadee Formation and the lower Yarragadee Formation aquifers.

Lower Yarragadee Formation aquifer

The lower Yarragadee Formation aquifer is about 2 500 m thick and includes all the Yarragadee Formation below the Otorowiri Siltstone. It extends beneath the upper Yarragadee Formation aquifer as far east as the Urella Fault, and as far west as the Warradarge Fault. It is the most widespread and important aquifer in the Perth Basin; Harley (1975) uses the term "Badgingarra aquifer system" for the lower Yarragadee Formation along the Watheroo borehole line.

To the depths drilled, the salinity is generally less than 1 000 mg/l, and in Eneabba No. 1 oil exploration well (Pudovskis, 1962) the formation water in the whole of the Yarragadee Formation was reported as fresh. Only in EL4 and 4A, where the salinity was just over 1 000 mg/l and in EL3A, at 2 900 mg/l, were the salinities higher.

The lowest salinity water occurs just west of the Dandaragan Scarp, and in the south of the outcrop area. The salinity increases in a northwesterly direction.

East of the Dandaragan Scarp the aquifer is confined by the Otorowiri Siltstone. The apparent hydraulic gradient along the Eneabba Line is very small, but with no information to the north or south the direction of groundwater flow can only be assumed to be south to north as this is the direction in the upper aquifer.

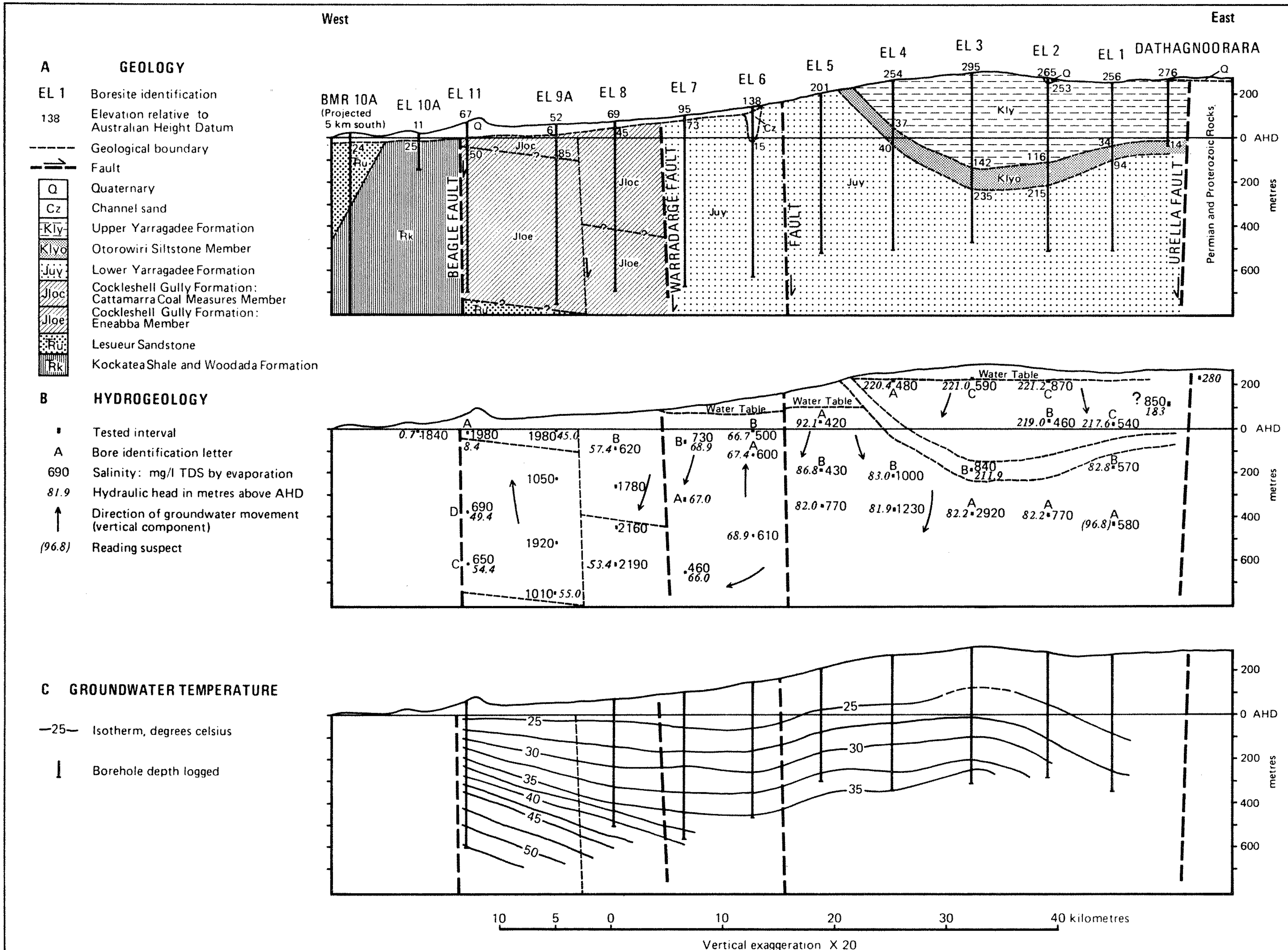
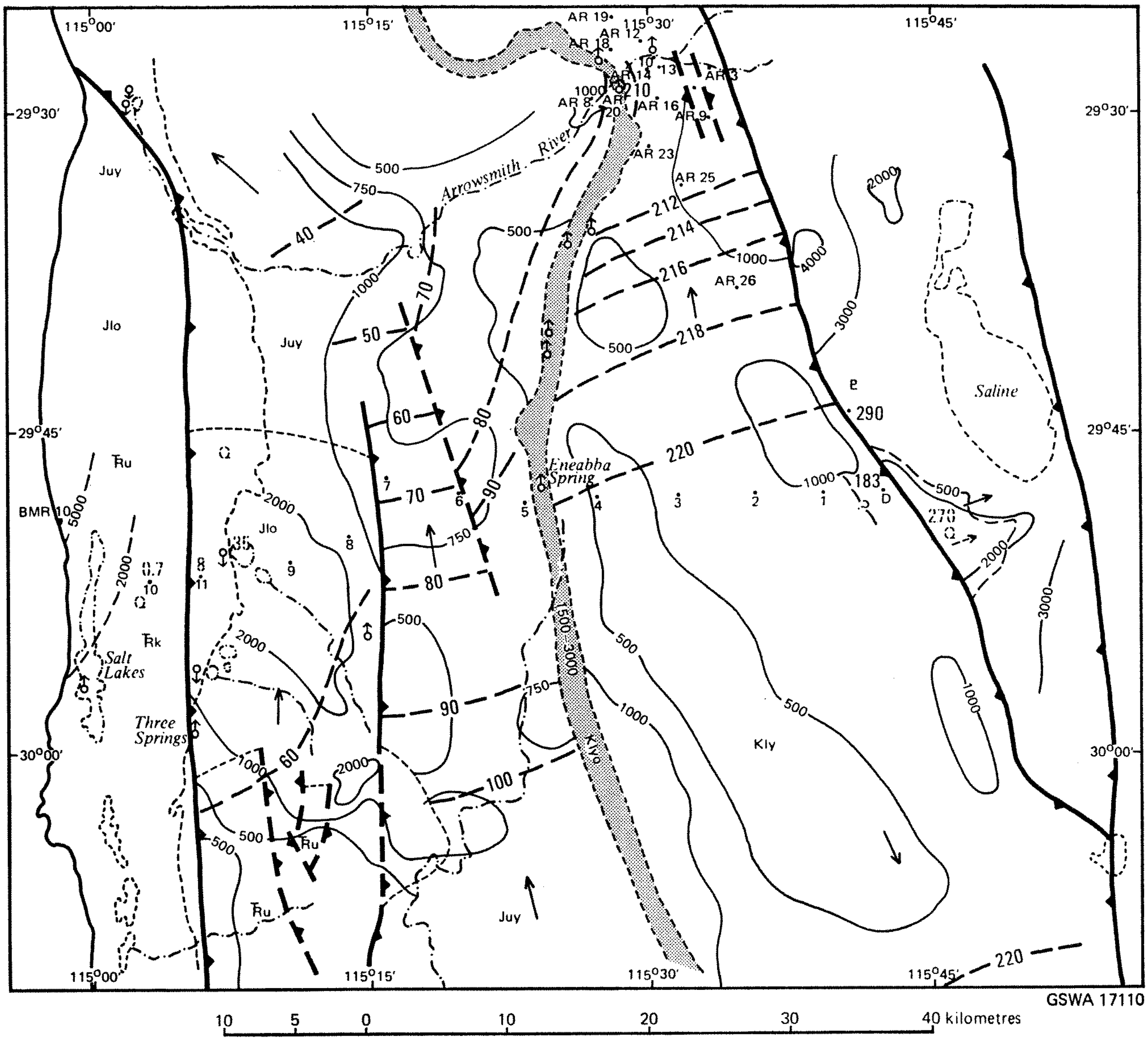


Figure 6 Geology, hydrogeology and groundwater temperature



REFERENCE

----	Formation Boundary	•6	Borehole Eneabba Line		Quaternary formations
	Fault major	•AR 1	Borehole Arrowsmith River Project	Kly	Upper Yarragadee Formation
	Fault minor	•D	Borehole Dathagnoorara	Klyo	Otorowiri Siltstone Member
	Ephemeral Creek	—750—	Salinity mg/l	Juy	Lower Yarragadee Formation
	Ephemeral Lake	--500--	Salinity mg/l (Quaternary)	Jlo	Cockleshell Gully Formation
	Spring	—210—	Potentiometric head (m)	Ru	Lesueur Sandstone
	Sinkhole	200	Potentiometric head (Quaternary)	Rk	Kockatea Shale and Woodada Formation
•	Borehole	——→	Direction of groundwater flow	P	Proterozoic rocks

Figure 7 Regional hydrogeology

West of the Dandaragan Scarp there is a regional north to northwesterly flow, the potentiometric heads declining from over 100 m in the south to less than 40 m near the Arrowsmith River (Fig. 7). Groundwater flow seems to be compartmentalized by north-south trending faults, acting as partial hydraulic barriers.

Recharge takes place from rainfall, and also possibly by concentration of surface run off. There may be some inflow from the upper Yarragadee Formation aquifer. Discharge is to the northwest and possibly some leakage may occur across the Warradarge Fault into the Cockleshell Gully Formation. The channel sand encountered at EL6 may act as a drain, as the potentiometric surface at EL6 is locally depressed (Fig. 6b).

Cockleshell Gully Formation aquifer

The Cockleshell Gully Formation was encountered in bores 8, 9 and 11 between the Warradarge and the Beagle Faults. It crops out south of the cross-section line and south of the Gingin Scarp, but along the cross-section line it is covered by Quaternary sands. The formation is about 1 200 m thick.

The salinity in the three bores ranged from 620 mg/l to 2 190 mg/l. The thicker sands in the lower Eneabba Member appear to contain the fresher water, whereas the salinity in the Cattamarra Coal Measures is usually brackish.

2—74499

Recharge to the formation takes place in its outcrop area and regional groundwater flow is northwards. The potentiometric heads are in the 50-60 m range just west of Eneabba, and bores in the low-lying areas flow. The thick shales provide good confining beds. There may be some leakage into the formation from the lower Yarragadee Formation aquifer and localized recharge at EL8 from the superficial sands.

The basal sands of the Eneabba Member are in hydraulic continuity with the Lesueur Sandstone and there is probably some upward leakage.

Spring discharge, apparently from the Cockleshell Gully Formation aquifer occurs along the Beagle Fault at Three Springs 25 km southwest of Eneabba. There may be other places where there is upward leakage along the fault zone, discharging into the overlying Tamala Limestone.

Lesueur Sandstone aquifer

The Lesueur Sandstone crops out 30 km southwest of Eneabba and extends northwards beneath the Cockleshell Gully Formation. It occurs just below the section drilled in EL9 and EL11, and is hydraulically connected to the overlying Eneabba Member. The formation is about 600 m thick.

The aquifer is recharged by rainfall and concentration of surface run-off on its outcrop area. Groundwater flow is northwards. The salinity is low in its outcrop area (300-800 mg/l) and is probably less than 1 000 mg/l below the cross-section line.

BEAGLE RIDGE

Tamala Limestone

The Tamala Limestone straddles the Beagle Fault and overlies the Cockleshell Gully Formation on the east and the Kockatea Shale on the west. It is in hydraulic connection with the Safety Bay Sand, and in EL10A there is a basal sand unit 20 m thick.

The eastern part of the limestone is a karst aquifer, and surface water from Lake Logue and Stockyard Gully flows directly into caves. In places where the base of the lime stone is above sea level there is no continuous water table. Between EL10A and BMR10 a water table is developed and the saturated thickness is 26 m.

The salinity of the surface water intakes is highly variable and in 1974 was in the 200 to 1 500 mg/l range. The salinity of groundwater in EL11, EL10A and a spring into salt lakes is in the range 1 200 to 2 000 mg/l, but the salinity increases to 5 000 mg/l at BMR10.

Kockatea Shale and Woodada Formation

The Triassic sediments encountered in EL10A were shales, and did not contain any usable water. These beds act as a barrier to westerly groundwater flow.

The top part of the Woodada Formation is known to contain water-bearing sands (Harley, 1975) so that north of the cross-section line there will be groundwater in the Upper and Middle Triassic sediments, but the salinity is unknown (as also in BMR10).

HYDROCHEMISTRY

All groundwater in the area is classified as sodium chloride type. There are no significant differences in chemical composition between water from the different aquifers. The most important influence on the chemical composition is probably the type and mode of recharge.

Laboratory measurements of pH range from 6.8 to 8.3, and it is known that low pH waters in the lower Yarragadee Formation aquifer are very corrosive.

Iron contents vary considerably and in places are as high as 5.7 mg/l; accurate sampling was not possible as samples were aerated during airlifting.

GROUNDWATER TEMPERATURE

The Eneabba Line was the first line of bores across the Perth Basin to have downhole temperature logs run (Fig. 6c).

The results show a high temperature gradient in the west and a low gradient in the east. This is possibly due to three factors: firstly, the Precambrian basement is shallower in the west; secondly, the more shaley Cockleshell Gully Formation in the west is probably a better thermal insulator than the sandier Yarragadee Formation; and thirdly, the direction of groundwater flow is downward in the east and upward in the west.

Actual gradients range from 1.7 to 2.7°C per 100 m in the sandier parts of the Yarragadee Formation to 5.5°C per 100 m in the Cockleshell Gully Formation. The highest temperature is 52.5°C at a depth of 600 m in EL11, and the water-table temperature is 23-24°C.

DEVELOPMENT

The lower Yarragadee Formation aquifer is the most important and extensive aquifer, and contains a large quantity of fresh water. About 50 000 m^3day^{-1} is abstracted from the aquifer by the mineral sand industry at Eneabba. Smaller amounts are used for town water supply at Eneabba and farm water supplies.

The upper Yarragadee Formation is also fairly extensive in the east of the Perth Basin. Its position adjacent to the Darling Fault means that it is the most convenient aquifer to supply water to towns on the Yilgarn Block. Morowa, Three Springs and Carnamah town water supplies are all drawn from the aquifer.

The Cockleshell Gully Formation and the Lesueur Sandstone aquifers are only exploited for the Leeman-Greenhead town water supply. There are also a few farm bores which draw water for domestic and stock consumption. There is considerable potential for further development for domestic and industrial water supplies.

The Tamala Limestone elsewhere is an important source of fresh water near the coast; in this area, however, the marginal quality of the water precludes development for domestic use.

CONCLUSIONS

There are four major aquifers in the area; these are, in order of importance, the lower Yarragadee Formation, the upper Yarragadee Formation, the Cockleshell Gully Formation and the Lesueur Sandstone. Fresh water is present in all the formations and, except in the upper Yarragadee Formation which was completely penetrated by the drilling, extends to below the depths drilled.

Recharge to these aquifers is by rainfall on their outcrop areas, and regional groundwater flow is northwards. Impermeable Triassic rocks on the Beagle Ridge are a barrier to westward groundwater movement. The Otorowiri Siltstone is a major aquiclude which separates the upper and the lower Yarragadee Formation aquifers, and maintains a 140 m head difference across it.

The geothermal gradient is highest in the west and may be due to the shallowness of crystalline basement, the presence of more thermally insulating beds and an upward direction of groundwater flow.

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GEOLOGY AND HYDROGEOLOGY OF THE BECHER POINT LINE AND GEOLOGICAL REINTERPRETATION OF ADJACENT BOREHOLE LINES

by A. D. Allen

ABSTRACT

The Becher Point Line consists of nine bores at five sites ranging in depth from 71 to 810 m and with an aggregate depth of 4 591 m. The bores were drilled to explore the hydrogeology and to provide a section across the Perth Basin about 45 km south of Perth. Results from drilling have shown that the Cockleshell Gully Formation (Early Jurassic) and Yarragadee Formation (Late Jurassic—Early Cretaceous) have been faulted into juxtaposition in large fault blocks and can be considered to form a basement to subsequent formations. This basement is overlain by the South Perth Shale (Early Cretaceous) except in the east where it pinches out, and by the Leederville Formation (Early Cretaceous) which extends over the whole area. Subsequently there have been several periods of erosion, followed by deposition in the Quaternary of the Rockingham Sand and the 'superficial formations'. Structurally the South Perth Shale and Leederville Formation form the eastern limb of a very gentle syncline, incised by deep channels infilled with Rockingham Sand, and covered by a veneer of 'superficial formations'.

Groundwater occurs in two major flow systems above and below the South Perth Shale but the two are interconnected near the Darling Scarp where the South Perth Shale is absent. In the upper system recharge is from rainfall and stream losses which sustain a body of unconfined groundwater in the 'superficial formations'. This body of groundwater is in hydraulic connection and provides recharge to the Leederville Formation and the Rockingham Sand. The latter also receives some recharge by upward and lateral discharge from the Leederville Formation. In the lower system recharge into the interconnected Cockleshell Gully and Yarragadee Formations takes place via the Leederville Formation adjacent to the Darling Scarp where the South Perth Shale is absent. Groundwater in both systems flows towards the west where it is presumably discharged into the sea in favourable stratigraphic and structural situations.

Moderate resources of low salinity (250-1 500 mg/l T.D.S.) groundwater are in the Leederville Formation across the width of the coastal plain, and in the Cockleshell Gully Formation at its intake near the Darling Scarp. More limited resources of good quality water are available in the 'superficial formations' and in favourable situations within the Rockingham Sand. Very large supplies of brackish water (1 500-3 000 mg/l T.D.S.) are available from the Rockingham Sand, Yarragadee and Cockleshell Gully Formations.

INTRODUCTION

LOCATION AND TOPOGRAPHY

The Becher Point Line of boreholes is situated about 45 km south of Perth (Fig. 8). The bores are sited about 6 km apart across the width of the coastal plain from Becher Point (Long Point) to near Serpentine, a distance of about 25 km. All the sites are accessible from existing roads, except for Becher Point No. 1 site which is reached by a track from Warnbro.

The coastal plain extends from the coast to the Darling escarpment. At its western edge it is composed of a series of parallel beach ridges rising to about 5 m above sea level. These extend about 6 km inland to abut against a steep scarp marking a former, small coastal cliff cut into a series of calcretized dunes. The dunes rise to about 30 m and on their eastern side are bounded by another less prominent erosional scarp, east of which is a flat plain with a few sandy hills. The plain gradually rises in elevation from less than 10 m to about 80 m at the foot of the Darling escarpment (Fig. 9b).

PURPOSE AND SCOPE

The Metropolitan Water Supply, Sewerage and Drainage Board (M.W.B.) is presently exploring the groundwater resources of the region. As part of the investigation the Becher Point Line and several other lines of deep exploratory bores have been drilled across the coastal plain. These lines of bores are intended to extend and supplement limited geological and hydrological information which has already been obtained from drilling programmes carried out by the Mines Department. The latest bores are also intended for permanent monitoring of water levels and salinity.

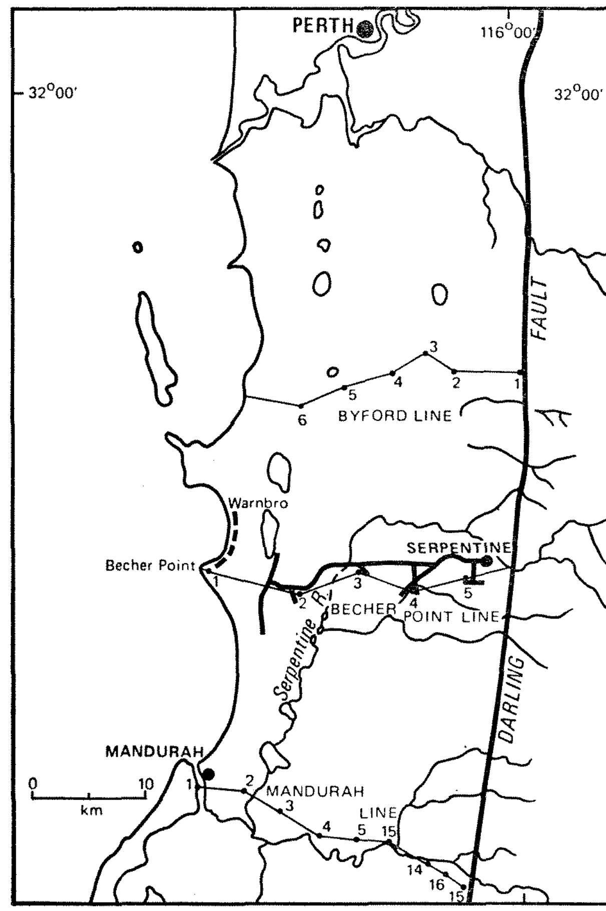

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Figure 8 Location map, Becher Point Line

DRILLING AND TESTING

Nine bores at five sites, ranging from 71 to 810 m deep, and with an aggregate depth of 4 591 m were drilled (Table 3). The bores were sunk by a contractor using a mud-flush rotary drilling rig with a depth capability of about 1 000 m.

At each site the deep bore was given the number of the site and shallower bores were designated A and B in order of decreasing depth.

Sludge samples were taken at 3 m intervals. On reaching total depth, gamma ray, long and short normals resistivity, and caliper, wire-line logs were run. From these up to 30 sidewall core targets were selected and shot for palaeontological examination. This was conducted in each of the deep bores and also in No. 5A where additional samples were required.

The usual procedure for bore construction was to first drill a 255 mm hole to about 50 m and then cement 205 mm pipe in place to act as a surface conductor. A 180 mm hole was then drilled to total depth. After logging and coring a casing string was inserted. This consisted of an 18 m sump of 76 mm pipe; 5 m of 0.5 mm wire-wound stainless steel screen; 12 m or 18 m of 76 mm pipe connector; a cement basket; and 76 mm pipe with centralisers back to the surface. The casing string was pressure cemented to the surface and set in a cement block. The top of the casing was fitted with either a hinged cap, or a valve with a tapping for a pressure gauge if artesian

TABLE 3. SUMMARY OF BORE DATA

Name	Latitude	Longitude	Drilling		Elevation (m) A.H.D.		Depth (m)	Completed Depth (m)	Screened Interval (m)	Head (m) A.H.D.[4]	Salinity T.D.S. by Evap. (mg/l)	Status
			Commenced	Completed	Surface	Casing						
Becher Point No. 1	32°22′04″S	115°43′03″	23/11/76	6/12/76	2·258	2·706[1]	804[2]	506	483–488	12·456[5]	2 890	Observation bore Yarragadee Formation
Becher Point No. 2	32°23′06″S	115°46′09″	24/3/77	2/4/77	9·151	9·497[1]	742	405	379–384	13·307[5]	1 710	Observation bore Yarragadee Formation
Becher Point No. 3	32°22′07″S	115°51′05″	1/3/77	9/3/77	8·08	9·08	795	398	375–380	13·047[5]	1 630	Observation bore Yarragadee Formation
Becher Point No. 3A	32°22′07″S	115°51′05″	17/3/77	18/3/77	8·02	8·25	130	130	107–112	4·267	360	Observation bore Leederville Formation
Becher Point No. 4	32°22′15″S	115°54′03″	19/2/76	1/1/77	16·33	17·01	810	578	(554–559[3]) 492–498	13·362	2 230	Deep observation bore Yarragadee Formation
Becher Point No. 4A	32°22′15″S	115°54′03″	15/1/77	21/1/77	16·60	17·12	303	303	280–285	13·348	....	Observation bore Yarragadee Formation
Becher Point No. 4B	32°22′15″S	115°54′03″	24/1/77	24/1/77	16·58	16·96	74	71	54–59	14·680	780	Observation bore Leederville Formation
Becher Point No. 5	32°22′10″S	115°57′04″	26/1/77	19/2/77	37·02	37·40	803	635	603–608	24·306	1 050	Deep observation bore Cockleshell Gully Formation
Becher Point No. 5A	32°22′10″S	115°57′04″	14/4/77	15/4/77	36·54	36·83	130	129	112–117	28·571	....	Observation bore Cockleshell Gully Formation
							4 591					

[1] Elevation to top of valve.
[2] Depth reached by gamma ray logging probe.
[3] Accidentally cemented off, perforated 492–498.
[4] Readings in May, 1977.
[5] Artesian flow.

water had been encountered. In No. 5 bore the cement basket is believed to have collapsed and the screen was filled with cement. This was subsequently rectified by perforating another interval with shaped explosive charges.

For monitoring it was intended to set screens over two intervals, one about 100 m below the bottom of the South Perth Shale as this is the usual production interval from the underlying formations; and the other in the middle of the Leederville Formation so that an 'average' pressure would be obtained. During the work the plan was modified because of the desire to obtain more information about the Cockleshell Gully and Yarragadee Formations, and because of difficulties with correlation. Bores No. 4 and 5 were left to monitor pressures about 300 m and 500 m respectively below the bottom of the South Perth Shale to give information about head variation with depth. In the latter case the screen was actually set in the upper part of the Cockleshell Gully Formation because of mistaken correlation. Financial constraints prevented construction of monitoring bores in the Leederville Formation at sites No. 1, 2 and 5.

The bores were either developed by airlifting, or in the case of artesian bores, were allowed to flow. Subsequently the non-artesian bores were pumped for up to 3 hours at rates of up to 1 l/sec and samples were taken at the end for standard analysis.

The bores were levelled to Australian Height Datum (Mean Sea Level) and left for monitoring pressure in the various formations. Subsequently, pressures have been measured each month and the data stored in the M.W.B. groundwater levels information system.

Sludge and core samples are stored at the Geological Survey of Western Australia (G.S.W.A.) core library. Other data are available on file at the M.W.B. or G.S.W.A.

PREVIOUS WORK

The G.S.W.A. has previously drilled lines of bores across the coastal plain between Byford and Medina, and from Mandurah to Pinjarra, the results of which have been published.

Berliat (1963, 1964) described the results of drilling 6 bores on the Byford Line.

Passmore (1962) and Emmenegger (1963) reported results from Mandurah No. 1 and No. 2 bores respectively. Later, Emmenegger (1964) gave a more comprehensive report on results from Mandurah No. 1 to No. 5 bores.

Commander (1974, 1975) described the hydrogeology of the Mandurah-Pinjarra area based on the results of 18 bores drilled by the G.S.W.A. for the Mandurah Line and from about 20 bores drilled by Alcoa of Australia (W.A.) Ltd. to exploit and monitor groundwater resources used at its refinery site.

The M.W.B. has also drilled a line of bores between Woodmans Point and Forrestdale, but these results have not yet been published.

GEOLOGY

STRATIGRAPHY

The coastal plain is developed on the eastern onshore edge of the Perth Basin, a long narrow trough of sedimentary rocks extending from about the Murchison River to Augusta. It is bounded in the east by the Darling Fault and extends about 120 km offshore (Playford and others, 1975, 1976).

The Becher Point Line was drilled in the southern part of the Dandaragan Trough, a major structural subdivision of the Perth Basin (Jones and Pearson, 1972), which contains about 6 000 m of Phanerozoic, (predominantly Mesozoic) rocks resting on a Precambrian basement. Surficial formations of Quaternary age conceal all the underlying formations.

The near surface formations considered in this report are given in Table 4, and described more fully below.

TABLE 4. STRATIGRAPHIC SEQUENCE, PERTH TO MANDURAH

Formal Age	Group	Formation	Maximum Thickness (m)	Summary Lithology	Remarks
CAINOZOIC— Quaternary	....	'Superficial formations'*	90	Sand, limestone, silt, clay	Major aquifer
		UNCONFORMITY			
	....	Rockingham Sand	110	Sand	Minor aquifer
		UNCONFORMITY			
Early Tertiary	....	Kings Park Formation	240	Siltstone, shale, minor sand	Aquiclude
		UNCONFORMITY			
MESOZOIC— Early Cretaceous	Coolyena	Osborne Formation	120	Siltstone, shale, minor sand	Aquiclude
	Warnbro	Leederville Formation	220	Sandstone, siltstone, shale	Major aquifer
		South Perth Shale .... Gage Sandstone Member	110 70	Shale, siltstone .... Sandstone, siltstone, shale	Aquiclude Aquifer
		UNCONFORMITY			
Early Cretaceous-Late Jurassic	....	Yarragadee Formation	1 200	Siltstone, sandstone, shale	Major aquifer
Middle Jurassic	....	Cadda Formation	?350	Shale, siltstone	Not definitely known
Early Jurassic	....	Cockleshell Gully Formation .... Cattamarra Coal Measures Member Eneabba Member	3 000	Siltstone, sandstone, shale, coal measures	Aquifer

* Informal name for various recognized Quaternary formations.

Jurassic

Cockleshell Gully Formation: The Cockleshell Gully Formation (Willmott, 1964) was encountered at Becher Point No. 2 and No. 5 sites. It consists of beds of sandstone, 10 to 30 m thick, composed of fine to coarse-grained, subangular sand with accessory garnet and heavy minerals. These are interbedded with beds of black, dark-grey, or grey-brown, hard to sticky, micaceous, carbonaceous and occasionally pyritic siltstone and shale of similar thickness.

The Cockleshell Gully Formation occurs in fault blocks in juxtaposition with fault blocks of Yarragadee Formation. It is unconformably overlain by the South Perth Shale and the Leederville Formation, and to the north may be conformably overlain by the Cadda Formation (Smith, 1967). The thickest section encountered was 706 m in No. 5 bore.

Sidewall cores from No. 2 bore (Backhouse, 1977e) indicated a Toarcian to Aalenian age, whereas in No. 5 bore (Backhouse, 1977f) they indicate a somewhat younger Aalenian to Bajocian age. The age and lithology suggest that the part of the formation encountered may be correlated with the Cattamarra Coal Measures, the uppermost member of the Cockleshell Gully Formation. The palynology also indicates the formation was deposited under nonmarine conditions.

Jurassic-Cretaceous

Yarragadee Formation: The Yarragadee Formation (McWhae and others, 1958) was intersected at Nos. 1, 3 and 4 sites. It is composed predominantly of thick-bedded sandstone with subordinate beds of siltstone and shale. The sandstone is light grey to light pink (garnetiferous), slightly clayey, fine to coarse-grained and composed of angular to subangular quartz grains. Garnet and heavy minerals are abundant in some beds and show peaks on the gamma ray logs which can be mistaken for shales. The siltstone and shale varies from black to light brown, frequently with micaceous laminae and occasionally with carbonaceous or pyrite laminae. Minor lenses of coal were found in No. 1 and No. 3 bores.

The formation occurs in fault blocks, faulted into juxtaposition with the Cockleshell Gully Formation. It may conformably overlie the Cadda Formation (Smith, 1967), and is unconformably overlain by the South Perth Shale and possibly by the Leederville Formation. The thickest section intersected was 625 m in No. 4 bore.

Many of the sidewall cores taken from the Yarragadee Formation were too sandy to contain palynomorphs, or yielded only sparse assemblages. In No. 1 bore the age of the formation was Kimmeridgian to Tithonian (Backhouse, 1977a), whereas in No. 4 bore the palynology indicated a Callovian or slightly older age (Backhouse, 1977b). Samples from No. 3 bore (Backhouse, 1977d) were non-diagnostic.

Cretaceous

South Perth Shale: The South Perth Shale (Fairbridge, 1953) was intersected at all sites with the exception of No. 5 where it has evidently not been deposited. It consists of a basal section of alternating sandstone and siltstone referred to as the Gage Sandstone Member, which can usually only be distinguished palaeontologically from the underlying Cockleshell Gully and Yarragadee Formations. This is overlain by black or brown-black, slightly silty shale, which grades upwards into a dark grey, slightly sandy, slightly micaceous siltstone, with rare glauconite (No. 1 bore). This upper, argillaceous section of the South Perth Shale can be fairly readily recognized on the gamma and resistivity logs.

The formation unconformably overlies the Cockleshell Gully or Yarragadee Formations without evidence of weathering and is conformably overlain by the Leederville Formation. The South Perth Shale is 138 m thick in No. 1 bore and appears to pinch out between No. 4 and No. 5 bores (Fig. 9b), whereas the Gage Sandstone Member has a uniform thickness of about 27 m.

Palynological analysis of sidewall cores taken from the formation (Backhouse, 1977a,b,d,e) indicate that in Nos. 1, 2 and 3 bores the formation is of Barremian age, whereas in No. 4 bore it is entirely of Aptian age. This confirms the inference from the section (Fig. 9b) that the formation was deposited as the sea trangressed to the east and presumably is youngest near where it pinches out. The formation was deposited in a marine to paralic environment and the Gage Sandstone Member appears to be a basal unit deposited during a slow eastward transgression of the sea.

Leederville Formation: The Leederville Formation (Cockbain and Playford, 1973) was encountered at all the sites. It consists of thin to medium-bedded, fine to medium-grained, slightly silty sandstone, composed of angular to subangular quartz grains, interbedded with grey micaceous siltstone and minor shale. At sites Nos. 1-3 the sandstones are glauconitic, and contain hard bands of calcareous and silicified sandstone. Fragments of molluscs are also present. Passmore (1962) and Emmenegger (1963, 1964) also noted the presence of glauconitic and fossiliferous sandstones. They proposed subdivisions of the unit which appear to be relevant only on a local scale and are not used in this account.

The formation either conformably overlies the South Perth Shale or unconformably overlies the Cockleshell Gully Formation (Site No. 5). Elsewhere it may also unconformably overlie the Yarragadee Formation. The maximum thickness of the Leederville Formation is about 190 m in No. 3 bore where it is estimated about 40 m of the formation may have been removed by erosion. It is conformably overlain by the Osborne Formation on the Byford Line and unconformably overlain by the Rockingham Sand or 'superficial formations'.

Palynological analysis of sidewall cores taken from the formation (Backhouse, 1977a,b,c,d,e,f) indicate that in the west (Sites Nos. 2 and 3 and presumably No. 1) the formation ranges from Barremian to Aptian age; however, in the east it is entirely Aptian. This is consistent with a gradual west to east transgression as previously noted. The palynology also indicates that the formation was deposited under marine conditions with some minor periods of nonmarine or paralic deposition.

The gamma ray and electric log characteristics of the formation intercepted by Becher Point Line bores differ considerably from those of bores nearer the type section in Perth. This reflects a southwestward change from nonmarine to marine facies within the formation.

Osborne Formation: The Osborne Formation (McWhae and others, 1958) was not found on the Becher Point Line where it has been removed by erosion, but was intersected by the Byford Line bores. It consists of black, frequently sandy, shale; green-black sandy shale with a high proportion of amorphous glauconite; and local beds of clayey, coarse-grained sand or well-sorted, fine-grained glauconitic sand.

On palaeontological evidence the formation is believed to disconformably overlie the Leederville Formation (Playford and others, 1975). However, to the south of Perth it overlies glauconitic Leederville Formation and appears to form a continuous, conformable marine sequence. It is unconformably overlain by the Rockingham Sand and by the 'superficial formations'.

The formation has a rich assemblage of microflora and microplankton of Albian-Cenomanian age (Cookson and Eisenack, 1958), which also indicates that it was deposited in a marine environment.

Quaternary

Rockingham Sand: The Rockingham Sand (Passmore, 1970) was encountered at No. 1 and No. 2 sites. It consists of brown to light grey, slightly silty, slightly feldspathic, medium to coarse-grained subangular sand. Within the formation are also occasional layers of oxidized pyrite, rare pebbles, and grains tentatively identified as oxidized glauconite.

The formation unconformably overlies the Leederville Formation and has apparently been deposited in channels. The maximum thickness of 106 m was encountered in No. 1 bore.

No sidewall cores were obtained from the formation. However, according to Passmore (1970) the formation is probably of Quaternary age judged by microfossils which were obtained in the type section in Rockingham No. 1 bore.

'Superficial formations': The term 'superficial formations' is used in this account as a collective term to describe the superficial sediments, which comprise a complex sequence of limestone, sand and clay in which various formations are recognized (Playford and others, 1976). They range in age from possible Late Pliocene to Holocene.

The 'superficial formations' unconformably overlie the Leederville Formation and Rockingham Sand. In broad terms their lithology may be related to the present physiography. The coastal strip extending for about 11 km inland is composed primarily of calcretized beach ridges, dune sand and shallow water calcarenite, which abuts against a belt of aeolian and littoral sand extending a further 15 km inland to the Darling Scarp. This general pattern is modified in the vicinity of the major rivers where there has been deposition of clayey alluvial and estuarine deposits.

STRUCTURE

Folding and faulting

The geological structure is illustrated in the sections given in Figure 9. The Cockleshell Gully and Yarragadee Formations can be considered to form a basement to the succeeding formations. They have a gentle regional dip to the east (Playford and others, 1975) but have been dislocated by large-scale faulting into a series of fault blocks bringing the two formations into juxtaposition.

The overlying Warnbro and Coolyena Groups appear to occupy a syncline which may result from folding or be a growth fold.

The Rockingham Sand is situated in former channels incised into the underlying formations. It is flat lying as are the 'superficial formations', and neither unit is known to be affected by folding or faulting.

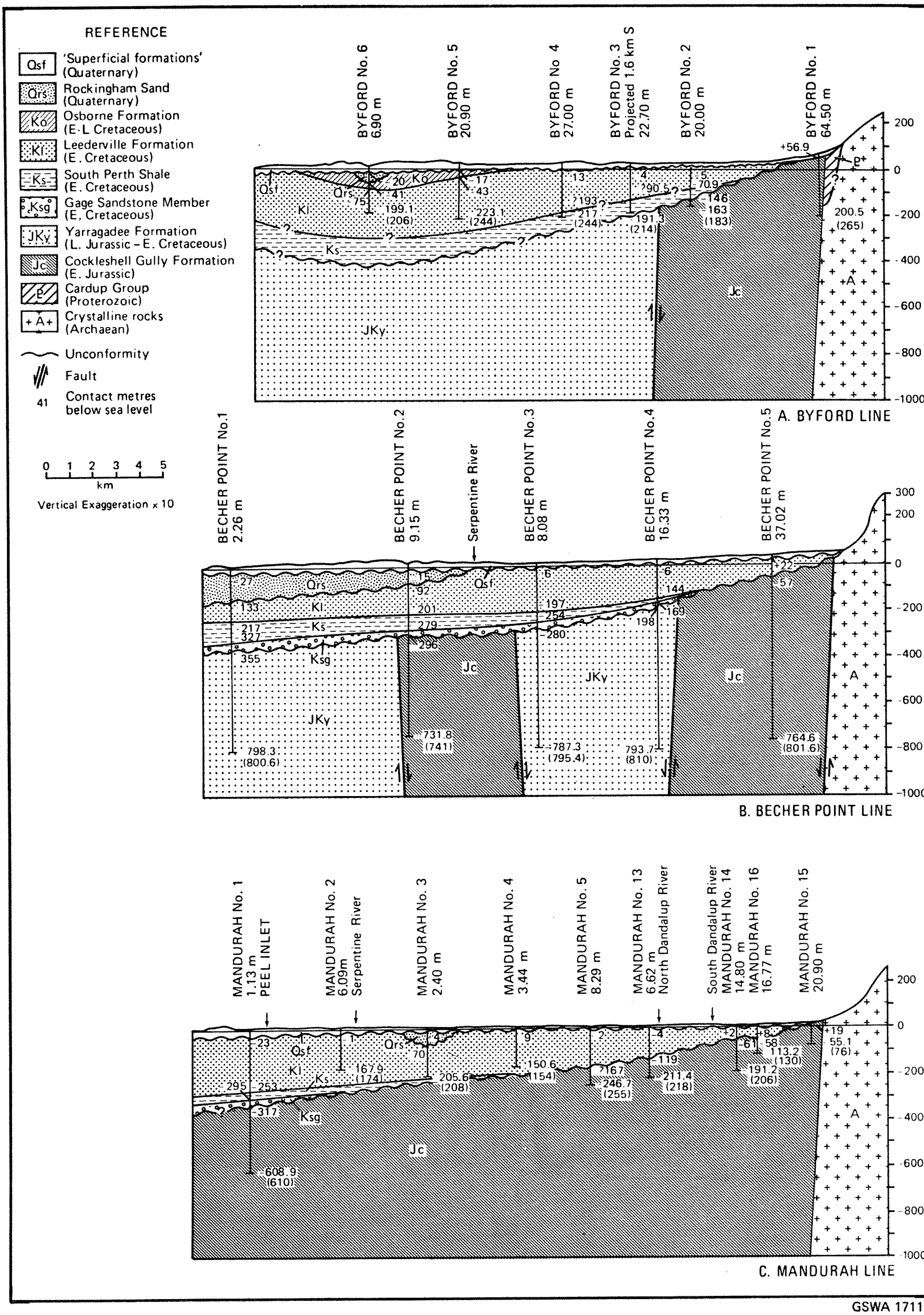


Figure 9 Geological sections

Reinterpretation of the Byford and Mandurah Lines

Results from the Byford Line were described by Berliat (1963, 1964). The deepest bore was only 244 m and identification of the various formations was based on lithology and palaeontology. Since then there has been further subdivision of the stratigraphic sequence and gamma ray logs have been obtained from Byford No. 2 and 5 bores.

A reinterpretation of the Byford Line is given in Fig. 9a. It differs from the section given by Berliat inasmuch as the section is now interpreted as a syncline; the Leederville Formation onlaps almost to Byford No. 1 bore; and the Kings Park Formation (not discussed here) does not extend inland from the coast.

Commander (1974, 1975) gave a composite cross section for the Mandurah area. He considered that the Gage Sandstone Member was well developed and distinctive; and that the upper part of the South Perth Shale had changed in facies to an interbedded sequence of glauconitic and calcareous sand and siltstone which he termed the South Perth Shale equivalent. The top of the South Perth Shale equivalent was defined by the 'green clay marker horizon' previously noted by Emmenegger (1963, 1964).

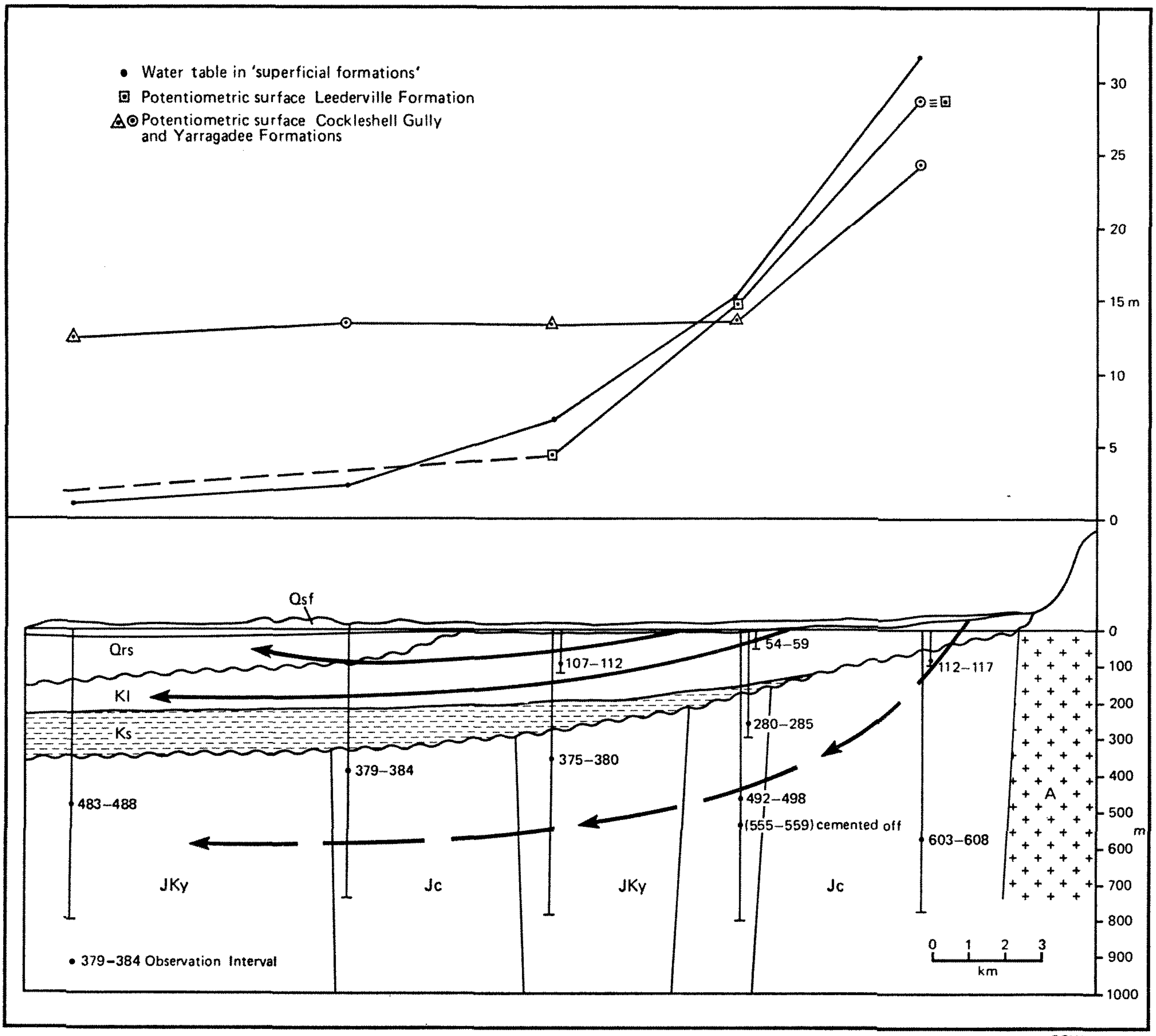
A reinterpretation of the section across the Perth Basin at Mandurah is given in Fig. 9c. The basic differences from Commander's interpretation are that the South Perth Shale can be recognized as a separate rock unit approximately equivalent to his Gage Sandstone (Commander, 1974, Fig. 13), and that the South Perth Shale equivalent is correlated with the Leederville Formation.

GEOLOGICAL HISTORY

During the Jurassic and Early Cretaceous the Cockleshell Gully and Yarragadee Formations were deposited in a continental fluviatile environment. In the mid-Neocomian these units were intensively faulted and subjected to subaerial erosion.

Sedimentation recommenced in the late Neocomian. As the sea transgressed eastward the basal Gage Sandstone Member was deposited. This was succeeded by the South Perth Shale which pinched out near the Darling Scarp and was overstepped by the Leederville Formation which locally transgressed across the Darling Fault. The marine transgression extended northeastward and the Osborne Formation, possibly together with some younger Cretaceous formations, were deposited.

In the Early Tertiary erosion took place in the Perth area (Playford and others, 1975) and probably elsewhere. Subsequently the Kings Park Formation was deposited. There is no evidence of succeeding events until the Late Pliocene or Pleistocene. At this time the Rockingham Sand was deposited probably in submarine channels, and the 'superficial formations' were deposited during the various Quaternary changes in sea level.



GSWA 17113

Figure 10 Relationship of aquifers

TABLE 5. WATER ANALYSES

Name	Date Sampled	G.C.L. No.	pH	Appearance	Turbidity (APHA Units)	Colour (APHA Units)	Odour	Specific Conductivity (uS/cm @ 25°C)	Saturation Index Longelier @ 20°C	mg/l T.D.S. (Evap.)	T.D.S. Cond.	Free CO_2	Total Hardness (as $CaCO_3$)	Total Alkalinity (as $CaCO_3$)	Ca	Mg	Na	K	CO_3	HCO_3
Becher Point No. 1	29/12/76	30598/76	8·7	Cl.sl.gry.dep.	9	10	Nil	4 600	+0·7	2 430	2 940	1	120	195	20	17	895	28	21	195
Becher Point No. 1	4/5/77	82292/77	7·8	Cl.sl.dep.	8	10	Nil	4 520	—0·3	2 510	2 890	6	112	186	17	17	886	27	Nil	226
Becher Point No. 2	13/9/77	84857/77	9·1	Cl.	1	8	Nil	....	....	1 710	....	....	....	....	....	....	....	....	....	....
Becher Point No. 3	13/9/77	84858/77	9·9	Cl.	10	6	Nil	....	....	1 630	....	....	....	....	....	....	....	....	....	....
Becher Point No. 3A	22/9/77	85226/77	9·3		2	3	Nil	....	....	360	....	....	....	....	....	....	....	....	....	....
Becher Point No. 4	22/9/77	85227/77	8·2		1	5	Nil	392	0·2	2 230	2 510	4	84	300	14	12	807	25	Nil	366
Becher Point No. 4A	15/2/78	80666/78	7·0	Cl.br.dep.	....	<5	Nil	148	....	750	950	....	175	117	11	36	210	6	Nil	143
Becher Point No. 4B	22/9/77	84859/77	6·6	Cl.s.br.dep.	380	9	Nil	....	....	780	....	....	....	....	....	....	....	....	....	....
Becher Point No. 5	12/12/77	86866/77	11·9	Cl.sl.br.dep.	9	5	Nil	....	....	1 050	....	....	....	....	....	....	....	....	....	....
Becher Point No. 5A	15/2/78	80667/78	11·2		....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....

Name	mg/l Cl	SO_4	NO_3	SiO_2	B	F	Fe	Mn	Cu	Pb	As	N (as ammonia)	N (as nitrate)	P (Total in solution)	Remarks
Becher Point No. 1	1 240	150	1	16	0·43	0·5	0·05	0·05	0·02	0·02	0·02	0·74	0·02	0·02	Deposit and turbidity could be due to precipitation of $CaCO_3$ after aeration
Becher Point No. 1	1 240	130	1	15	0·63	0·5	0·05	0·05	0·02	0·01	0·01	0·74	0·02	0·02	
Becher Point No. 2	825	....	....	....	....	....	....	....	....	....	....	....	....	....	Sample affected by cement contamination
Becher Point No. 3	861	....	....	....	....	....	....	....	....	....	....	....	....	....	Sample affected by cement contamination
Becher Point No. 3A	106	....	....	....	....	....	0·16	....	....	....	....	....	....	....	
Becher Point No. 4	1 030	115	1	13	1·51	1·8	0·18	0·04	0·02	0·01	0·01	0·81	0·02	0·02	
Becher Point No. 4A	352	25	<1	13	0·15	<0·1	....	....	....	....	....	....	....	....	
Becher Point No. 4B	352	....	....	....	....	....	....	....	....	....	....	....	....	....	Not air free
Becher Point No. 5	189	....	....	....	....	....	....	....	....	....	....	....	....	....	pH suggests sample contaminated with cement
Becher Point No. 5A	....	....	....	....	....	....	....	....	....	....	....	....	....	....	Cement contaminated

HYDROGEOLOGY

INTER-RELATIONSHIP OF AQUIFERS

Within the 'superficial formations' there is a body of unconfined groundwater which extends throughout the coastal plain (Allen, 1976a, 1976b). This is directly recharged from rainfall or by run-off from rivers and streams rising on the Darling Scarp. This groundwater provides recharge to the underlying Rockingham Sand or Leederville Formation by downward leakage. In turn the Leederville Formation provides recharge by leakage into the underlying Cockleshell Gully and Yarragadee Formations, over a limited area near the Darling Scarp where the South Perth Shale is absent.

The groundwater flow system is effectively divided into two parts by the South Perth Shale. A lower part comprising the Cockleshell Gully and Yarragadee Formations in apparent hydraulic continuity, and an upper part formed by the 'superficial formations', the Rockingham Sand and the Leederville Formation. The relationship of the various aquifers and the inferred flow system indicated by arrows is shown in Figure 10.

DETERMINATION OF SALINITY

In the drilling programme it was only possible to get a water sample from the intervals which were selected for observation (Table 5). The salinity of many other beds of sand encountered was estimated from the long-normal resistivity logs. For the calculations it was assumed that the geothermal gradient was 1.9°C per 100 m depth, the Cockleshell Gully and Yarragadee Formations had a formation factor of 7.5, and that the Leederville Formation had a formation factor of 6.

The results should be within ± 20% of real values. Actual samples and estimated values are given in Figure 11 and compare reasonably well, with the exception of No. 1. The estimates for the aquifers not sampled are therefore expected to closely approximate the actual salinities.

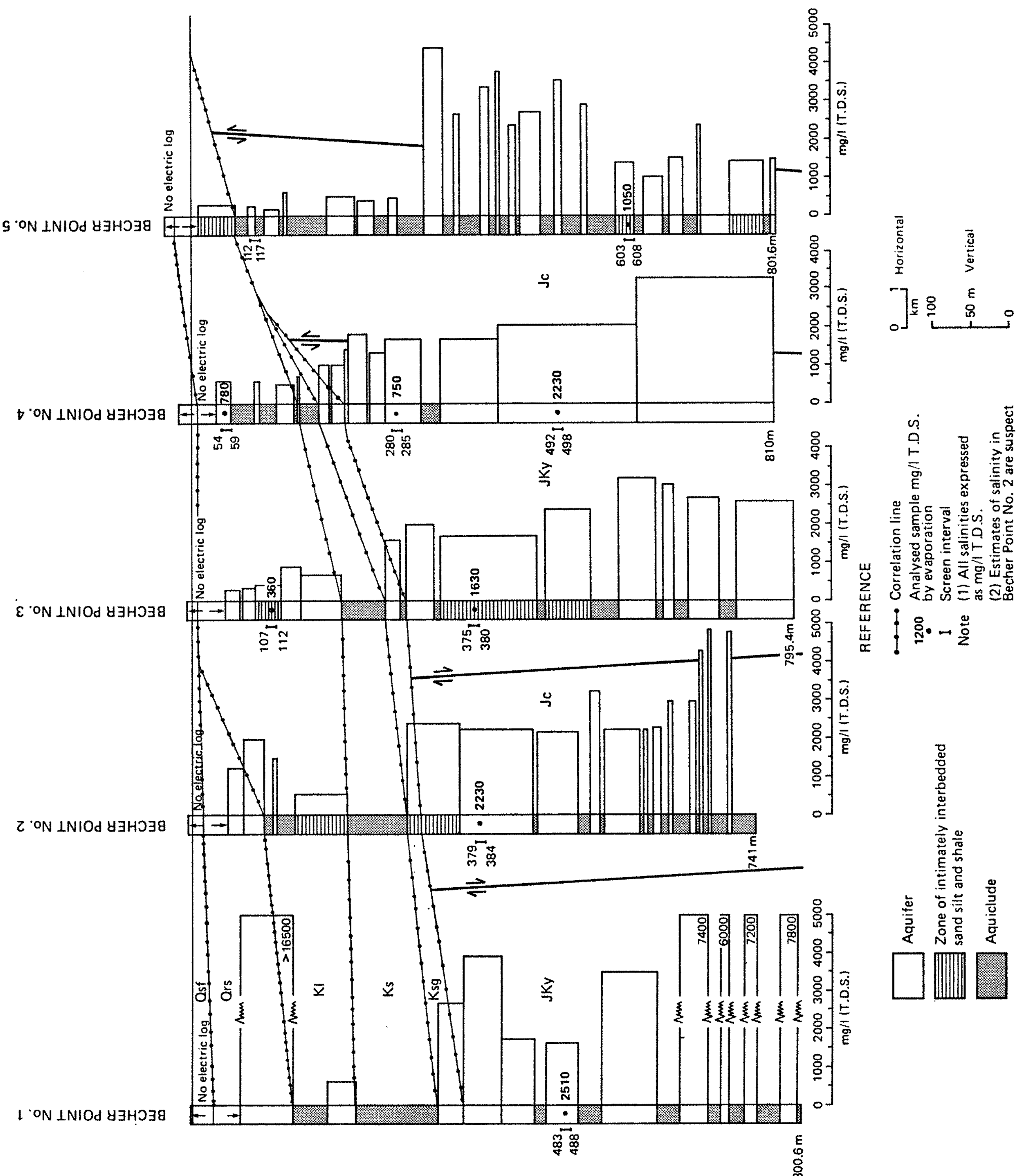


Figure 11 Groundwater salinity estimated from log-normal resistivity logs

AQUIFERS

'Superficial formations'

The 'superficial formations' consist of a complex sequence of sand, limestone and clay. They contain unconfined groundwater throughout the coastal plain.

Groundwater within these formations originates from direct infiltration of rainfall and from stream flow off the Darling Scarp. The saturated thickness of the aquifers is less than 20 m, and the volume in storage is relatively small. Groundwater movement under gravity is towards the west where discharge takes place into the Serpentine River and the sea. Along the coast a seawater interface is developed within the aquifers. In addition, a proportion of the groundwater in storage infiltrates into the underlying formations.

The groundwater salinity is variable but usually less than 1 000 mg/1 T.D.S. except along the coast.

Rockingham Sand

The Rockingham Sand is a thick, relatively clean and uniform sand which contains a body of unconfined groundwater. Recharge to the formation takes place from the overlying 'superficial formations', and in the east presumably by lateral and upward leakage from the Leederville Formation (Fig. 9b).

As the formation has a substantial thickness, a very large volume of water is in storage. In No. 1 bore near the coast salt water occurs from 70 m to the base of the formation. This is overlain by low salinity groundwater which was tapped by shallow bores sunk to supply water for the drilling operation. It is inferred that the salt water is seawater beneath an interface which extends inland to between No. 1 and No. 2 bores (Fig. 11). From this evidence the groundwater flow is inferred to be toward the west with discharge taking place upward through the 'superficial formations', into the sea.

The largest volume of usable water occurs in the eastern part of the formation where it is estimated to be about 1 300 - 2 000 mg/1 T.D.S. increasing in salinity with depth. Elsewhere the formation contains brackish water overlain by a thin layer of low salinity water. Because of its lithology the formation has considerable potential for yielding large supplies of groundwater from suitably constructed bores. Unfortunately, however, most of this water is brackish.

Leederville Formation

The Leederville Formation is an interbedded sequence of sand, siltstone and shale in which the proportion of sand is 40-60 per cent. It contains unconfined groundwater where recharge occurs but where shales occur the groundwater may be confined.

Recharge to the formation is via the overlying 'superficial formations' where the Osborne Formation is absent (Fig. 9b). The Leederville Formation reaches about 200 m in thickness in No. 3 bore but to the east it thins out and to the west it is partially removed by erosion and replaced by the Rockingham Sand. Nevertheless, consideration of Figure 11 indicates that because of the thickness and extent of the formation there must be a large volume of groundwater in storage.

The apparent hydraulic gradient shown in Figure 10 indicates that groundwater movement is from east to west. The reason for the marked change in gradient in the vicinity of No. 3 site presumably results from lateral and upward groundwater discharge into the contiguous more permeable Rockingham Sand.

With the exception of a thin bed of sand in No. 2 bore (Fig. 11) all the groundwater in the formation has a salinity of less than 1 000 mg/1 T.D.S. There is no apparent pattern to the variation of salinity within the formation. This may result from the variability in salinity of the recharge from the 'superficial formations'.

Supplies of low salinity water appear to be available from this formation across the width of the coastal plain. The most prospective site appears to be immediately to the east of the subcrop of the Rockingham Sand.

Gage Sandstone Member

The Gage Sandstone Member is an interbedded sequence of sand and siltstone at the base of the South Perth Shale. It is about 27 m thick and difficult to differentiate from the underlying Cockleshell Gully and Yarragadee Formations. The member is confined beneath shale and siltstone and is in apparent hydraulic continuity with the underlying formations, with which it is grouped for the purpose of describing the aquifer systems. Nevertheless, estimated groundwater salinity in the member is usually somewhat less than the underlying formations.

Yarragadee Formation

On the Becher Point Line the Cockleshell Gully and Yarragadee Formations are faulted into juxtaposition. In the western fault block of Cockleshell Gully Formation (Fig. 9b) the salinity (Fig. 11) and hydraulic gradient (Fig. 10) appear to indicate hydraulic connection with the Yarragadee Formation. However, between the eastern fault block of Cockleshell Gully Formation and the adjoining Yarragadee Formation (Fig. 11) wide differences in salinity are evident, even though the potentiometric head appears to be consistent. Both formations could probably be considered together as a single aquifer but because the Cockleshell Gully Formation is an extensive aquifer further to the south it is discussed separately.

The Yarragadee Formation encountered on the Becher Point Line is composed predominantly of sand with minor beds of siltstone and shale.

Recharge to the formation is inferred to take place from the Leederville Formation and via the Cockleshell Gully Formation along the foot of the Darling Scarp. This is suggested in Figure 10 which shows that adjacent to the Darling Scarp where the South Perth Shale is absent there is a downward head potential from the Leederville Formation to the Cockleshell Gully Formation which is presumed to be in hydraulic connection across fault boundaries with the Yarragadee Formation. Figure 10 also shows that about 7 km west of the scarp the heads in the Yarragadee and Leederville Formations are about the same; whereas further west the head in the Yarragadee Formation is about 10 m higher. This suggests that recharge takes place along the foot of the Darling Range and to the west the South Perth Shale is an effective confining bed.

The substantial thickness of sand in the Yarragadee Formation (Fig. 11) indicates that there is a very large volume of water in storage. The maximum thickness encountered was 572 m in No. 4 bore. The apparent direction of groundwater flow (Fig. 10) is from east to west and the low hydraulic gradient indicates that the aquifer has a high transmissivity. Discharge from the formation probably takes place offshore where the South Perth Shale has been breached by erosion or by faulting.

The estimated groundwater salinity varies from about 1 500-8 000 mg/l T.D.S. Apart from small local variations (Fig. 11) the salinity in the aquifer shows a general increase with depth and towards the west, consistent with what would be expected for a westward-flowing groundwater system.

Very large supplies of groundwater ranging from 1 500 - 3 000 mg/1 T.D.S. are indicated in the Yarragadee Formation. These may have potential for industrial supplies or for desalination.

Cockleshell Gully Formation

The Cockleshell Gully Formation consists of alternating beds of sand and siltstone or shale but contains considerably less sand than the Yarragadee Formation (Fig. 11).

Recharge to the formation appears to take place adjacent to the Darling Scarp as described for the Yarragadee Formation.

In No. 5 bore the salinity in the top 300 m of the formation is estimated to range between 270 and 700 mg/1 T.D.S., after which it increases but then decreases somewhat toward the bottom of the bore (Fig. 11). The salinity in the adjacent No. 4 bore (Yarragadee Formation) shows a marked dissimilarity in the salinity pattern, the reason for which is not evident. The salinity in No. 2 bore appears slightly higher than would be expected but the estimates from this bore are not particularly good because extraneous earth currents affected the resistivity logs.

The eastern fault block of Cockleshell Gully Formation appears to contain large volumes of low salinity water in storage. This fault block does not appear to be the same as the one adjacent to the Darling Scarp near Pinjarra, noted by Commander (1974). This is composed predominantly of siltstone and contains saline groundwater.

CONCLUSIONS

The Becher Point Line of bores has provided valuable new geological and hydrogeological data in an area between two previously explored section lines to the south of Perth. Comparison with these earlier results has facilitated a stratigraphic reinterpretation.

The Warnbro Group has been shown to form the eastern limb of a very gentle syncline resting on fault blocks of the Cockleshell Gully and Yarragadee Formations. The South Perth Shale at the base of the Warnbro Group has been proven to extend southwards to Mandurah but to pinch out toward the Darling Scarp, and the overlying Leederville Formation which extends over the area appears to have been deposited under predominantly marine conditions. The Quaternary Rockingham Sand has been deposited in channels eroded to greater than 100 m below present sea level.

Groundwater occurs below the regional water table in a flow system separated into two parts, except near the Darling Range where the South Perth Shale is absent. A large volume of low salinity groundwater is available from the Cockleshell Gully Formation in a fault block of unknown size adjacent to the Darling Scarp, and from the Leederville Formation. Very large volumes of brackish water are present in the Cockleshell Gully and Yarragadee Formations beneath the plain and also from the Rockingham Sand.

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PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1977

by K. Crank

ABSTRACT

Oil exploration in Western Australia continued at about the same level as in 1976.

Eight wells were completed, compared with six in 1976; three were drilling ahead at the end of the year for a total penetration of 35 339 m, 13 168 m more than in 1976. Drilling was mainly offshore, in the Perth, Carnarvon, Browse, and Bonaparte Gulf Basins; only two onshore wells were completed, both in the Perth Basin. No major discoveries were made during the year although significant gas shows were encountered in West Australian Petroleum Pty Ltd's Warro No. 1, and in Woodside Petroleum Development Pty Ltd's Haycock No. 1. Woodside drilled a successful extension well within the North Rankin Field.

Geological activity, consisting mainly of marine seismic surveys, decreased by 30% compared with 1976. There were no land surveys. An encouraging feature was a marked increase in permits granted; 22 new permits were granted in 1977 compared with 9 in 1976, to give a total of 67 current permits, compared with 49 current at the end of 1976.

INTRODUCTION

Exploratory drilling for petroleum in Western Australia over the past two years is shown in the following table:

	Wells completed		Wells drilling on 31st December	
	1976	1977	1976	1977
New Field Wildcats	5	7	1	3
Extension Wells	0	1	1	0
Stratigraphic Tests	1	0	0	0
Total	6	8	2	3

Total effective drilling: 1976—22 171 m
1977—35 339 m*

* The aborted Scott Reef No. 1, which drilled to 310 m, and the side-tracked hole at Warro No. 1, are not included in these tabulations.

Only one successful well, North Rankin No. 5, an extension well within North Rankin Field, was drilled in 1977.

Geophysical survey activity for 1977 is shown below (with 1976 figures in brackets). No geological surveys were reported.

Type of Survey	Line km		Party months or geological months
Land seismic	Nil	(443)	....
Marine seismic	5 994*	(8 599)	....
Magnetic	579	(490)	....
Gravity marine	147	(108)	....
Geological	....	....	Nil (3·0)

* This does not include 2 384 km of marine seismic conducted outside permit areas by Geophysical Services International which was classed as a "Scientific Investigation".

PETROLEUM TENEMENTS

A summary of the status of petroleum tenements is given in the following table:

	1976		1977	
	Offshore	Onshore	Offshore	Onshore
Permits current at 31 Dec.	20	29	34	33
Production licenses	....	2	....	2
Permits surrendered or cancelled	....	2	3	5
Permits partially relinquished	....	8	....	1
Permits—surrender pending	1	2	1	6
New permits granted	2	7	15	7
Permit applications under consideration at 31 Dec.	15	3	7	5
Production licenses under application	1	....	6	....

Petroleum tenements current on December 31st, 1977 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 Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-13-P R1 Part 1 R1 Part 2	110, 84 } 194	29/8/79	West Australian Petroleum Pty. Ltd.
WA-14-P R1 Part 1 R1 Part 2	77, 121 } 198	29/8/79	West Australian Petroleum Pty. Ltd.
WA-16-P R1	40	16/4/80	Arco Aust. Ltd.
WA-18-P R1	105	16/4/80	Arco Aust. Ltd., Australian Aquitaine Petroleum Pty. Ltd.
WA-19-P* R1	49	20/3/80	Alliance Oil Development Aust. N.L.

* Surrender pending.

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
WA-23-P R1	199	3/10/79	West Australian Petroleum Pty. Ltd.
WA-24-P R1	104	17/10/79	West Australian Petroleum Pty. Ltd.
WA-25-P R1	128	16/10/79	West Australian Petroleum Pty. Ltd
WA-28-P R1 Part 1 R1 Part 2	52, 126 } 178	24/3/80	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-29-P R1 Part 1 R1 Part 2	36, 84 } 120	18/5/80	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-32-P R1	100	2/7/80	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-33-P R1	194	18/5/80	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-34-P R1	149	2/7/80	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-35-P	123	2/7/80	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
WA-36-P R1	18	18/5/80	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Shell Development (Aust.) Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd.
WA-37-P R1	59	2/6/80	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Shell Development (Aust.) Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd.
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	7/3/83	Oxoco-International Inc., Mid-American Oil Co., Peyto Oils Ltd., Voyager Petroleums Ltd., Australian Oil & Gas Corp. Ltd., Bridge Oil Ltd., Endeavour Oil Co. N.L., A.A.R. Ltd., Offshore Oil N.L.
WA-64-P	22	28/2/83	Offshore Oil N.L., Southern Cross Exploration N.L., Hallmark Minerals N.L.
WA-68-P	249	7/3/83	Oxoco-International Inc., Mid-American Oil Co., Peyto Oils Ltd., Voyager Petroleums Ltd., Bridge Oil Ltd.
WA-70-P	251	12/4/83	Getty Oil Development Co. Ltd., Union Texas Aust. Inc.
WA-74-P	253	24/6/83	Pelsart Oil N.L.
WA-77-P	254	1/8/83	Magnet Metals Ltd., Jeerinah Mining Pty. Ltd., Sundance Resources (Cayman) Ltd., Crux (International) Ltd., Scorpio Petroleum Ltd., Pluto Petroleum Ltd.
WA-79-P	235	1/8/83	Getty Oil Development Co. Ltd., Hematite Petroleum Pty. Ltd., The Shell Co. of Aust. Ltd., Continental Oil Co. of Aust. Ltd.
WA-80-P	16	6/10/83	Otter Exploration N.L., Target Petroleum N.L., Endeavour Oil Co. N.L., Timor Oil Ltd., Spargo's Exploration N.L. Alkane Exploration (Terrigal N.L.
WA-81-P	249	13/10/83	Continental Oil Co. of Aust. Ltd., General Crude Oil Co., International Ltd.
WA-83-P	233	Appn.	Oxoco-International Inc.

PETROLEUM TENEMENTS UNDER THE PETROLEUM (SUBMERGED LANDS) ACT 1967—*continued*

Exploration Permits—continued

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
WA-84-P	400	18/11/83	Mobil Oil Aust. Ltd., Phillips Aust. Oil. Co., Australian Gulf Oil Co., M.I.M. Investments Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd.
WA-90-P	400	18/11/83	Woodside Petroleum Development Pty. Ltd., Woodside Oil Ltd., Mid-Eastern Oil Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co., The Shell Co. of Aust. Ltd., Hematite Petroleum Pty. Ltd.
WA-93-P	400	18/11/83	Hudbay Oil (Aust.) Ltd., Canadian Superior Oil International Ltd., Pan Canadian Petroleum Ltd., Australian Oil and Gas Corp. Ltd.
WA-96-P	400	18/11/83	Esso Exploration and Production Aust. Inc., Hematite Petroleum Pty. Ltd.
WA-97-P	400	18/11/83	Esso Exploration and Production Aust. Inc., Hematite Petroleum Pty. Ltd.
WA-102-P	234	Appn.	Canada North West Land Ltd., Star Oil & Gas Ltd., Oakwood Petroleums Ltd., Cultus Pacific N.L.
WA-103-P	247	29/12/83	Natomas of West. Aust. Inc., Wainoco International Inc., Bonaparte Petroleum Ltd., Petro Energy Ltd., Lennard Oil N.L., White Pine Mining Pty. Ltd.
WA-104-P	242	Appn.	Oberon Oil Pty. Ltd.
WA-105-P	44	Appn.	Agha-Jahri Exploration Co., North West Mining N.L., North West Mining (Petroleum) Pty. Ltd.
WA-106-P	14	Appn.	Agha-Jahri Exploration Co., North West Mining N.L., North West Mining (Petroleum) Pty. Ltd.
WA-107-P	15	Appn.	Agha-Jahri Exploration Co., North West Mining N.L., North West Mining (Petroleum) Pty. Ltd.
WA-108-P	242	Appn.	Metro Industries Ltd., Pluranpe Pty. Ltd., Westwools Holdings Ltd., Westwools Exploration Ltd., Lennard Oil N.L., Malita Exploration Pty. Ltd.

Production Licences

WA-1-L WA-2-L WA-3-L WA-4-L WA-5-L WA-6-L	5 4 5 4 5 4	Appn. Appn. Appn. Appn. Appn. Appn.	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.

* Surrender pending.

PETROLEUM TENEMENTS UNDER THE PETROLEUM ACT 1936

Petroleum Leases

Number	Area (km²)	Expiry date of current term	Holders
1H	259	9/2/88	West Australian Petroleum Pty. Ltd.
2H	259	9/2/88	West Australian Petroleum Pty. Ltd.

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	West Australian Petroleum Pty. Ltd.
EP 13* R1	23	27/8/80	West Australian Petroleum Pty. Ltd.
EP 19* R1	18	27/8/80	West Australian Petroleum Pty. Ltd.
EP 21 R1	32	26/7/80	West Australian Petroleum Pty. Ltd.
EP 23 R1	33	6/8/80	West Australian Petroleum Pty. Ltd.
EP 24 R1 Part 1 R1 Part 2 R1 Part 3	39 24 } 85 22	6/8/80	West Australian Petroleum Pty. Ltd.
EP 25 R1	36	6/8/80	West Australian Petroleum Pty. Ltd.
EP 35 R1	1	15/4/81	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
EP 36	1	15/4/81	Woodside Oil Ltd., Woodside Petroleum Development Pty. Ltd., Mid-Eastern Oil Ltd., North West Shelf Development Pty. Ltd., B.P. Petroleum Development Aust. Pty. Ltd., California Asiatic Oil Co.
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	West Australian Petroleum Pty. Ltd.
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., Canadian Superior Oil (Aust.) Pty. Ltd., Australian Superior Oil Co. Ltd.
EP 58 R1	150	20/7/81	A.A.R. Ltd., Australian Aquitaine Petroleum Pty. Ltd., Abrolhos Oil and Investments Ltd., Flinders Petroleum N.L., Longreach Oil Ltd., Pursuit Oil N.L.
EP 59 R1	139	18/7/81	A.A.R. Ltd., Australian Aquitaine Petroleum Pty. Ltd., Abrolhos Oil and Investments Ltd., Flinders Petroleum N.L., Longreach Oil Ltd., Pursuit Oil N.L.
EP 60	2	Appn.	West Australian Petroleum Pty. Ltd.
EP 61 .... R1	4	19/9/81	West Australian Petroleum Pty. Ltd.
EP 62 R1	8	19/9/81	West Australian Petroleum Pty. Ltd.
EP 63 R1	4	19/9/81	West Australian Petroleum Pty. Ltd.
EP 64	1	Appn.	West Australian Petroleum Pty. Ltd.
EP 65 R1	2	19/9/81	West Australian Petroleum Pty. Ltd.
EP 66 R1	1	19/9/81	West Australian Petroleum Pty. Ltd.
EP 88	1	18/6/81	Esso Exploration & Production Aust. Inc., Western Mining Corp. Ltd.
EP 89	2	18/6/81	Esso Exploration & Production Aust. Inc., Western Mining Corp. Ltd.
EP 90	4	18/6/81	Esso Exploration & Production Aust. Inc., Western Mining Corp. Ltd.
EP 91	7	18/6/81	Esso Exploration & Production Aust. Inc., Western Mining Corp. Ltd.
EP 96	3	3/11/81	X.L.X. 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 100	163	3/10/82	Agha-Jahri Exploration Co., North West Mining N.L., Landshire Investments Pty. Ltd., J. M. Goldberg, Wise Nominees Pty. Ltd., R.W.W. Pty. Ltd., Cladium Mining Pty. Ltd., A. R. Burns, V. W. Burns, D. R. Gascoine, J. Gascoine, B. C. Forster, Exploration Geophysics Pty. Ltd.
EP 101	172	24/6/82	Whitestone Petroleum Aust. Ltd., Amax Iron Ore Corp., Pennzoil Producing Aust. Ltd., Australian Consolidated Minerals Ltd.

* Surrender pending.

PETROLEUM TENEMENTS UNDER THE PETROLEUM ACT 1967—*continued*

Exploration Permits—continued

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
EP 102	200	24/6/82	Whitestone Petroleum Aust. Ltd., Amax Iron Ore Corp., Pennzoil Producing Aust. Ltd., Australian Consolidated Minerals Ltd.
EP 103	184	22/8/82	Whitestone Petroleum Aust. Ltd.
EP 104	199	31/8/82	Esso Exploration & Production Aust. Inc.
EP 105	4	29/11/82	Colgas Inc.
EP 106	1	Appn.	Oberon Oil Pty. Ltd.
EP 107	146	Appn.	Era South Pacific Pty. Ltd., Era West. Aust. Inc., E.S.P. Explorations Pty. Ltd., Cambridge Royalty Co., Cambridge Petroleum Royalty Ltd. *et al*
EP 108	193	29/12/82	Houston Oil & Minerals Aust. Inc.
EP 109	1	Appn.	Metro Industries Ltd., Pluranpe Pty. Ltd., Westwools Holdings Ltd., Westwools Exploration Ltd., Lennard Oil N.L., Malita Exploration Pty. Ltd.

Production Licences

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

PETROLEUM TENEMENTS UNDER THE PETROLEUM PIPELINES ACT 1969

Pipeline Licences

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 exploration during 1977 are shown in Figure 13. Details relating to wells drilled during the year are given in Table 6. All petroleum exploration wells drilled in Western Australia up to the end of 1977 are listed in the Geological Survey Record 1978/1 (Crank, 1978). A summary of the principal results of drilling in each basin during the year is as follows:

PERTH BASIN

One offshore and two onshore wells were completed during the year, and one was drilling ahead (Warro No. 2) on December 31st. Peel No. 1 was located on a culmination on the Peel Arch 30 km southwest of Fremantle, and was drilled by Phillips Australian Oil Company under a farmout agreement with WAPET. No shows of oil or gas were encountered, and the well was abandoned as a dry hole at a total depth of 3 714 m.

WAPET completed Denison No. 1 which was commenced in 1976. This well, located in a fault block to the west of Dongara Gas Field, was drilled to a total depth of 2 300 m. No shows were encountered, and it was plugged and abandoned as a dry hole.

WAPET's Warro No. 1 was drilled on the Warro Anticline on the east flank of the northern part of the Dandaragan Trough. The original hole had to be abandoned at a total depth of 4 435 m because of mechanical difficulties after several gas shows. A sidetrack hole was drilled from 3 356 m to a total depth of 4 385 m, but this had to be plugged and abandoned after encountering high pressure shales. Four separate zones were tested in this well, but the results were inconclusive because of apparent formation damage and communication across perforations. A second well is to be drilled in 1978.

CARNARVON BASIN

One exploration well, Haycock No. 1, and one extension well, North Rankin No. 5, were completed by Woodside in the Carnarvon Basin in 1977 (Fig. 14). Haycock No. 1 was drilled on a north-trending fault block on the northwest margin of the Kendrew Depression adjacent to the Rankin Platform. The well was drilled to a total depth of 3 668 m and, although, some gas pay was encountered between 3 232 and 3 359 m, the well was abandoned as non-commercial.

North Rankin No. 5 was successfully completed as an extension gas well within the North Rankin Gas Field.

WAPET completed one well, Hermite No. 1, and was drilling another, Bundegi No. 1, at the end of 1977. Hermite No. 1, 100 km west of Dampier, was drilled on an anticlinal closure, on the downthrown side of the Flinders Fault System in the Barrow Sub-basin. Only minor gas and oil shows were encountered, and the well was abandoned as a dry hole at a total depth of 3 300 m.

Bundegi No. 1, a new field wildcat in the Exmouth Gulf, was drilling ahead at the end of the year.

BROWSE BASIN

One well Scott Reef No. 2A was completed by Woodside in the Browse Basin; it was drilled downdip on the same closure as No. 1, the gas-condensate discovery well which was completed in 1971. Some gas was encountered, but the well was abandoned as a dry hole. Scott Reef No. 2 was abandoned at 310 m because of mechanical problems.

At the end of 1977, Woodside was also drilling Caswell No. 1, 70 km southeast of Scott Reef.

BONAPARTE GULF BASIN

Arco Australia Ltd completed one well in the offshore Bonaparte Gulf Basin in 1977. Plover No. 3, 30 km southwest of Plover No. 1, was a stratigraphic trap play in the Jurassic. No shows were encountered and the well was plugged and abandoned at a total depth of 1 219 m in the Lower Triassic.

GEOPHYSICAL SURVEYS

SEISMIC

During 1977 seismic surveys were conducted in the offshore Perth, Carnarvon, Canning and Browse Basins. There were no land surveys. Details are as follows:

SEISMIC SURVEYS

Basin	Tenement	Company	Line km
Perth	WA–13–P	West Australian Petroleum Pty. Ltd.	400
	WA–14–P	West Australian Petroleum Pty. Ltd.	85
Carnarvon/ Perth	WA–59–P	Esso Exploration and Production Inc.	465
Carnarvon	WA–1–P	Woodside Petroleum Development Pty. Ltd.	86
	WA–28–P	Woodside Petroleum Development Pty. Ltd.	1 704
	WA–24–P	West Australian Petroleum Pty. Ltd.	17
	WA–25–P	West Australian Petroleum Pty. Ltd.	639
	WA–24–P	Wapet (Continental Oil Co. of Aust. Ltd.—farminee)	571
	WA–58–P	Western Energy Pty. Ltd.	180
Canning	WA–29–P	Woodside (Amax Petroleum (Aust.) Inc.—farminee)	428
Browse	WA–34–P	Woodside Petroleum Development Pty. Ltd.	94
	WA–35–P	Woodside Petroleum Development Pty. Ltd.	715
	WA–37–P	Woodside Petroleum Development Pty. Ltd.	177
Outside Permit areas	....	Woodside Petroleum Development Pty. Ltd.	411
	....	West Australian Petroleum Pty. Ltd.	22
		Total	5 994

GRAVITY

A gravity survey carried out in conjunction with an offshore seismic survey in the Browse Basin was as follows:

GRAVITY SURVEYS

Basin	Tenement	Company	Line km
Browse	WA–35–P	Woodside Petroleum Development Pty. Ltd.	147

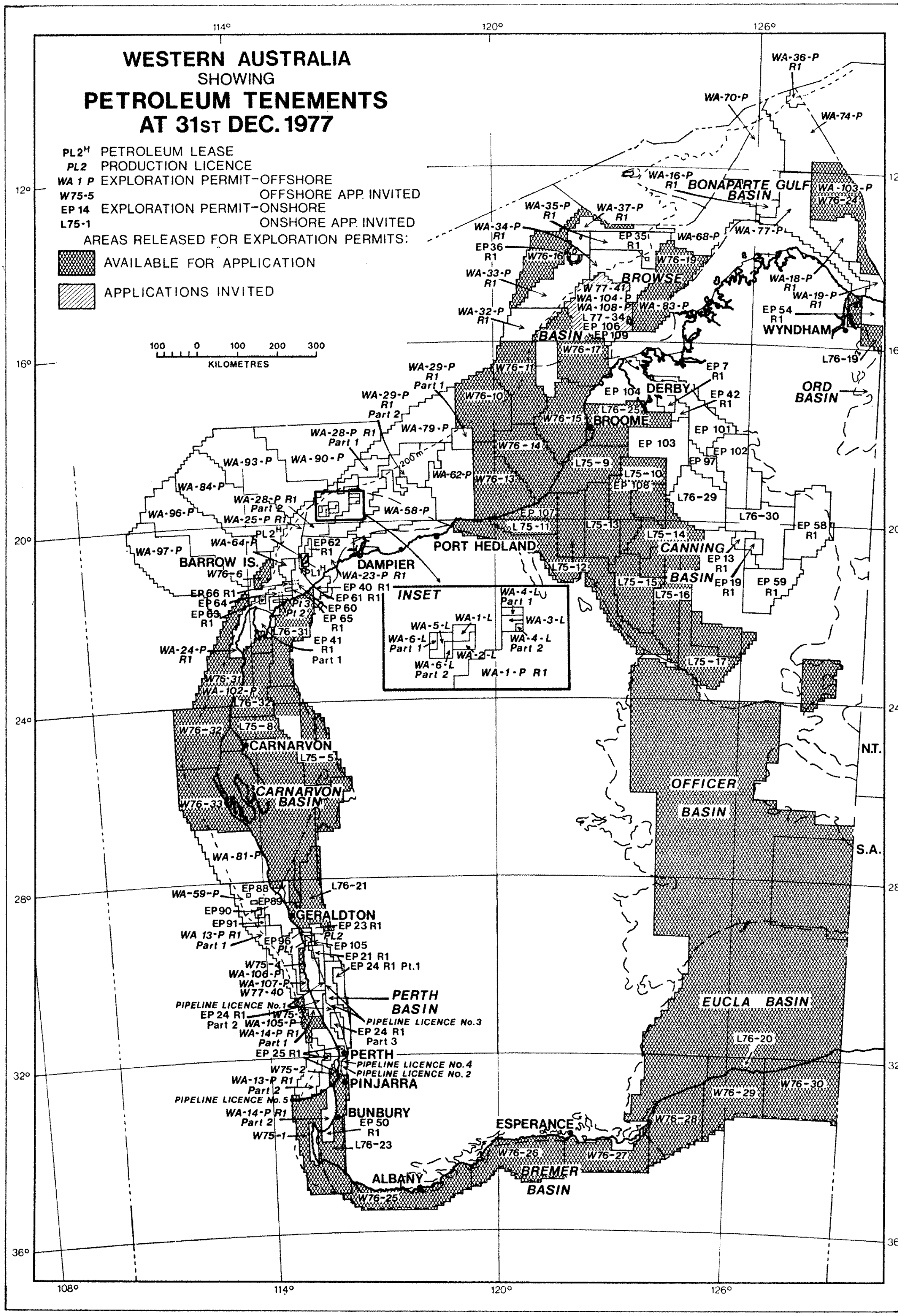


Figure 12 Petroleum tenements at 31st December 1977

GSWA 17115

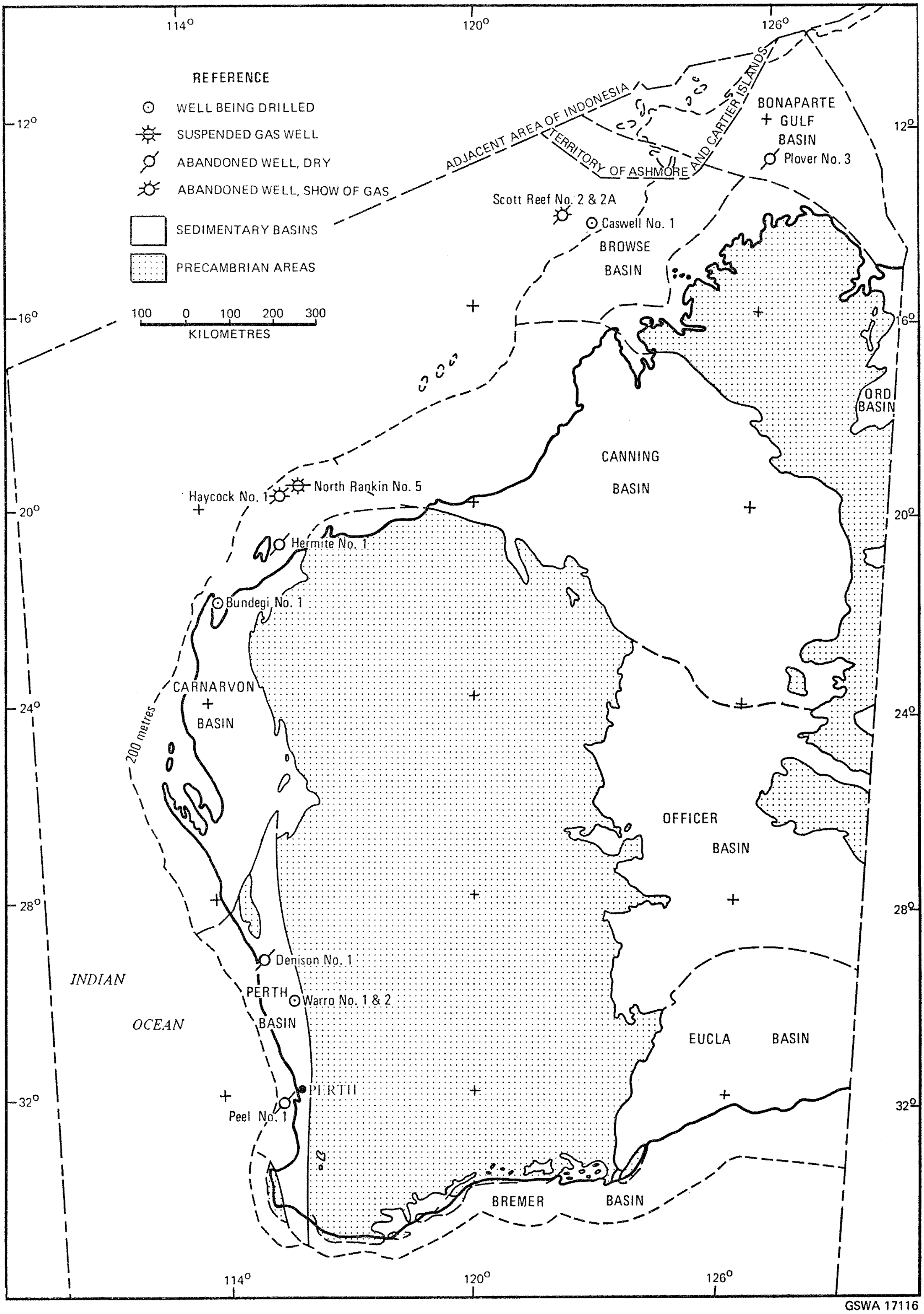
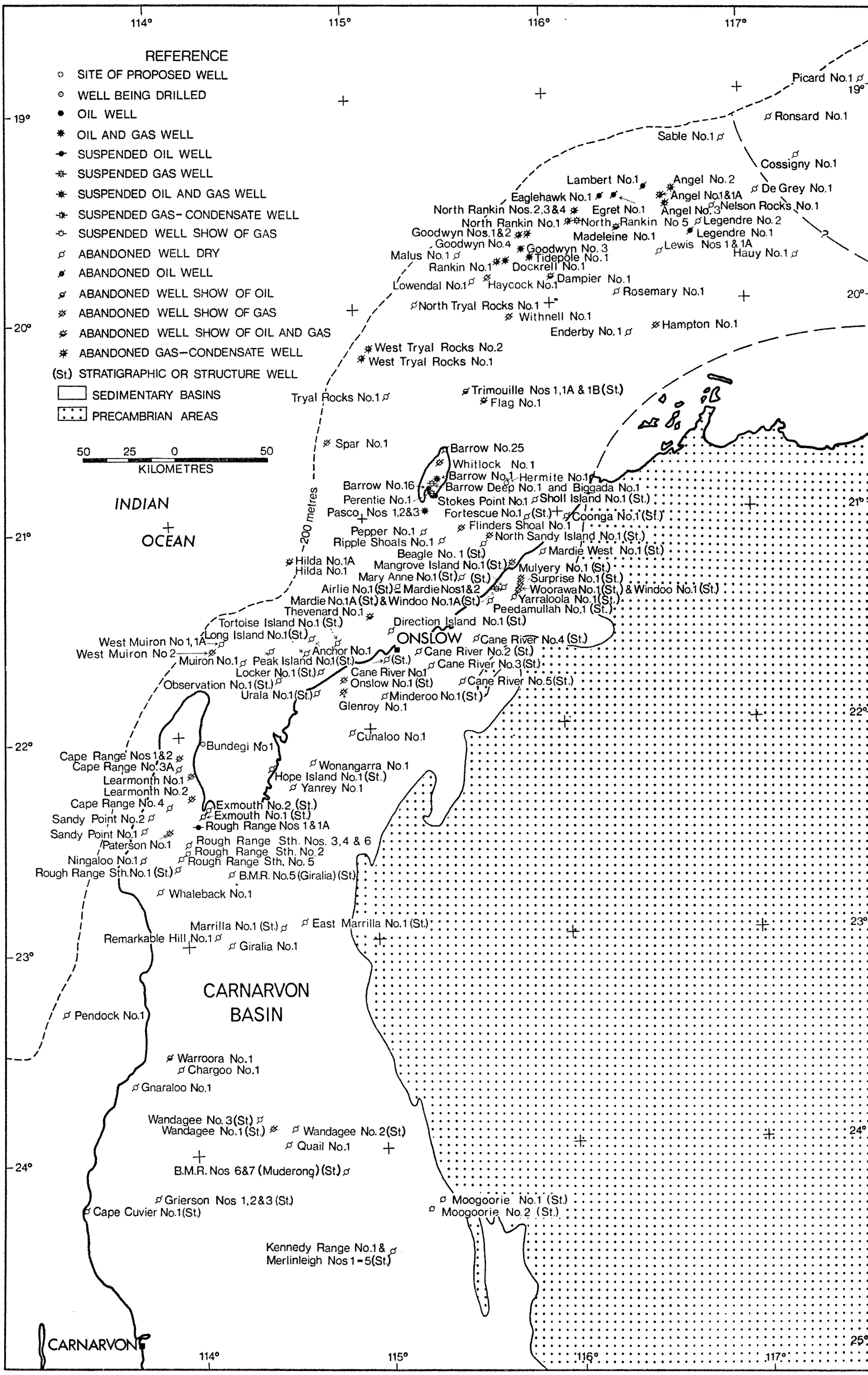


Figure 13 Wells drilled for petroleum in WA during 1977

3—74499



GSWA 17117

Figure 14 Northern Carnarvon and southwestern Canning Basin showing wells drilled for petroleum to 31st December 1977

TABLE 6. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1977

Basin	Well	Concession	Operating company	Type	Position: Latitude south ° ′ ″	Position: Longitude east ° ′ ″	Elevation and water depth (metres): G.L.	R.T.	W.D.	Dates: Commenced	Reached T.D.	Rig released	Total depth (or depth reached) m	Bottomed in	Status on 31/12/77
Carnarvon	North Rankin No. 5	WA-28-P	Woodside	EXT	19 34 19	116 09 30	....	30	123	8/10/76	9/2/77	23/4/77	3 500	U. Triassic	Gas cond. well, p & a
	Haycock No. 1	WA-28-P	Woodside	NFW	19 50 58	115 43 17	....	8	85	1/2/77	7/4/77	15/4/77	3 668	U. Triassic	Gas shows, p & a
	Hermite No. 1	WA-23-P	WAPET	NFW	20 49 58	115 42 08	....	27	16	15/9/77	24/11/77	29/11/77	3 300	U. Triassic	Dry, p & a
	Bundegi No. 1	EP 41	WAPET	NFW	22 01 06	114 09 33	....	32	16	4/12/77	....	....	2 217	....	Drilling
Perth	Denison No. 1	PL 2	WAPET	NFW	29 13 32	114 57 17	<7	35	....	23/12/76	18/1/77	21/1/77	2 300	?Silurian	Dry, p & a
	Warro No. 1	EP 24	WAPET	NFW	30 10 06	115 44 11	291	299	....	27/2/77	3/7/77	11/9/77	4 435	M. Jurassic	Gas shows, p & a
	Peel No. 1	WA-14-P	Phillips	NFW	32 15 48	115 26 43	....	30	42	7/10/77	2/12/77	10/12/77	3 714	U. Jurassic	Dry, p & a
	Warro No. 2	EP 24	WAPET	NFW	30 10 05	115 44 03	291	299	....	12/11/77	....	....	3 907	....	Drilling
Browse	Scott Reef No. 2	WA-33-P	Woodside	NFW	14 06 04	121 51 27	....	8	55	18/4/77	25/4/77	27/4/77	310	....	Mechanical problems p & a
	Scott Reef No. 2A	WA-33-P	Woodside	NFW	14 06 06	121 51 28	....	8	55	27/4/77	1/8/77	9/8/77	4 820	L. Jurassic	Gas shows, p & a
	Caswell No. 1	WA-34-P	Woodside	NFW	14 14 29	122 28 04	....	8	345	16/8/77	....	....	4 042	....	Drilling
Bonaparte	Plover No. 3	WA-16-P	ARCO	NFW	12 49 05	126 06 57	....	21	75	13/12/77	25/12/77	....	1 219	L. Triassic	Dry, p & a

Woodside = Woodside Petroleum Development Pty. Ltd.
WAPET = West Australian Petroleum Pty. Ltd.
Phillips = Phillips Australian Oil Co.
Arco = Arco Australia Ltd.
EXT = Extension test well
NFW = New field wildcat well
p & a = plugged and abandoned

MAGNETOMETER

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

MAGNETOMETER SURVEYS

Basin	Tenement	Company	Line km
Carnarvon	WA-1-P	Woodside Petroleum Development Pty. Ltd.	85
	WA-28-P	Woodside Petroleum Development Pty. Ltd.	347
Browse	WA-35-P	Woodside Petroleum Development Pty. Ltd.	147
		Total	579

GEOLOGICAL SURVEYS

No geological surveys were carried out by exploration companies in 1977.

REFERENCES

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CRETACEOUS STRATIGRAPHY AND SEDIMENTOLOGY, NORTHEASTERN MARGIN OF THE CARNARVON BASIN, WESTERN AUSTRALIA

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

ABSTRACT

Sediments deposited by a major Early Cretaceous transgression are divisible into three facies groups along the northeastern margin of the Carnarvon Basin. In the present-day Kennedy Range area, low sediment-supply rates combined with high erosion produced a transgressive shallow-marine sequence (Winning Group) in which all basal lagoonal deposits were reworked. In the present-day Robe River area, sediment supply relative to coastal erosion was high enough to form a prograding delta (Nanutarra Formation and Yarraloola Conglomerate). In the present-day Ashburton River area, sediment-supply rates were only moderate, but lagoonal and fluviatile deposits were protected by a long, discontinuous offshore barrier of Precambrian rock. This, combined with irregular basement relief behind the barrier, produced a local sequence (Nanutarra Formation) with complexly varying, shallow-marine to fluviatile facies. Correlatives of the open-basin Winning Group can be traced through the Nanutarra Formation, in a less-mature form.

INTRODUCTION

In the Carnarvon Basin, the Early Cretaceous transgression produced a shallow-marine, laterally persistent, simple layered sequence called the Winning Group. In the central and northern parts of the basin, this consists of, in ascending order, the Birdrong Sandstone, Muderong Shale, Windalia Radiolarite and Gearle Siltstone. However, near the basin margin in the Yanrey and Yarraloola Sheet areas (Fig. 15, inset), this sequence grades laterally into a much coarser grained and less-mature, siliciclastic sequence mapped as Yarraloola Conglomerate and Nanutarra Formation. The lithology of these units is described by Playford and others (1975) and van de Graaff and others (1977). Depositional environments in the marginal sequence range from open marine to fluviatile, and the sequence is characterized by rapid lateral and vertical facies changes. The facies distribution presents several stratigraphic and sedimentological problems which are of practical significance, as the principal study area (Fig. 15) has been a major target for uranium exploration. The understanding of depositional environments in these sediments is therefore economically important, as facies changes could be expected to influence any possible uranium mineralization.

The Cretaceous sequences in the Kennedy Range, Ashburton River and Robe River areas (Fig. 15, inset) are compared, using facies interpretations and the relationships of the various stratigraphic units. These sequences are compared to the models of sedimentation along a drowning coast described by Fischer (1961) and Swift (1975) and shown in Figure 16. Figure 16a shows the theoretical arrangement of facies across a drowning coast. Depending on the balance between erosion and sedimentation, very different facies sequences are formed as sea level rises. If deposition predominates (Fig. 16b) a *depositional regressive* sequence forms under transgressive conditions. In this situation, the dune and beach barrier sands function both as protection for landward fluviatile, lagoonal, and swamp deposits (hereafter called 'coastal deposits'), and as a sediment dump. They migrate seawards and coastal deposits are preserved behind and beneath them. Under conditions of net coastal erosion, the sea advances and a *depositional transgressive* sequence forms, with partial or total destruction of coastal deposits (Fig. 16c and 16d). In the first case a *coarsening upwards* sequence (Oomkens, 1967) is preserved, whereas in the second, a *fining upwards* sequence (Allen, 1965) is preserved.

In this paper we demonstrate that, north of the Yannarie River, coastal erosion during deposition of the Nanutarra Formation was insufficient to destroy coastal deposits, and significant progradation of the coast occurred during the later stages of the transgression. In areas where the Winning Group is typically developed, erosion destroyed all coastal deposits. Correlatives of the Birdrong Sandstone, Muderong Shale and Windalia Radiolarite can be traced within most sections of the Nanutarra Formation, but they reflect shallower conditions nearer to the shore than the sequence in the Kennedy Range area.

SECTION ANALYSIS AND CORRELATION

Two groups of sections, in sequences ranging from open marine to fluviatile, have been used to test the validity of the models proposed for the Lower Cretaceous by Fischer (1961) and Swift (1975). The first group (Fig. 17) forms a roughly east-west line through the various facies-realms in the Ashburton area of the Yanrey Sheet (Fig. 15), and illustrates the transition from the simply layered Winning Group sedimentation to the complexly varying Nanutarra Formation. In this area, sediments are preserved in isolated mesas but because they are flat-lying, altimetric data from the Division of National Mapping 1:100 000 compilations can be used where needed to support correlations between sections up to 8 km apart. The second group of sections (Fig. 18) forms a roughly north-south line. It includes, for comparison with Nanutarra Formation sections, the Birdrong Sandstone type section in the Kennedy Range, and a section near the Yarraloola Conglomerate type section in the Robe River area.

EAST-WEST PROFILE

Sections 1 and 2 are essentially open-basin transgressive sequences, except that in Section 1 the Birdrong Sandstone is replaced by the less mature Nanutarra Formation. This fines upwards, with waning terrigenous supply, into Muderong Shale, which is in turn overlain by Windalia Radiolarite. Section 2 illustrates the pronounced relief on the Cretaceous unconformity, in that only the Windalia Radiolarite and the upper facies of the Muderong Shale are present, resting directly on Precambrian bedrock.

Section 3, on the western edge of a large area of granitic bedrock, also demonstrates basement relief. Clean, well-sorted, medium-grained to pebbly Birdrong

Sandstone abuts granite tors and is interpreted as a probable littoral bar, whereas 200 m west at the same level, white siltstone of the Windalia Radiolarite crops out. No Muderong Shale is exposed, and the siltstone coarsens upwards into immature silty to pebbly sandstone identical with the upper Nanutarra Formation further east. This sandstone is replaced in Section 4 by the Peepingee Greensand Member of the Nanutarra Formation, which overlies Windalia Radiolarite and pebbly, immature, Nanutarra Formation, possibly of fluviatile origin, with a minor disconformity. Hoelscher and McKellar (McWhae and others, 1958) originally defined the 'Peepingee Greensand', and tentatively correlated it with the Alinga Formation and Gearle Siltstone. We correlate the unit with the upper part of the Nanutarra Formation (Fig. 17) and reduce it to member status. The unconformity at the base of the unit is a locally significant channel-base scour which is relatively common within the Cretaceous sequence in the Ashburton area. The coarse-grained basal layer of the Peepingee Greensand Member correlates with part of Section 5, 3.5 km to the east at the same elevation. This interval of Section 5 is a cyclic conglomeratic sequence

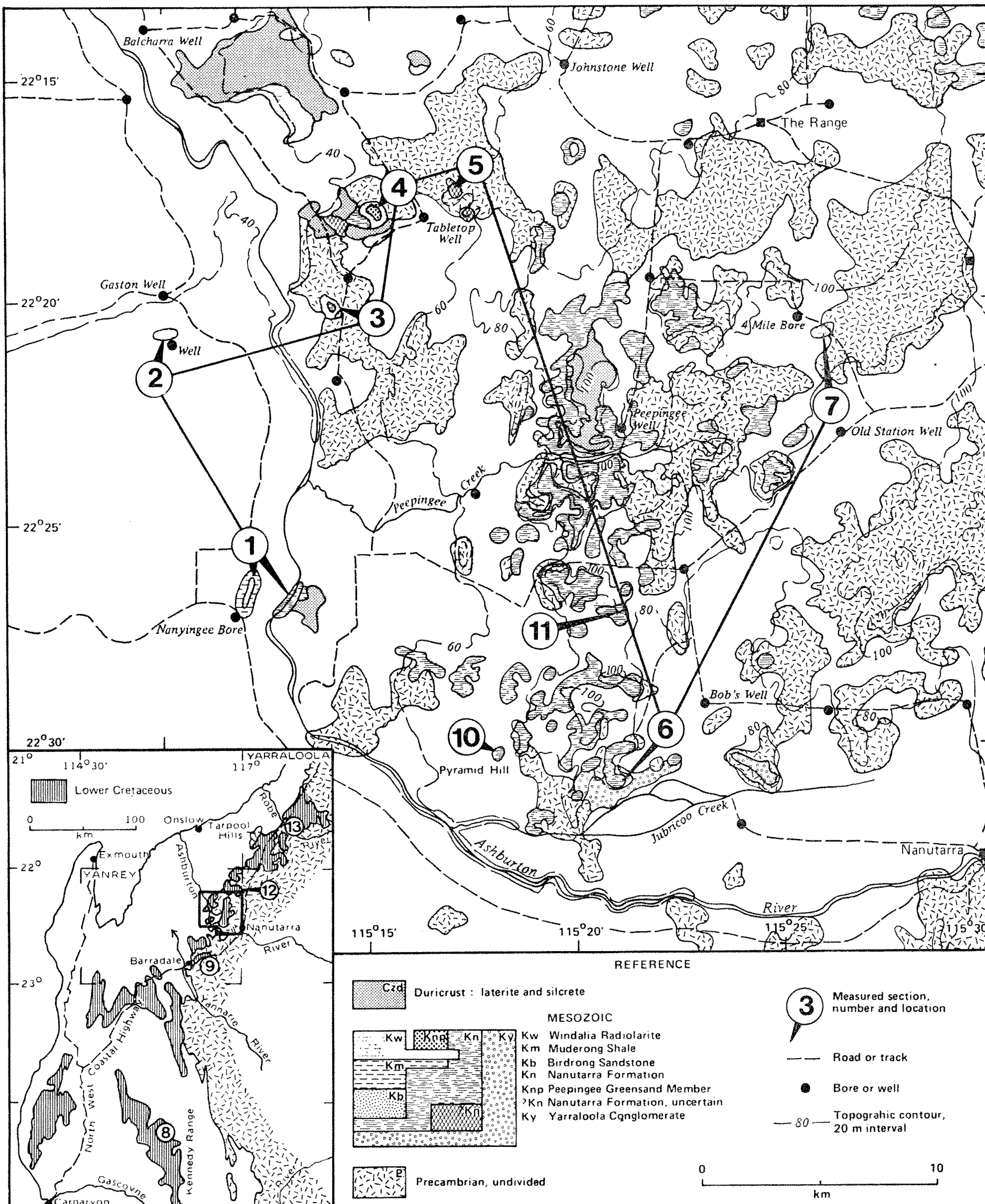

Figure 15 Distribution of Lower Cretaceous and Proterozoic units, Ashburton River area
Inset: Lower Cretaceous sediments in north-east Carnarvon Basin

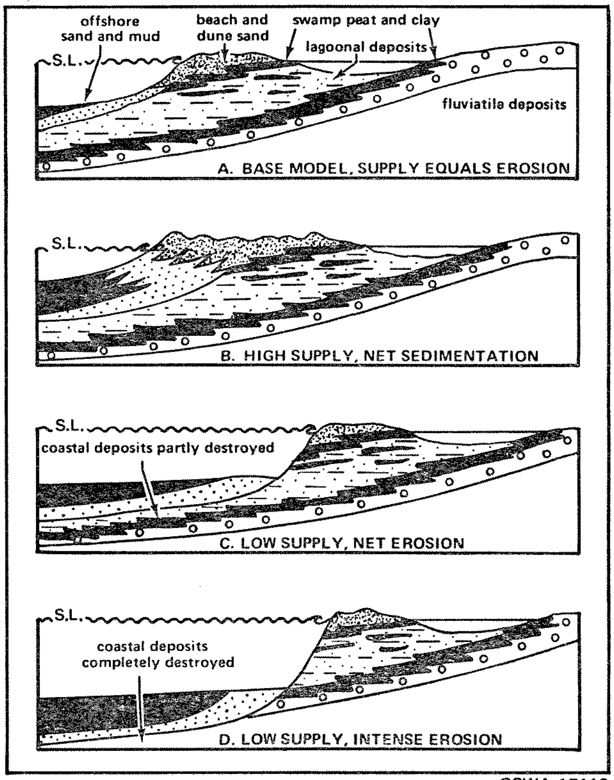

Figure 16

Coastal stratigraphic sequence developed by marine transgression, under different ratios of erosion to sediment supply. *A* and *D* modified from Fisher (1961), *B* and *C* from Swift (1975).

containing several beds, each with an erosional base, and coarse sand to granule-size matrix. The framework of each bed coarsens upwards from granule to pebble size, although the section as a whole is a fining-upwards sequence. We favour an origin by submarine shoaling, rather than fluviatile deposition.

Section 6 is the most complete section of Nanutarra Formation and Yarraloola Conglomerate. The latter is a fluviatile, valley-fill boulder conglomerate which fines upwards into cross-bedded pebbly sandstone of the Nanutarra Formation. In this area the Nanutarra Formation is divided into four units. The basal unit consists of cross-bedded, poorly sorted sandstone, with minor conglomerate and intensely burrowed siltstone. This is overlain with a sharp erosive contact by a fining-upwards sequence, consisting of large-scale, cross-bedded, moderately sorted sandstone (the second unit), grading up into finer grained, horizontally bedded siltstone, sandstone and claystone (the third unit). This grades into the fourth unit, which consists of locally burrowed coarse-grained to locally pebbly sandstone, and contains an intensely ferruginized (?originally calcareous) bed with *Panopea glaessneri,* a burrowing bivalve, in life position.

As a whole, the Nanutarra Formation in Section 6 is a lagoonal to shallow-subtidal, transgressive sequence, although the fining-upwards character is indistinct. Its four part nature and sequence of depositional environments suggests that the cross-bedded second unit correlates with the Birdrong Sandstone, and the overlying fine-grained unit with the Muderong Shale and/or Windalia Radiolarite. From this, we correlate the upper unit with the Nanutarra Formation in Section 3 and the Peepingee Greensand Member in Section 4, as it represents a change from low to medium energy conditions, and hints at depositional regression.

Five kilometres east of Section 6, conglomerate and sandstone mapped as Yarraloola Conglomerate rests on basement hills at the same elevation as the fine-grained, third unit of the Nanutarra Formation. This sequence is probably of fluviatile origin, similar to the conglomeratic fining-upwards sequences of Section 7, and illustrates both the lateral equivalence of the Nanutarra Formation and Yarraloola Conglomerate, and the proximity of much of the Nanutarra Formation to the Cretaceous shoreline.

NORTH-SOUTH PROFILE

Section 8, the Birdrong Sandstone type section, (Fig. 18) is a fining-upwards shallow-marine sequence, intensely bioturbated in the upper half, but with no body fossils preserved. No lagoonal, swamp, or fluviatile facies are present at the base of the section, indicating low sediment-supply rates and complete removal and reworking of coastal deposits by the transgression. The intensity of internal erosion and recycling is indicated by a scour 3 m deep about one third the way up the type section. In contrast, sections in the Ashburton area commonly contain coastal sediments, with local soil deposits.

In Section 9, Nanutarra Formation is exposed both at the base and the top of the section, with subtidal Birdrong Sandstone and Muderong Shale between. The basal part is of lagoonal and fluviatile origin, whereas the uppermost part is a subtidal pebbly sandstone. Similarly, in Sections 6, 10 and 11, basal fluviatile deposits are overlain firstly by lagoonal, moderately sorted, partly fine-grained deposits, then by subtidal deposits (Birdrong Sandstone and Muderong Shale/Windalia Radiolarite correlatives), and finally by coarser-grained subtidal to tidal deposits; except in Section 10 where the lagoonal facies is replaced by a thicker Birdrong Sandstone correlative.

Only the low-energy, subtidal, Muderong Shale/Windalia Radiolarite correlative, and the upper coarse-grained facies are exposed in Section 12, the Nanutarra Formation type section. The upper facies of the Nanutarra Formation results from an increase in sediment supply relative to the underlying silty facies, and probably reflects a prograding delta to the east. It is uncertain, though, whether the upper facies was deposited in the distal parts of the delta or by longshore drift from the delta.

Section 13 is located approximately 2 km east of the Yarraloola Conglomerate type section, and has at its base very fine to medium-grained silty sandstone, interpreted as Nanutarra Formation. The Yarraloola Conglomerate which overlies this consists of fining-upwards cycles from conglomerate to pebbly sandstone. The cyclic nature of this sequence, the scoured contacts, and the immaturity of the sediments suggest an origin as a delta fan with meandering channels, prograding over shallow marine Nanutarra Formation. This environment was first inferred by Williams (1968) for this area.

SYNTHESIS

Three distinct types of marginal-marine sedimentation are present in the Lower Cretaceous sequence between the Kennedy Range and the Robe River. The first of these is represented by the Winning Group at the Birdrong Sandstone type area, in the Kennedy Range. This sequence fits a model of transgressive sedimentation along a coast where erosion greatly exceeds supply (Fig. 16d, 18, inset). To the east, the Cretaceous is faulted out, and we do not know if barrier and lagoonal sediments were originally preserved.

The second type of marginal-marine sedimentation is seen in the Ashburton area, where coastal deposits are present in the Nanutarra Formation implying a high-supply model like Figure 16b, except there are no barrier-sand deposits. The absence of the barrier sands suggests lower supply rates than are implied by the extensively preserved coastal deposits. However, we consider that relief on the basal Cretaceous unconformity was of major importance in preserving these coastal deposits. On a medium to small scale, the extent of this relief is well illustrated in the Section 9 area, where the Early Cretaceous landscape is presently largely exhumed. Long, narrow Precambrian strike-ridges are still mostly higher than mesas of Cretaceous rocks and would have formed an Early Cretaceous ria coast between Nanutarra and Barradale. North of Section 11, Nanutarra Formation is present at the base of Peepingee Well, which is 20 m deep, yet less than 2 km east the Precambrian crops out more than 10 m above the top of the well. Such irregular relief would have interfered with local marine reworking processes.

On a regional scale, the western limit of the Nanutarra Formation coincides with a belt of Precambrian rocks extending discontinuously from Barradale to the Tanpool Hills. In the Cretaceous this would have been a long, offshore barrier behind which coastal sediments were protected from reworking. Because of this barrier, only a moderate sediment supply is needed to explain observed facies distributions, as distinct from the high level of sediment input required for the model of an unprotected coast. Moderate sediment supply is also suggested by the condensed nature of the Nanutarra Formation, indicated by soil development at depositional hiatuses, and the correlation of the Nanutarra Formation with the Birdrong Sandstone, Muderong Shale, and Windalia Radiolarite, which are much thicker to the west.

This correlation raises a problem of apparent age discrepancies between the upper part of the Nanutarra Formation and the Windalia Radiolarite. Brunnschweiler (1959) dated the Windalia Radiolarite as Aptian to Albian, whereas Cox (1961) and Skwarko (1967) dated the Nanutarra Formation as Neocomian to Aptian. Considering that the two units were dated by different fossil groups and in widely separated areas, we disregard this discrepancy in favour of the local field evidence.

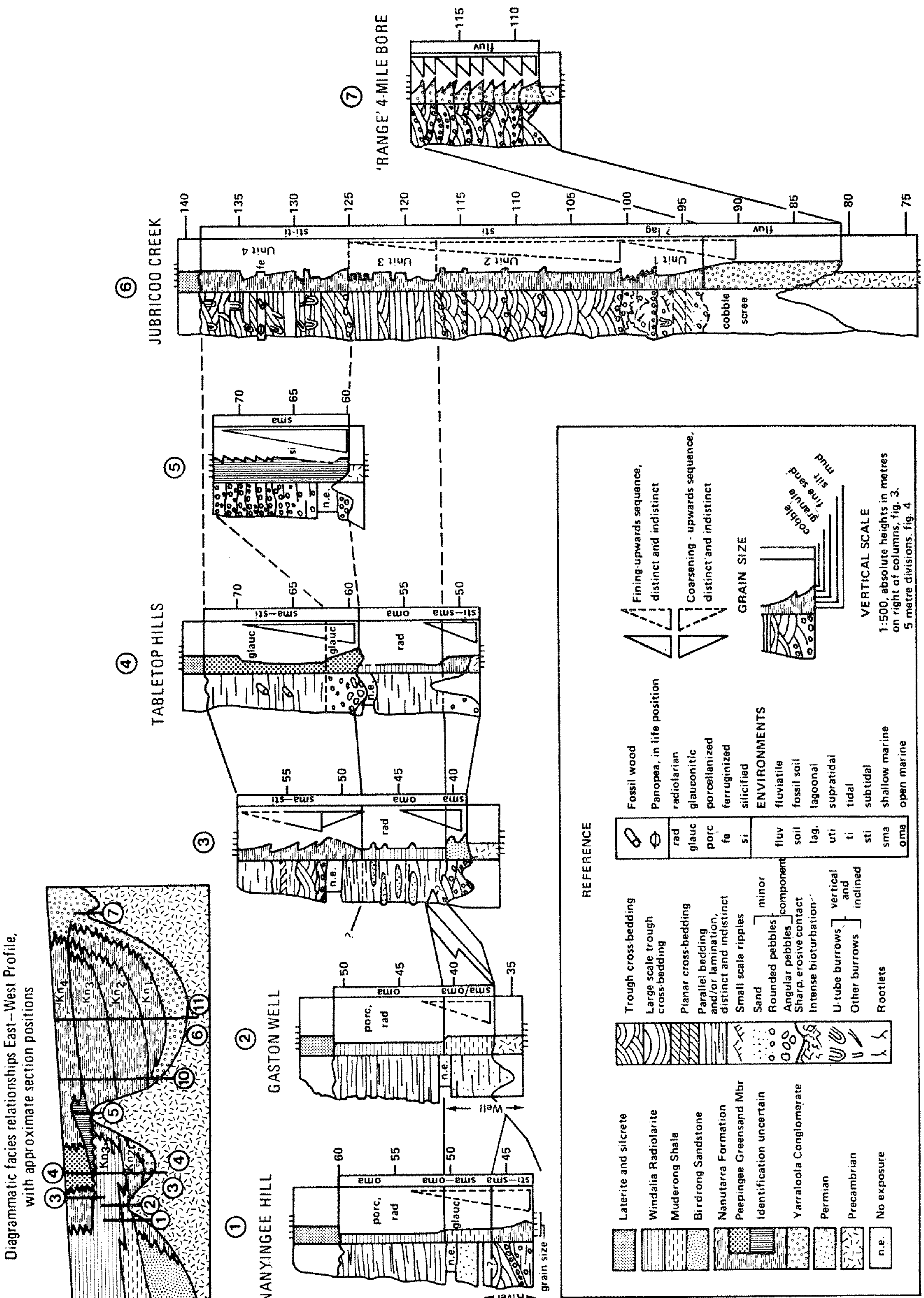

Figure 17 East-west profile and facies relationships, Ashburton River area

The third type of marginal-marine sedimentation is in the Robe River area, where the Yarraloola Conglomerate extends over the Nanutarra Formation. This is a more complete development of the trend seen in the uppermost facies of the Nanutarra Formation. Terrigenous supply increased during deposition of this sequence. In the Robe River area it greatly exceeded marine reworking and erosion of the coastal sediments, resulting in an extensive, prograding delta fan.

CONCLUSIONS

Of the three types of Lower Cretaceous marginal-marine sedimentation in the northern-central Carnarvon Basin, only the Winning Group in the Kennedy Range area fits a simple

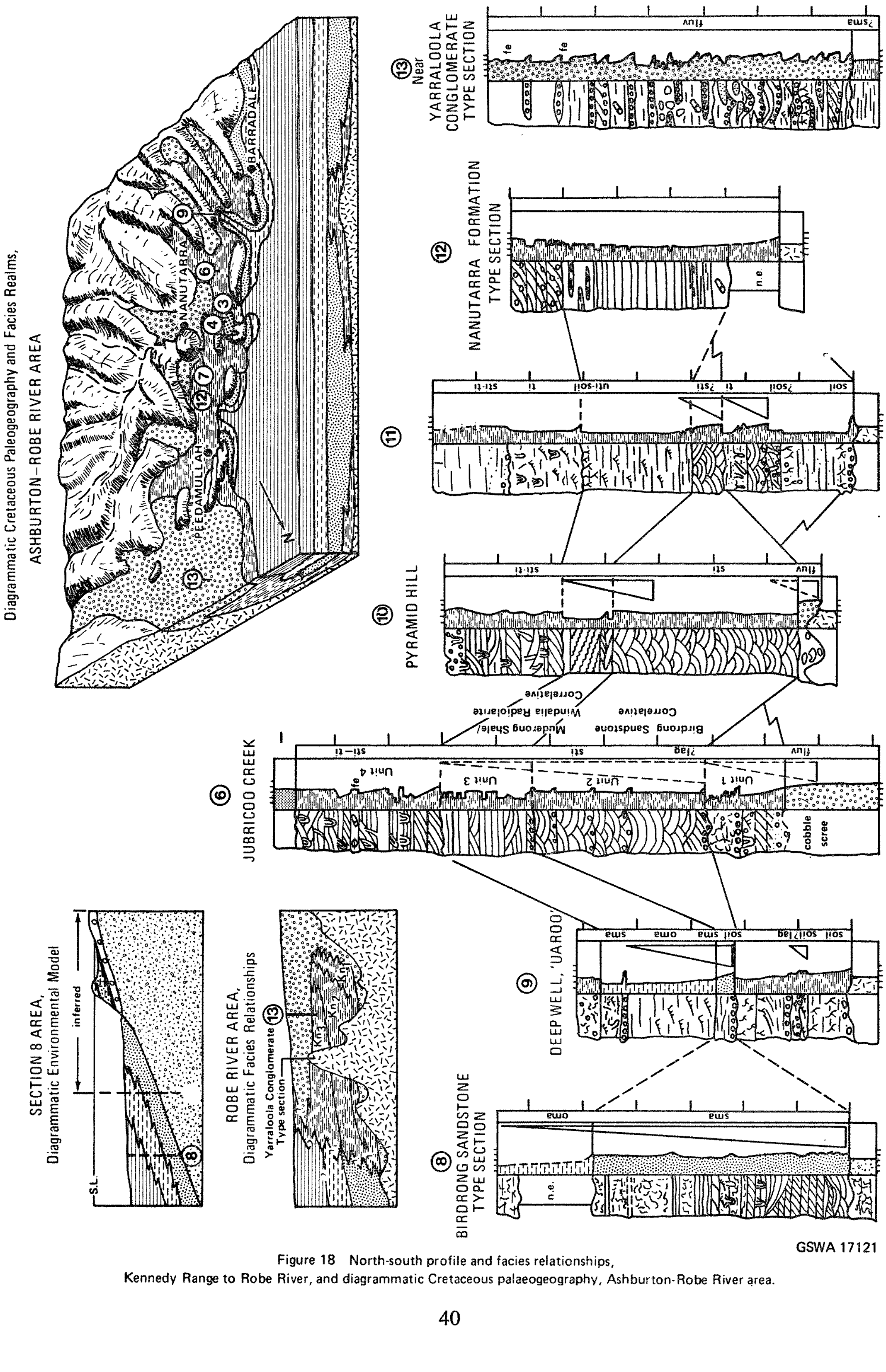

Figure 18 North-south profile and facies relationships, Kennedy Range to Robe River, and diagrammatic Cretaceous palaeogeography, Ashburton-Robe River area.

model of a drowning, low-sedimentation/high-erosion, coastline. Coastal deposits, characterized by rapid lateral and vertical facies changes in the Nanutarra Formation, are preserved mainly because of the protection given by pronounced and irregular relief on the basal Cretaceous unconformity, rather than high rates of sediment supply. In the Robe River area, supply exceeded erosion and a delta of Yarraloola Conglomerate prograded over the Nanutarra Formation.

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PALAEOCURRENT DIRECTIONS IN THE PERMIAN COLLIE COAL MEASURES, COLLIE, WESTERN AUSTRALIA

by S. A. Wilde and I. W. Walker

ABSTRACT

Foreset bedding directions in cross-bedded sandstones of the Collie Coal Measures indicate palaeo-currents from the south. This direction is consistent across the area and throughout the sequence, and suggests that the present Collie Basin is a remnant of a much larger area of sedimentation.

INTRODUCTION

Coal-bearing Permian strata lie in a northwest-trending basin at Collie (the Collie Basin), 160 km south-southeast of Perth, Western Australia (Fig. 19). The basin is 26 km long and 15 km wide and contains over 1 300 m of weakly lithified sediments. A smaller basin of similar trend occurs 36 km south of Collie at Wilga. It contains up to 365 m of Permian strata, including several coal seams; the rocks are not exposed and no mining has taken place. The only operating coal mines in Western Australia are located in the Collie Basin.

The first detailed survey of the Collie Basin was undertaken by Lord (1952). He summarized the history and development of the coalfield to 1950. Further information from a deep drilling programme, instigated by the Geological Survey of Western Australia in 1950, is contained in Low (1958).

The Permian strata of the Collie Basin consist of the Stockton Formation and the overlying Collie Coal Measures. The Stockton Formation is up to 260 m thick and rests on a glacially striated pavement of Archaean rocks. It comprises a basal tillite overlain by a sequence of mudstone, siltstone and fine-grained sandstone. The Collie Coal Measures appear to conformably overlie the Stockton Formation and are a succession of conglomerate, grit, sandstone, siltstone and shale, with intercalated seams of sub-bituminous coal. They attain a maximum thickness of at least 1 050 m. Three main periods of coal formation are recognized and each of these 'members' contains several coal seams.

The Collie Basin is divided into three units: the Cardiff, Shotts and Muja sub-Basins (Fig. 19). These are separated by basement highs covered by a thin veneer of Permian strata, except in the southeast where the basement reaches the surface between the Cardiff and Muja sub-Basins as the Stockton Ridge. Each sub-basin is asymmetric in profile, with the southwestern margin being much steeper than the northeastern one, and the greatest thickness of strata occurring close to the southwestern boundary. A correlation of the various coal-bearing 'members' between the sub-basins is presented in Table 7 (based on Playford and others, 1975).

TABLE 7. CORRELATION OF COAL-BEARING MEMBERS OF THE COLLIE COAL MEASURES.

		CARDIFF SUB-BASIN	SHOTTS SUB-BASIN	MUJA SUB-BASIN
PERMIAN Upper	Collie Coal Measures	Cardiff Member	Not Present	Muja Member
PERMIAN Upper	Collie Coal Measures	Collieburn Member	Premier Member	Premier Member
PERMIAN Lower	Collie Coal Measures	Ewington Member	Ewington Member	Ewington Member

PALAEOCURRENT OBSERVATIONS

GENERAL

During the 1:250 000 scale mapping of the Collie sheet (SI/50-6, International Series), foreset dip directions were measured in cross-bedded sandstone units of the Collie Coal Measures to determine the direction of sediment transport.

The Collie Coal Measures are everywhere obscured by later superficial deposits, and all underground workings have been restricted to the coal seams themselves. Observations are, therefore, limited to accessible parts of open-cut mine sites and to a collapsed area above the old Cardiff Colliery. All available sites were studied and these are shown in Figure 19.

Observations were taken on tabular cross-bedded units that make up approximately fifty per cent of the exposed sandstone sequences. These sandstones are poorly lithified, are medium to coarse-grained, and have a high clay content. The quartz grains are angular and much of the clay appears to be derived from decomposed feldspar. Some grit and pebble horizons occur and a few large pebbles of well-rounded quartz are scattered throughout the sandstones. A few clay galls are also present.

The cross-bedded units average about 30 cm in thickness and generally show some compositional variation between adjacent foreset laminae. Following the terminology of Allen (1963), the units are either solitary or grouped in cosets, and are of large scale. The bottom surfaces are mostly planar and either erosional or non-erosional. Alpha, beta and pi-cross stratification have been observed and, although these cannot be used to precisely define the environment of deposition, the variation in style indicates

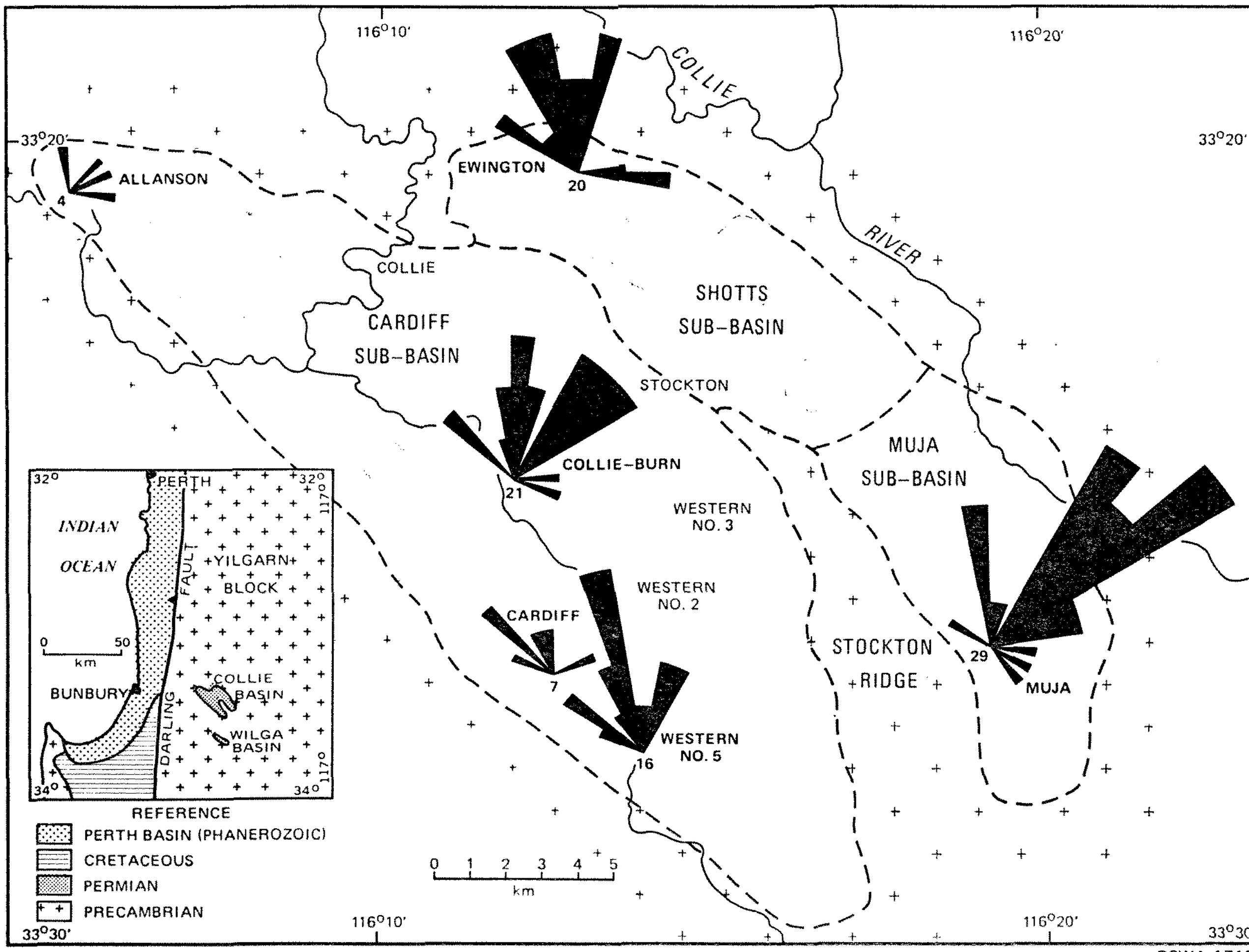

Figure 19 Locality diagram and paleocurrent data for the Collie Basin - readings grouped in 10° intervals, length of segment in rosette proportional to number of readings.

that conditions of sedimentation were changing rapidly. Lowry (1976) has postulated that the sandstones were fluviatile, with deposition as transverse or longitudinal bars in a braided river system.

METHOD

Measurements were made on cross-bedded sandstone units that were continuous for at least 10 m in length; obvious lensoid or trough units were avoided. The friable nature of the sandstones and the irregular pit faces enabled readings to be made directly on bedding surfaces. Measurements were made on separate units where possible, and not closer than 5 m apart when taken on the same horizon. The strike and dip of coal seams closest to the cross-beds were also recorded and used to apply a stereographic correction for tilt, assuming that the coal was horizontal at the time of deposition.

The Lower Permian succession was investigated above the Moira Seam of the lowermost Ewington Member (Table 7) at the Ewington and Allanson (Black Diamond) open cuts. Strata above the Wyvern Seam of the Upper Permian Collieburn Member were measured at the Collie-Burn open cut. Sandstones within the topmost Cardiff Member were measured at Cardiff Colliery and Western Collieries No. 5 (above the Cardiff Seam), and the equivalent Muja Member in the Muja sub-Basin was studied above the Hebe, Galatea, Eos, Ceres and Bellona Seams at the Muja open cut.

The foreset dip measurements thus cover all the main coal-bearing sequences of the Collie Coal Measures and have a span in geological time from Early to Late Permian (Table 7). The sample sites give a reasonable spread across the basin, although more would be desirable.

RESULTS

Foreset dip azimuths from the six available sites are plotted in Figure 19 as rosettes, using a 10° grouping. The number of observations at each site is also recorded.

The prevailing current direction at the Ewington and Western Collieries No. 5 sites was from the south-southeast, whereas at Collieburn and Muja it was from the southwest. Only a small number of readings were obtained at Allanson (4) and Cardiff (7), but these are in harmony with the results from the other four sites, indicating a general current flow from the south (the paucity of data was due to the lack of suitable strata). All 97 readings from across the basin are plotted stereographically in Figure 20. This plot illustrates the strong northerly transport of sediment, with a mean current direction of 015° (based on the arithmetic mean of the foreset dip azimuths). The only observed exceptions to this overall trend were trough units of limited extent, indicating some lateral transport. These may perhaps be equated with larger scale tabular units, represented by a small cluster of points in Figure 20, that indicate currents from the west. There are also a few extremely crudely defined cross-beds above the Flora Seam at the Muja open cut, which seem to indicate transport from the north.

SIGNIFICANCE OF OBSERVATIONS

Since the early days of investigation, two main theories have been advanced to account for the somewhat anomalous position of the Collie Basin; that it originated as a topographic depression in the Precambrian Yilgarn Block (Maitland, 1899) or that it was the result of later downfaulting (Jack, 1905). Lord (1952) has detailed the early history of this debate and favours the topographic depression model, with possible accentuation of the basin by Early Permian glacial scouring. More recently, Lowry (1976) has supported the downfaulting hypothesis. Although the palaeocurrent data cannot be used to prove or disprove either theory of origin, they do impose certain constraints on future interpretations.

In discussing the topographic depression hypothesis, it has generally been assumed that the present asymmetric profile of the basin existed during deposition of the Collie

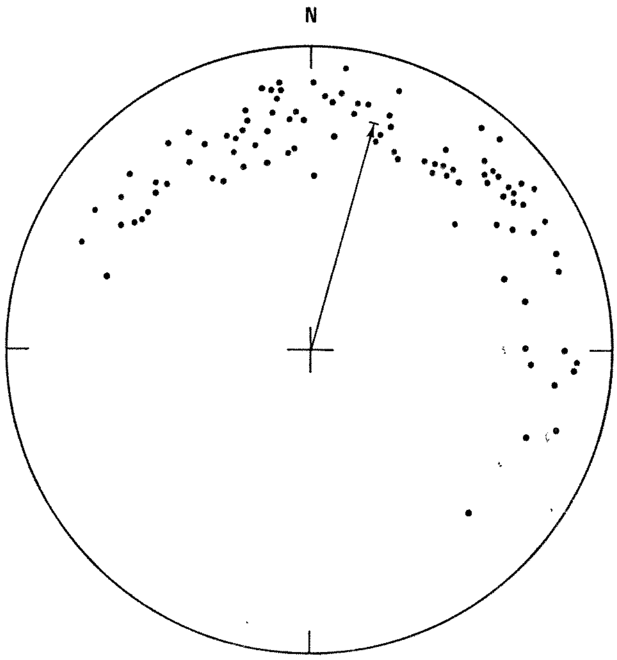

Figure 20 **GSWA 17123**

Stereographic projection of 97 dip azimuths from the Collie Coal Measures. The arrow represents the arithmetic mean azimuth (015°) and amount of dip (22N°).

Coal Measures and that their low dip to the south was in part primary, with the implication of sediment transport from the north (see Balme, *in* Lord, 1952). This was supported by the original gravity survey of the area (Chamberlain, 1947), which showed that the Permian/Archaean contact has a marked southerly dip over most of the basin. However, the palaeocurrent observations, bearing in mind the limitations imposed by the small number of sample sites, indicate derivation mainly from the south. Of particular importance are the observations at Ewington and Allanson. These sites are close to the northern margin of the basin, but still indicate currents from the south. There was thus a 'flow through' of material and the present Collie Basin could not have been an enclosed depression, at least during the Early Permian when the Ewington Member was deposited (Lowry, 1976). A fluviatile origin for the cross-bedded sandstones (Lowry, 1976) would support this conclusion, although swamp to lacustrine conditions must have existed over extensive areas and for long periods of time to account for the coal seams.

One argument used against the downfaulting hypothesis was the lack of evidence for northwesterly faults affecting the Archaean basement in this area (Lord, 1952). However, recent mapping by this survey has proved the existence of such faults at Quindanning, north of Collie, and bounding the volcanogenic Saddleback Group at Boddington (Wilde, 1976), though the age of faulting is unknown and may well be pre-Permian. But, although the possibility of such faults at Collie cannot be lightly dismissed, there are no photolineaments suggestive of faulting, either along the southwestern boundary or marginal to the Stockton Ridge. It is clear from the palaeocurrent data (Fig. 19) that northwesterly faults did not control the direction of Permian sedimentation at Collie. They do not support Lowry's (1976) hypothesis that graben faults were active during the deposition of the Upper Permian succession for, although measurements within the Cardiff Member at Western Collieries No. 5 do indicate flow subparallel to the present basin axis, those within the Collieburn Member at Collieburn open cut and in the uppermost Muja Member at the Muja open cut are almost perpendicular to the basin trend.

Post-depositional compaction has been invoked for the simple asymmetric synclinal arrangement of the coal measures, with axes aligned along and parallel to the deepest parts of the sub-basins and longest limbs dipping gently to the south. There would certainly have been some differential compaction of the mudstone sequence at the top of the Stockton Formation, coupled with a marked reduction in volume during transformation of peat horizons to coal. Furthermore, the available information on the glacigene Stockton Formation suggests that it varies greatly in thickness over short distances, implying gross irregularities in the basement surface. Therefore, the floor on which the Collie Coal Measures were laid down need not have had the same configuration as the glacially modified basement surface (Brown and others, 1968, indicate ice movement from the southeast). However, these factors are insufficient to account for the predominant southerly dip of the Collie Coal Measures (and the Permian/Archaean contact) over most of the Collie Basin, that is, contrary to the current directions. Some post-depositional tilting must have occurred. The amount and nature of the tilt is uncertain, owing to the general lack of information on the floor and margins of the Collie Basin.

CONCLUSIONS

Sediment transport in the Collie Coal Measures was almost exclusively from the south. This direction, so far as can be ascertained, is consistent throughout the Collie Basin and suggests that the present area does not represent an enclosed palaeo-topographic depression. If a topographic basin existed in Permian times, then its centre lay to the north and has subsequently been removed by erosion. The palaeocurrent trends are also subparallel to the inferred direction of Permian ice movement in the area.

Since the direction of sediment transport in the coal measures is opposite to the present overall southerly dip of the strata and the Permian/Archaean contact, some post-depositional tilting has occurred.

It is suggested that both glacial erosion and tectonics played a part in the formation of the Collie Basin. Glacial topography probably controlled the distribution of the Stockton Formation, whereas the present disposition of the Collie Coal Measures was aided by compactional deformation and post-depositional tectonics.

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HORNBLENDE-BEARING GRANITOIDS OF QUARTZ-MONZONITE AFFINITY FROM THE SOUTHWEST OF THE YILGARN BLOCK

by I. W. Walker

ABSTRACT

Two distinct types of quartz-deficient, hornblende-bearing, xenolithic granitoids of quartz monzonite affinity crop out in the southwest of the Archaean Yilgarn Block. Textural and chemical characters distinguish the two types: the Gilbralter Quartz Monzonite is a metamorphic tectonite and has a dynamic metamorphic history similar, in part, to the lithologies adjoining it; in the Darkan Quartz Monzonite igneous mineralogy and textures predominate. The Gilbralter Quartz Monzonite contains more K_2O, Sr and Ba, and less MgO, CaO, H_2O^+, Li and Ni than the Darkan type.

The Boyup Brook Lineament separates rocks with prominent tectonite fabrics, including the Gilbralter Quartz Monzonite, from extensive areas of adamellite and the Darkan Quartz Monzonite. A second lineament, the Hester Lineament, occurs west of the Boyup Brook feature. It extends over 70 km in length and separates the Gilbralter Quartz Monzonite to the east from a suite of metamorphic rocks, including gneiss, sediments and ultramafic rocks.

The favoured hypothesis for the origin of these rocks is that they are products of discrete magma types. Unlike syenitic and monzonitic bodies elsewhere in the Yilgarn Block, which intrude regional granitoid batholiths, the two quartz monzonite bodies described were emplaced prior to the main period of regional granitoid intrusion.

INTRODUCTION

Rocks of quartz monzonite affinity crop out over part of the Collie and Pemberton 1:250 000 Sheets (SI 50-6 and SI 50-10, International Series, respectively) (Fig. 21). These rocks contain between 3 per cent and 12 per cent hornblende, have low contents of quartz, and consequently are unlike the common granitoid types that crop out extensively in the southwest of the Archaean Yilgarn Block.

Textural characters can be used to identify two contrasting types: the Gilbralter and Darkan quartz monzonites. The Gilbralter Quartz Monzonite is a medium-grained, inequigranular xenolithic rock. Recrystallization during regional metamorphism has destroyed the igneous textures and imparted a tectonic foliation. The type locality for the Gilbralter Quartz Monzonite is at Gilbralter Rock, 8.5 km east-northeast of Mumballup. The Darkan Quartz Monzonite is a xenolithic rock with an igneous porphyritic fabric. The type locality for this quartz monzonite is at Dunleath, 5 km east-southeast of Darkan.

Elsewhere in the Yilgarn Block there are small, scattered areas of quartz-deficient granitoids. Wilde and Low (1973) described quartz diorite, monzonite and syenite on the Perth 1:250 000 Sheet which are associated with mobilized amphibolitic gneiss of the Archaean Jimperding Metamorphic Belt. Rocks with syenite-monzonite affinity intruded into rocks of adamellite composition have been documented by Gower and Bunting (1972) from the Lake Johnston Sheet, and by Bunting and Williams (1976) from the Sir Samuel Sheet. In contrast to the Lake Johnston and Sir Samuel occurrences of quartz-deficient granitoids, the Darkan and Gilbralter quartz monzonites relate more closely to the gneiss terrains than to the voluminous, post-tectonic granitoids. Although no isotopic dating is available, the field relationships suggest that the quartz monzonites predate the regional granitoid intrusions.

This paper summarizes the petrography, chemistry and regional relationships of the Gilbralter and Darkan quartz monzonites, and discusses the possible origin of the rocks.

MINERALOGY AND TEXTURES

Thin sections were stained for potash feldspar and plagioclase according to the method of Laniz and others (1964), and assemblages were point counted. Counts in most cases were made of two separate slides from each of three planes; one parallel, the others at right angles, to the foliation. Included with the modal compositions, shown in Table 8, is a specimen of adamellite (47113) adjoining the Darkan Quartz Monzonite.

Both the Gilbralter and Darkan quartz monzonites are hornblende-bearing, but the variable amounts of quartz, microcline and plagioclase prevent a rigid mineralogical classification. The majority fall within the quartz monzonite field of Streckeisen (1967), others correspond with adamellite, granodiorite, or syenite (Fig. 22).

GILBRALTER QUARTZ MONZONITE

Modal compositions are shown in Table 8. Porphyroblasts of microcline, enveloped by a fine to medium-grained xenoblastic groundmass, are commonly perthitic, and contain inclusions of plagioclase. Hornblende is abundant as pale-coloured, aligned grains with poikiloblastic cores that contain inclusions of quartz and plagioclase. Hornblende also forms grains which are pleochroic from pale green-brown (X) to pale green (Y) to deep blue-green (Z). South of Mumballup, clinopyroxene rimmed by hornblende is the chief mafic mineral. Deformation accompanying regional metamorphism generated the tectonite fabrics in this quartz monzonite.

Small (generally less than 25 cm) mesocratic to melanocratic attenuated xenoliths within the Gilbralter Quartz Monzonite are composed of xenoblastic hornblende and plagioclase. A gneissic fabric is evident within some of these amphibolite xenoliths. In individual exposures the surface area covered by the xenoliths is generally less than 5 per cent of the outcrop area.

DARKAN QUARTZ MONZONITE

Megacrysts of microcline occur within a hypidiomorphic to allotriomorphic granular mosaic of saussuritized plagioclase, microcline, hornblende, and strained quartz. Some of the microcline is microperthitic, and is replaced by myrmekite along some grain boundaries. Plagioclase is zoned, and occurs as subhedral to anhedral inclusions in

TABLE 8. MODAL COMPOSITIONS OF HORNBLENDE-BEARING GRANITOID ROCKS

Specimen Number	Gilbralter Quartz Monzonite				Darkan Quartz Monzonite					Adamellite
	47154	48426	48444	50977	47107	47130	47136	47159	48475	47113
Plagioclase	37·8	30·3	41·3	41·4	45·9	49·4	43·0	41·5	52·6	33·2
Microcline	46·6	56·6	34·9	35·9	24·4	29·0	24·0	37·9	18·0	24·5
Quartz	11·0	2·0	15·8	13·2	13·0	15·0	17·3	10·6	20·4	31·0
Hornblende	3·0	3·6	5·9	5·5	8·9	1·4	11·6	7·1	3·2	....
Chlorite	....	....	....	....	4·8	1·8	....	....	1·0	....
Biotite	....	....	....	....	....	....	....	....	....	9·3
Accessories (Epidote + sphene)	1·6	7·6	2·0	4·0	3·0	3·5	4·0	2·9	4·9	2·0
Total	100·0	99·9	99·9	100·0	100·0	100·0	99·9	100·0	100·1	100·0
Number of points counted—from three planes at right angles to each other	8 000	10 000	5 600	6 900	10 260	12 500	6 000	10 700	12 400	1 860
Area counted (mm² approx.)	2 000	2 500	1 250	1 750	2 500	3 100	1 500	2 500	3 100	500

microcline and hornblende. The microcline and quartz of the groundmass are interstitial to plagioclase. Hornblende predominantly occurs as subhedral grains, pleochroic from pale green-brown (X) to fawn-brown (Y) to olive-green (Z). Less commonly, hornblende pseudomorphs a fibrous mineral, with pale green augite occurring as cores in some of these fibrous grains. In places, chlorite pseudomorphs biotite. Accessory minerals include epidote, apatite, and sphene. An igneous fabric in the Darkan Quartz Monzonite is formed by the planar orientation of tabular megacrysts.

The texture of the xenoliths varies from a xenoblastic aggregate of hornblende and plagioclase, with no evidence of a pre-existing fabric, to those with a gneissic or schistose foliation. In the cores of xenoliths hornblende is homogeneous and twinned, but replaces a fibrous mineral towards the rims of the xenoliths.

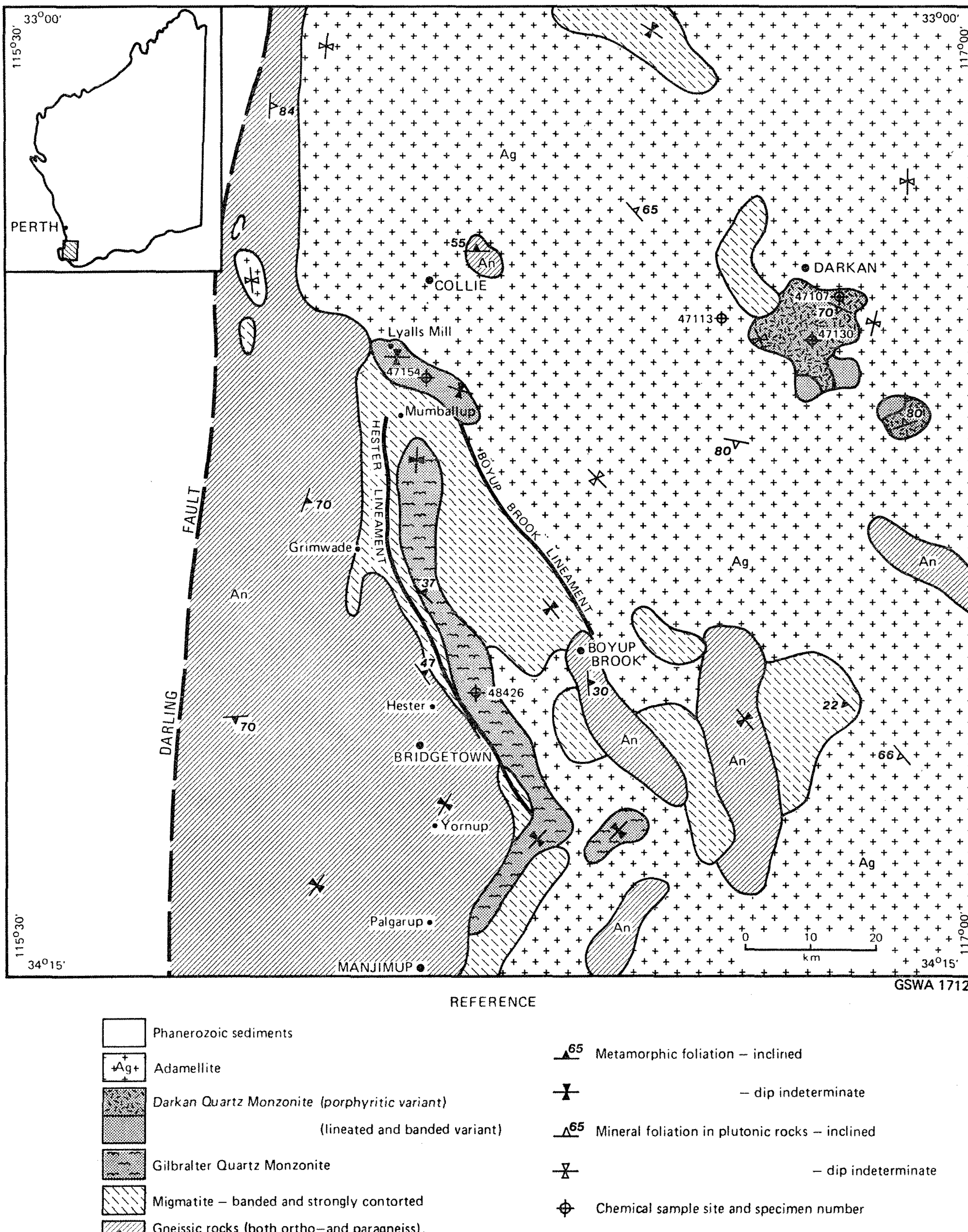

Figure 21 Regional setting of the hornblende-bearing granitoids.

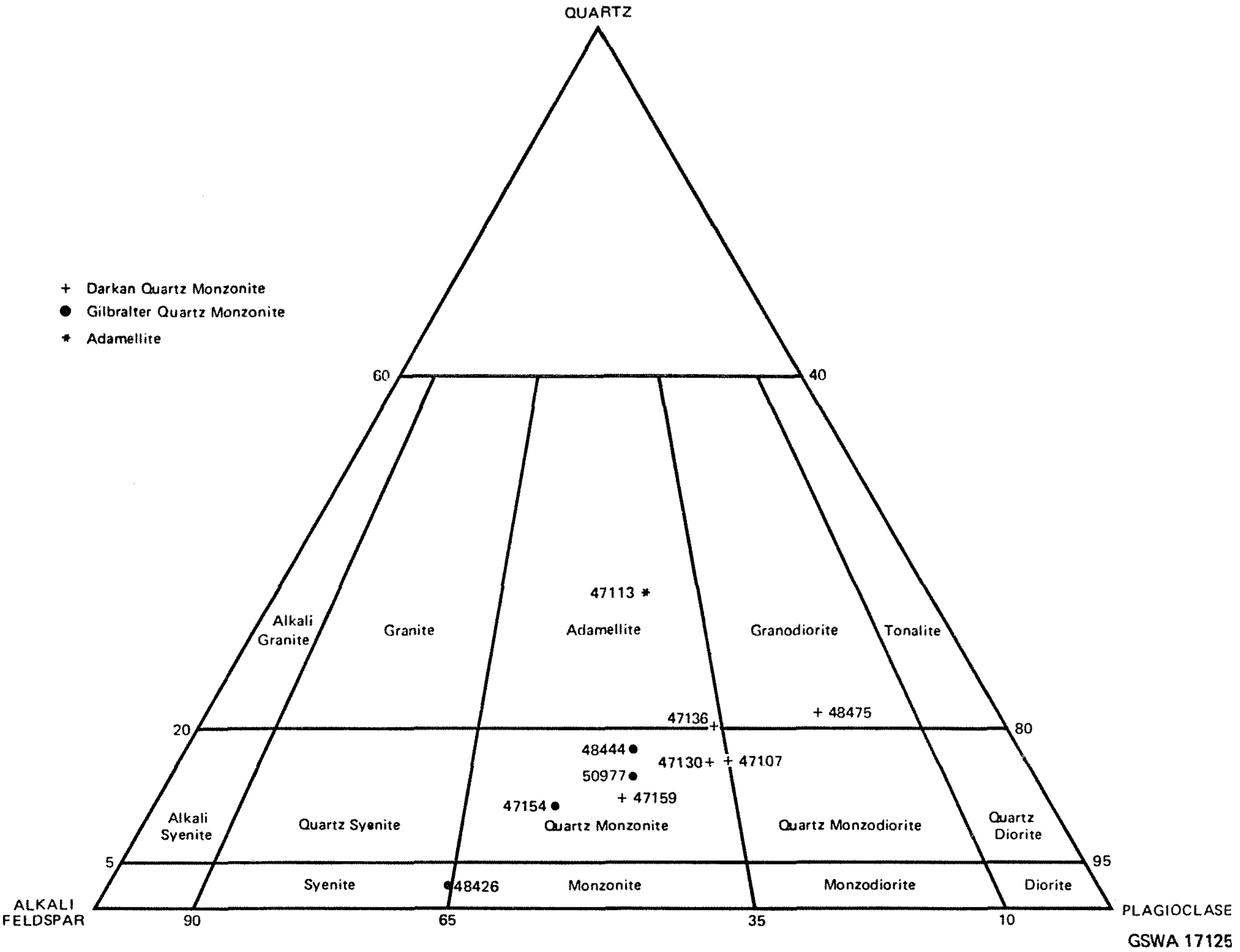

Figure 22 Mineralogical classification of the hornblende-bearing granitoids on the quartz-potash feldspar-plagioclase triangle according to their actual mineral composition (after Streckeisen, 1967).

GEOCHEMISTRY

Whole rock and trace element analyses of two specimens of each quartz monzonite are presented in Table 9. Analyses of granitoids adjoining the two quartz monzonite types are not available. The only analysis available of a granitoid from the area discussed in this paper is of adamellite from Bannister on the Pinjarra Sheet, and this is included for comparison. Also included is an analysis of syenite from Fitzgerald Peaks (Lewis and Gower, 1976).

Discernible differences in both major and trace elements exist between the Gilbralter and Darkan quartz monzonites. The Gilbralter Quartz Monzonite has more K_2O than the Darkan Quartz Monzonite, but is lower in MgO, CaO and H_2O^+. The Sr and Ba values are greater in the Gilbralter Quartz Monzonite, but Li and Ni are more abundant in the Darkan Quartz Monzonite.

The Darkan Quartz Monzonite when compared with the Bannister adamellite is higher in Fe_2O_3, MgO, CaO and H_2O^+, Al_2O_3, Na_2O and P_2O_5, but lower in SiO_2, K_2O and FeO contents.

Figure 23 is a normative Q-Or-Ab plot calculated from analyses presented, and illustrates the contrast between the Gilbralter and Darkan types. The liquidus curves for the system at water vapour pressures of 50 and 500 MPa have been added to the diagram (after Mehnert, 1968). At low pressure the field of the Bannister adamellite plots close to the cotectic trough (m). The spread in the projection of the norms of both types of quartz monzonite at positions away from the cotectic trough (m) for the adamellite indicate that it is unlikely that either the Gilbralter or Darkan quartz monzonites are fractionation products of a melt crystallizing the adamellite.

REGIONAL RELATIONSHIPS

The two types of hornblende-bearing, quartz-poor granitoids help to emphasize major partitions between regions of different rock types and tectonic styles in the southwest of the Yilgarn Block.

GILBRALTER QUARTZ MONZONITE

The Gilbralter Quartz Monzonite extends discontinuously over a strike-length of 90 km, mainly in contact with gneiss and migmatized gneiss. An isolated occurrence 30 km east of Yornup is totally enveloped by massive adamellite. The irregular nature of the contact and the absence of a tectonic fabric in the adamellite are taken to indicate that the adamellite intrudes the quartz monzonite. East of Bridgetown, the contact of the migmatite with the Gilbralter Quartz Monzonite corresponds with a curvilinear aeromagnetic low (from unpublished data). This feature is named the Hester Lineament by Blockley (in press). Another linear aeromagnetic anomaly, here termed the Boyup Brook Lineament, extends parallel to the Hester Lineament, about 20 km to the east of it. This separates migmatized gneiss terrain from the extensive adamellite to the east. It also serves as the locus of emplacement of at least one and possibly two of the outlying bodies of Gilbralter Quartz Monzonite.

The Gilbralter Quartz Monzonite and the adjoining gneiss both participated in a structural event that generated the tectonite fabrics. A later event of regional, open-style refolding is evident southeast of Bridgetown where the trend of the gneissic foliation swings from northeast to northwest. Superimposed folds and transposition structures are found in the banded iron-formation and gneissic rocks of the succession west of the Hester Lineament but not in the Gilbralter Quartz Monzonite. This suggests that the quartz monzonite has not undergone all episodes of deformation experienced by the rocks of the Bridgetown succession, and further suggests that the quartz monzonite was emplaced late in the evolution of the gneiss terrain.

DARKAN QUARTZ MONZONITE

The Darkan Quartz Monzonite crops out in an extensive area of granitoids which lack tectonite fabrics. These granitoids are regionally homogeneous, except for a belt of

TABLE 9. COMPLETE CHEMICAL ANALYSES OF HORNBLENDE-BEARING GRANITOIDS

Specimen number	Gilbralter Quartz Monzonite		Darkan Quartz Monzonite		Adamellite (Bannister)	Syenite (Fitzgerald Peaks area)
	47154	48426	47107	47130		29821
SiO_2	66·1	63·3	62·7	65·3	72·0	61·7
Al_2O_3	16·5	17·3	17·4	17·6	12·5	16·2
Fe_2O_3	1·4	1·8	1·7	1·5	0·6	1·1
FeO	1·1	0·9	2·3	1·0	3·1	1·9
MgO	0·3	0·5	1·8	0·9	0·3	0·6
CaO	2·1	2·2	4·3	3·8	1·4	2·6
Na_2O	4·0	4·2	4·2	4·4	3·5	5·7
K_2O	6·6	8·4	3·6	3·6	5·9	5·6
H_2O^+	0·5	0·5	1·3	1·1	0·3	0·6
H_2O^-	0·1	0·1	0·2	0·1	0·2	0·1
CO_2	0·1	....	....	0·1	0·0	....
TiO_2	0·3	0·5	0·4	0·3	0·4	0·6
P_2O_5	0·2	0·2	0·3	0·2	0·0	0·3
MnO	0·1	0·1	0·1	0·1	0·0	0·1
Total	99·4	100·0	100·3	100·0	100·2	97·1
Trace Elements (ppm)						
Li	5	1	15	25	....	....
Rb	110	140	130	135	....	....
Sr	1 300	1 060	600	690	....	....
Ba	3 550	5 100	1 600	2 200	....	....
Zr	350	25	240	180	....	....
Sn	<20	<20	<20	<20	....	....
Ni	10	10	130	60	....	....
Cu	10	40	40	30	....	....
Zn	50	80	100	60	....	....
U	< 1	2	4	2	....	....
C.I.P.W. Norms						
Q	13·9	5·4	13·5	20·3	25·1	2·5
C	....	....	....	1·2	....	....
Or	39·0	49·6	21·3	21·3	34·7	32·9
Ab	32·8	31·9	34·2	32·8	29·4	48·6
An	8·2	5·4	18·8	16·8	1·0	2·1
Di	0·6	2·5	0·5	....	....	6·3
Wo	0·3	1·3	0·2	....	2·4	3·2
En	0·2	1·2	0·2	....	0·3	1·4
Fs	0·1	....	0·1	....	2·3	1·7
Hy	1·0	....	6·5	2·4	....	....
En	0·6	....	4·3	2·1	0·3	....
Fs	0·4	....	2·2	0·3	2·3	....
Mt	2·0	1·9	2·5	2·2	0·9	1·7
Il	0·6	0·9	0·8	0·6	0·7	1·1
Ap	0·4	0·5	0·8	0·8	0·1	0·7
Cc	0·2	0·1	....	0·2	....	....

discontinuous rafts of migmatite and gneiss trending northwest through Darkan. The two bodies of Darkan Quartz Monzonite are closely associated with this discontinuous belt of migmatized gneiss.

The larger body of Darkan Quartz Monzonite is bounded to the northwest by migmatite, but all other contacts are with adamellite. The adamellite is transgressive, and is inferred to intrude the quartz monzonite.

In places, between the Darkan Quartz Monzonite and surrounding adamellite, are two unusual rock types. One is a fine to medium-grained, mesocratic lineated monzodiorite. The second is a conspicuously banded, medium-grained rock consisting of alternating quartzofeldspathic and hornblende-rich bands. As with the porphyritic Darkan Quartz Monzonite, xenoliths of amphibolite and gneiss are scattered throughout these two variants.

DISCUSSION

Field observations, and some petrographic and chemical data, allow tentative but perhaps important comments to be made on the origin and significance of these quartz monzonites.

The Darkan Quartz Monzonite is the oldest granitoid recognized east of the Boyup Brook Lineament. Two alternative hypotheses for its origin are considered. Firstly, the presence of amphibolite xenoliths suggests the rock may result from assimilation of amphibolitic gneiss by adamellite. However, the assimilated material would require an unusual chemistry to explain the high Al_2O_3 content of the Darkan Quartz Monzonite. A second hypothesis is that the Darkan Quartz Monzonite is the product of a discrete magma type. De Laeter and Lewis (1978) proposed a magmatic origin for the rocks of syenitic affinity from Fitzgerald Peaks on the Lake Johnston Sheet. The Darkan Quartz Monzonite could be derived from a melt of quartz monzonite affinity, modified in part by assimilation, which invaded a migmatite and gneiss terrain. Significantly, the difference between this melt crystallizing the Darkan Quartz Monzonite and those crystallizing the various quartz-poor granitoids elsewhere in the Yilgarn Block, is that this melt was emplaced prior to the invasion of the main adamellite mass and not following it.

The Gilbralter Quartz Monzonite is chemically distinct from the Darkan Quartz Monzonite, and is not simply the deformed equivalent of the Darkan Quartz Monzonite. The Gilbralter Quartz Monzonite was emplaced into a metamorphic succession as narrow, discontinuous bodies. Metamorphism and deformation continued to affect the region after emplacement. Assimilation to produce a melt corresponding to the composition of the Gilbralter Quartz Monzonite, as with the Darkan type, is doubtful. To obtain the high Al_2O_3 and K_2O contents of the Gilbralter Quartz Monzonite would require the host rock, now represented by the gneissic and amphibolite xenoliths, to have unusually high Al_2O_3 and K_2O contents, and remnants of such rocks have not been identified. A more favoured origin is that the Gilbralter Quartz Monzonite is the product of a melt of quartz monzonite affinity, somewhat potassium and aluminium rich, and perhaps modified to some extent by assimilation.

Whatever their origin, both the Gilbralter and the Darkan quartz monzonites are probably the earliest record in the southwest, and possibly the whole Archaean Yilgarn Block, of a melt crystallizing rocks of quartz monzonite to syenite affinity.

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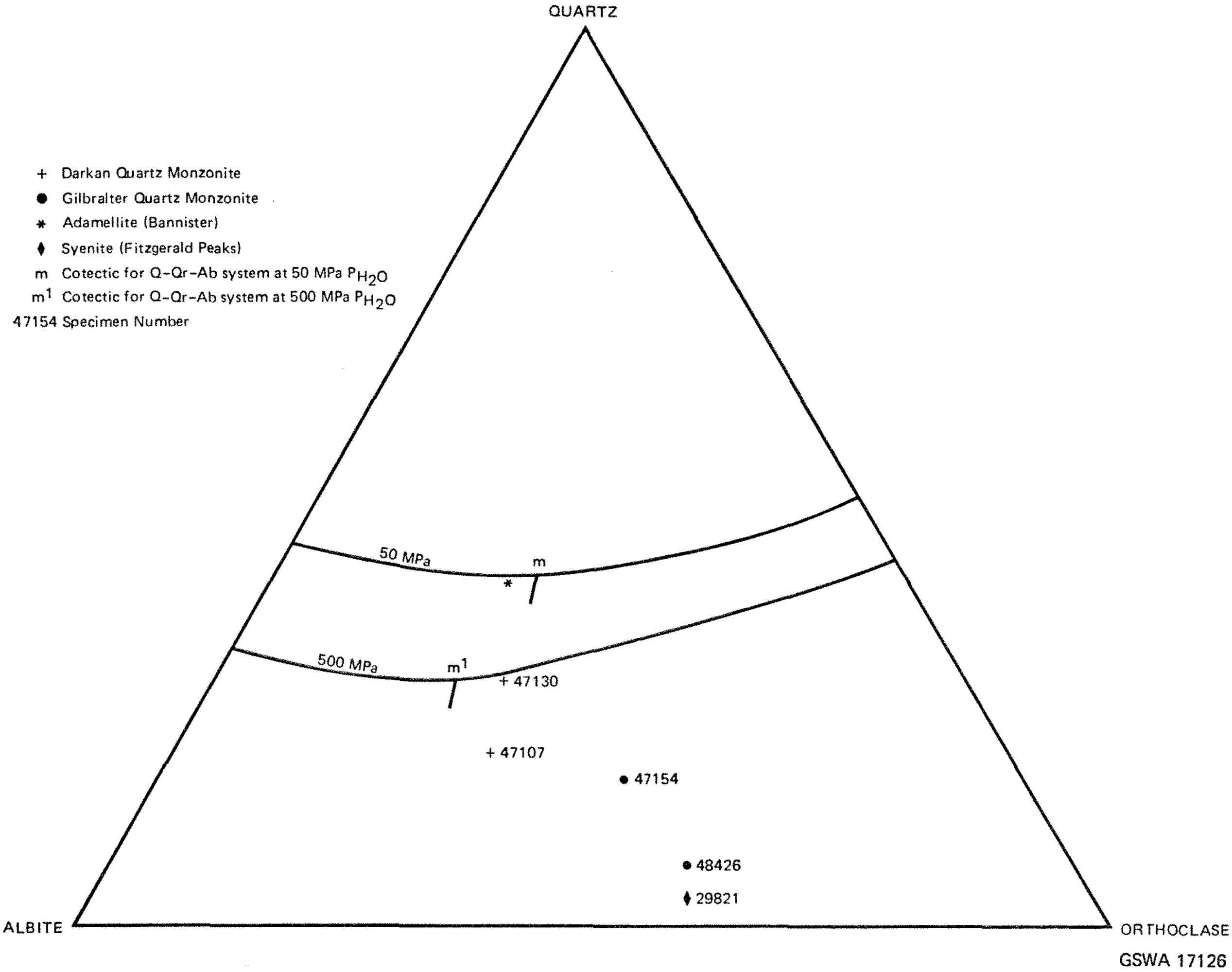

Figure 23 Normative Q-Or-Ab plot for the Darkan Quartz Monzonite, Gilbralter Quartz Monzonite, adamellite (Bannister) and syenite (Fitzgerald Peaks). Full linês are liquidus curves for the ternary system at 50 and 500 MPa (0.5 and 5.0 Kb) water vapour pressure (after Mehnert, 1968)

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AGE OF A TIN-BEARING PEGMATITE AT GREENBUSHES

by J. R. de Laeter * and J. G. Blockley

ABSTRACT

Microcline and muscovite in a cassiterite-bearing pegmatite from the South Cornwall tin mine at Greenbushes give model Rb-Sr ages of about 2 650 m.y. This is considered to be the age of intrusion and agrees well with an earlier date on the closest large body of granitic rocks.

INTRODUCTION

Mineralized pegmatites occurring in a belt 6 km long and up to 600 m wide have been the ultimate source of 18 250 tonnes of cassiterite and 1 360 tonnes of tantocolumbite mined from the Greenbushes Mineral Field in the southwestern Yilgarn Block.

The geology of the Greenbushes Mineral Field is dealt with by Hobson and Matheson (1949). A feature of the deposits is that no granites crop out in their immediate vicinity. The nearest granitic rocks are exposed about 8 km east of Greenbushes, where they are apparently in faulted contact with the metamorphic rocks of the Balingup Metamorphic Belt (Blockley, in press). A sample of this granite, collected from Hester, 12 km southeast of Greenbushes, was dated by Wilson and others (1960) at about 2 700 m.y. using a decay constant for ^{87}Rb of $1.386 \times 10^{-11} yr^{-1}$.

The Greenbushes pegmatites cut mainly metasedimentary rocks of the Balingup Metamorphic Belt on which the only previously available geochronology (all on pegmatites) indicates Proterozoic ages. Wilson and others (1960) found muscovite in a pegmatite at Mullalyup, 14 km northwest of Greenbushes, to be 1 100 m.y. old. The pegmatite was stated to be "clearly related to the granitization of the pelitic sediments" of the area. Riley (1961), using a decay constant of $1.386 \times 10^{-11} yr^{-1}$, obtained concordant muscovite and biotite ages of about 675 m.y. from a 4-cm wide pegmatite vein cutting coarse granitic gneiss

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at Wellington Dam, 55 km northwest of Greenbushes. He considered the age to be that of intrusion of the pegmatite. Compston and Arriens (1968), referring to the work done by Riley but not presented by him, cite an age of about 675 m.y. for feldspar, muscovite and pegmatized gneiss near Donnybrook, 35 km northwest of Greenbushes. Biotite from this material had an age of 500 m.y. Riley (1961) considered that "young" pegmatite ages found near the Darling Scarp represented a period of metamorphism occurring some 2 000 m.y. after the host rocks had formed.

Recalculated using the presently accepted decay constant of $1.42 \times 10^{-11} yr^{-1}$, the previously published ages become 2 650 m.y. for the Hester granite, 1 070 m.y. for the Mullalyup pegmatite, and about 660 m.y. for the Wellington Dam and Donnybrook pegmatites.

From the point of view of future prospecting for tin in the southwestern part of the State, it is important to know whether the mineralized pegmatites are related to the main period of granite emplacement (2 550 to 2 700 m.y.) in the Yilgarn Block, or to possible younger granite intruded during a later metamorphic event affecting the margins of the block.

MATERIAL USED

The mineralized pegmatites at Greenbushes consist mainly of quartz, albite, muscovite, tourmaline, rarer microcline and various rare-metal minerals, some of which are of economic importance. The greater part of the dykes are kaolinized to depths of 30 to 50 m and, despite the large open cuts, fresh material is only available as bore cores and specimens from earlier deep mining operations. Metamorphism sometime after emplacement produced a strong cataclastic foliation and a mineral banding in the pegmatite, although some parts of the dykes escaped these effects. Material suitable for obtaining an estimate of intrusive age is therefore restricted to a few samples of unmetamorphosed pegmatite obtained from the deeper openings in the field. The sample chosen, 40292 (4660 on the old G.S.W.A. numbering system), is of massive cassiterite-bearing pegmatite obtained from the South Cornwall mine in about 1903. It consists of quartz, greenish muscovite, albite, spessartine, abundant cassiterite and two large crystals of microcline which poikilitically enclose grains of quartz and cassiterite.

Samples of microcline and muscovite concentrates were prepared by knapping or scraping appropriate parts of the specimen and hand picking the required mineral grains. The microcline concentrate contained a little quartz and cassiterite, and the muscovite sample contained small quantities of cassiterite, quartz and fluorite.

EXPERIMENTAL PROCEDURE

The experimental procedure for Rb-Sr analyses used in this laboratory is essentially the same as that described by Lewis and others (1975). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project is 0.7102 ± 0.0001, normalized to a $^{88}Sr/^{86}Sr$ value of 8.3752. The value of $1.42 \times 10^{-11} yr^{-1}$ was used for the decay constant of ^{87}Rb (Steiger and Jäger, 1977). It should be noted that this is the first time this value for the decay constant has been used by this laboratory, as in earlier publications a value of $1.39 \times 10^{-11} yr^{-1}$ has been adopted.

The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios, as well as the calculated $^{87}Rb/^{86}Sr$ ratios are given in Table 8. Errors accompanying the data are at the 95 per cent confidence level. The Rb and Sr concentrations in each sample are also listed. However these concentrations are only accurate to $\pm$ 7 per cent and the Rb/Sr ratios may not correspond exactly to the ratios which would be derived from the separate Rb and Sr values listed.

TABLE 8. ANALYTICAL DATA FROM GREENBUSHES PEGMATITE

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
40292 .... (Microcline)	4 500	62	71·9 ± 1	952 ± 15	37·343 ± 0·037
40292 .... (Muscovite)	2 700	34	79·4 ± 1	1 630 ± 25	63·144 ± 0·059

RESULTS

Model ages for the feldspar and mica samples can be determined by assuming an appropriate initial ratio. Since the measured $^{87}Sr/^{86}Sr$ ratios for both samples are large, the actual assumed initial ratio is of little consequence. Model ages of 2 659 m.y. and 2 647 m.y. are obtained from the feldspar and mica respectively (using an R_i = 0.700). If the data are treated as a two-point isochron, the resulting mineral age is 2 630 m.y. but the initial ratio of 1.116 is improbably high.

Considering the experimental error involved and the lack of a reliable isochron, the age of the Greenbushes pegmatites is best stated as "about 2 650 m.y.".

DISCUSSION

The results indicate that the metasedimentary rocks of the Balingup Metamorphic Belt are of Archaean age, a conclusion generally accepted (for example, State Geological Map, 1973) but not proven by previous geochronology. They also give the youngest possible age for the Greenbushes pegmatites, representing either the date of intrusion, or the time of a later metamorphism. The close correspondence between the microcline and muscovite ages suggests that the date found is probably that of intrusion rather than metamorphism.

The date of 2 650 m.y. agrees well, when adjustment for the new decay constant is made, with that of the granite from Hester dated by Wilson and others (1960). Blockley (1973) found that the petrography and chemistry of the granitic rocks contiguous with the Hester outcrops showed no characteristics typical of tin granites, and concluded that they were not related to the Greenbushes tin deposits. However, the new information presented here strongly suggests that such a relationship exists. The most plausible explanation is that Greenbushes is situated over a stock or cusp of 2 650 m.y. granite intruded at a much higher structural level than any of the material accessible for sampling to the east of the Balingup Metamorphic Belt.

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GEOCHRONOLOGY AND EVOLUTION OF THE EASTERN GASCOYNE PROVINCE AND THE ADJACENT YILGARN BLOCK

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ABSTRACT

Rubidium strontium age determinations are presented for whole rocks, biotite, and muscovite, from the eastern part of the Gascoyne Province and the adjacent parts of the Yilgarn Block. Archaean ages are confirmed for granitoids that intrude gneissic terrain south of the Murchison Tectonic Lineament and Bullbadger Shear Zone. The Rocky Bore granite (2 608 m.y.), the Dog Rocks granodiorite (2 573 m.y.), and the Roadside Bore granite (2 461 m.y.) form part of the northern Yilgarn Block, which was stable during Proterozoic orogenesis. A period of dynamic metamorphism and deformation within the Gascoyne Province is indicated by a model muscovite age of 1 700 m.y. for quartz-muscovite schist near Mica Bore. This was followed by a period of granitoid intrusion as indicated by the Red Rock adamellite (1 604 m.y.) and the Forty Mile Well adamellite (1 557 m.y.). Whole rock ages of around 750 m.y. are indicated from reworked Archaean migmatite (suggested initial age of around 2 800 m.y.) from within the Errabiddy Shear Zone. The Red Rock and Forty Mile Well adamellites also have biotite ages of 750-800 m.y. This was probably an age of uplift, although a short thermal event throughout the Gascoyne Province is also possible.

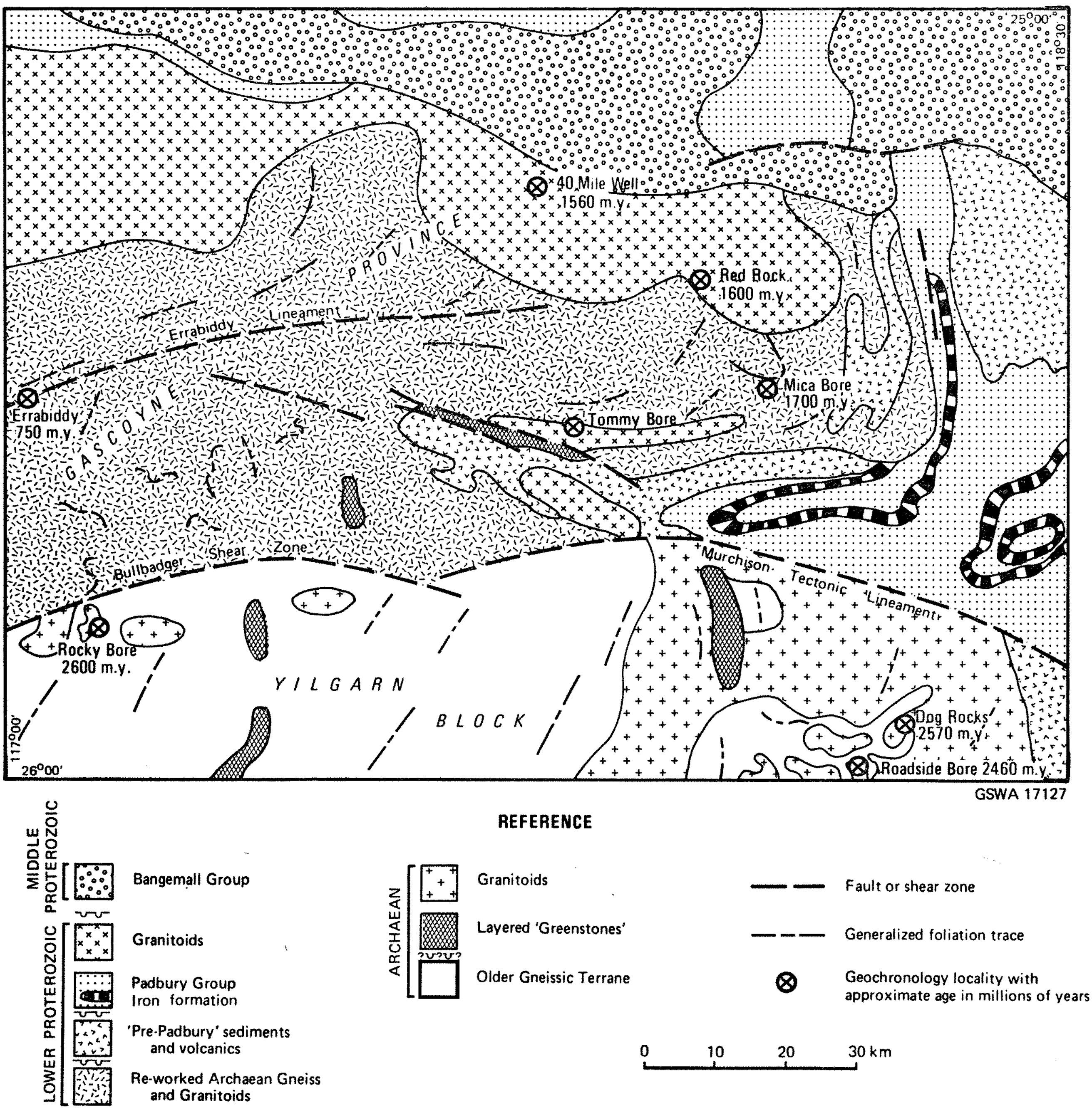

Figure 24 Generalized geology and sample sites, including approximate ages in millions of years.

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INTRODUCTION

The Archaean Yilgarn Block of Western Australia is bounded to the north by the Gascoyne Province, a region of Proterozoic sedimentation, granite intrusion, and polyphase metamorphism. Daniels (1975) gave the first comprehensive account of the province, based on reconnaissance traverses and some regional mapping. Subsequently, regional mapping of the Robinson Range sheet in 1974 and 1975, and more recently of the Mount Phillips and Glenburgh sheets (Fig. 1) has led to an increased understanding of the nature of this complex province. Early in the mapping program however, it became evident that a number of fundamental problems required solution before a unified tectonic framework of the northern marginal area of the Yilgarn Block could be erected. The problems were essentially geochronological, and in 1975, a Rb/Sr geochronological investigation was implemented. This paper reports on the results of the first stage of this program, which was carried out on the Robinson Range sheet. The main objectives were to define the ages of metamorphic and intrusive events across the Yilgarn Block-Gascoyne Province transition, and thereby define the limits of the two provinces in the area studied.

Previous geochronological work in the Gascoyne Province is limited, and its effectiveness is hampered by inadequate knowledge of regional geology. The most recent investigation is by de Laeter (1976), who also reviews earlier isotopic work. No previous work has been carried out on the Yilgarn Block-Gascoyne Province transition. An account of the regional geology of the Robinson Range sheet, on which the following discussion is largely based, is given by Elias and Williams (1977).

REGIONAL TECTONIC SETTING

YILGARN BLOCK

The northern margin of the Yilgarn Block extends across the southern part of the Robinson Range Sheet (Fig. 24). In this part of the block Elias and Williams (1977) identified three distinct rock associations.

The first is gneissic, and consists predominantly of quartz-feldspathic orthogneiss containing elongate enclaves of metamorphosed igneous and sedimentary rocks, which have a complex structural and metamorphic history. The enclaves consist of calc-silicate paragneiss, amphibolite and pyroxene rocks of both sedimentary and igneous origin, banded quartz-magnetite rock, commonly containing iron-rich silicates, quartzite, and ultramafic schist. Regional metamorphic grade ranges from middle amphibolite to granulite facies. The lithological characteristics of the gneiss association suggest an origin as a supracrustal sequence, probably fragmented by granitoid intrusion prior to or during metamorphism.

A second association is of mafic and ultramafic volcanics and intrusives (greenstones) that occur in narrow, linear belts. These rocks are isoclinally folded and metamorphosed in the greenschist to lower amphibolite facies, and they are similar to greenstone belts elsewhere in the Yilgarn Block.

Granitoids form the third association, and intrude the other two. The granitoids are predominantly even-grained biotite adamellite and granite, with seriate and porphyritic phases. Minor granodiorite and alkali granites also occur.

GASCOYNE PROVINCE

The Gascoyne Province is a region of Lower Proterozoic tectonism and metamorphism. The effects range from folding and shearing in the southern part of the province to high-grade metamorphism and migmatization to the north. In the south adjacent to the Yilgarn Block, the rocks affected are Archaean gneiss, granite, and minor greenstone; progressively more Lower Proterozoic supracrustals become involved to the north and east. The Proterozoic supracrustals include possible equivalents of the Wyloo Group (Daniels, 1975). Granitoids were intruded, both during and after the Lower Proterozoic tectonism.

On the Robinson Range sheet, most of the Gascoyne Province rocks are tectonically reworked Archaean basement. Lower Proterozoic structural and metamorphic effects appear north of the Bullbadger Shear Zone and the Murchison Tectonic Lineament (Fig. 24), starting with folding of Archaean foliations, and accompanied by gradually increasing grade of metamorphism towards the north. North of Errabiddy, grade may have reached the point where anatexis and migmatization could occur. Large granitoid bodies intrude the reworked Archaean gneiss, post-dating the main reworking event. These granitoids are lithologically similar to those introding gneiss and greenstone in the northern Yilgarn Block, but age determinations have established a clear difference.

In the eastern part of the Robinson Range sheet, a sequence now consisting of quartz-mica schist, micaceous quartzite, and minor volcanogenic sediments represents Lower Proterozoic supracrustal sediments weakly metamorphosed and folded into the Archaean basement during the main Lower Proterozoic orogenic events. The stratigraphic constitution of this sequence has not yet been formalised and they have been referred to by Elias and Williams (1977) as the 'pre-Padbury Group' supracrustals. A younger sequence of quartzitic sediments and banded iron-formation, the Padbury Group (Barnett, 1975), rests unconformably on reworked Archaean basement and deformed Lower Proterozoic supracrustals. The Padbury Group is also tightly folded, but in a separate event to the main Proterozoic deformation. Its deformation is probably related to the upwelling of the large mass of Proterozoic granitoids to the west and northwest.

EXPERIMENTAL PROCEDURE

The experimental procedure for Rb/Sr analyses used in this laboratory is essentially the same as those described by Lewis and others (1975). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project is 0.7102 ± 0.0001, normalised to a $^{88}Sr/^{86}Sr$ value of 8.3752. The value of $1.42 \times 10^{-11}\ yr^{-1}$ was used for the decay constant of ^{87}Rb (Steiger and Jäger, 1977). It should be noted that this is the first time this value for the decay constant has been used by this laboratory, as in earlier publications a value of $1.39 \times 10^{-11}\ yr^{-1}$ had been adopted. In view of this fact, and for the purposes of comparison, previously published ages quoted in this paper have been adjusted to conform to the newer value for the decay constant.

The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios, as well as the calculated $^{87}Rb/^{86}Sr$ ratios are given in Table 9. Errors accompanying the data are at the 95 per cent confidence level. The Rb and Sr concentrations in each sample are also listed. However these concentrations are only accurate to $\pm$ 7 per cent and the Rb/Sr ratios may not correspond exactly with the ratios which would be derived from the separate Rb and Sr values listed.

RESULTS

The data listed in Table 9 have been regressed using the least squares program of McIntyre and others (1966). The age data are listed in Table 10. If the mean square of the weighted deviates (MSWD) is less than or equal to 1.0, the regression fits within the assigned limits for experimental error and the program does not proceed beyond Model 1. Greater scatter indicates departure from the geological assumptions of homogeneous initial $^{87}Sr/^{86}Sr$ and subsequent chemical closure of the samples to Rb and Sr. The program then proceeds to Models 2 and 3 which test alternative methods of distributing the excess residual variance.

Model 2 tests the assumption that the geological variance of $^{87}Sr/^{86}Sr$ (in excess of the assigned experimental limits), is proportional to $^{87}Rb/^{86}Sr$ for each sample, and therefore gives stronger weighting to samples of low $^{87}Rb/^{86}Sr$. This model could be appropriate for samples which have a real spread in ages but the same initial ratio. Model 3 tests the assumption that the excess geological variance of $^{87}Sr/^{86}Sr$ is independent of $^{87}Rb/^{86}Sr$, and therefore adds the same variance to each sample. Model 3 is therefore more appropriate for rocks which have the same age but different initial ratios.

The program examines the trend of the absolute differences between the observed and estimated $^{87}Sr/^{86}Sr$ divided by the respective standard errors as a function of $^{87}Rb/^{86}Sr$. From the gradient of this trend the program may recommed either Model 2 or Model 3 as the best fitted line. In some regressions neither Model 2 nor Model 3 is preferred, and the analysis may stop or continue to Model 4 in which the weighting of the excess geological variance contains elements of Models 2 and 3.

Table 10 lists one, three or four fitted isochrons as appropriate. Where the program has given a preferred model, this is indicated in the table. Uncertainties in age and initial ratio are at the 95% confidence limits. For the cases where the MSWD exceeds unity, the error limits given for Model 1 indicates what the uncertainties would have been if all the samples had fitted within experimental error. One of the Errabiddy 'isochrons' consists only of

TABLE 9. ANALYTICAL DATA FOR 48 WHOLE ROCK SAMPLES, 1 SEPARATED MUSCOVITE AND 5 SEPARATED BIOTITES FROM LOCALITIES MENTIONED IN THE TEXT

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
			Rocky Bore		
47045	150	225	0·66 ± 0·01	1·92 ± 0·02	0·781 96 ± 0·000 31
*47042	163	140	1·16 ± 0·01	3·40 ± 0·03	0·854 51 ± 0·000 33
47043	195	160	1·21 ± 0·01	3·54 ± 0·04	0·841 22 ± 0·000 41
47040	190	145	1·30 ± 0·01	3·81 ± 0·04	0·852 30 ± 0·000 38
47044	225	165	1·37 ± 0·02	4·01 ± 0·04	0·860 11 ± 0·000 51
47041	210	150	1·40 ± 0·02	4·11 ± 0·04	0·866 88 ± 0·000 47
			Errabiddy		
47046	185	125	1·51 ± 0·02	4·40 ± 0·05	0·832 17 ± 0·000 53
47047	125	135	0·93 ± 0·01	2·71 ± 0·03	0·814 27 ± 0·000 39
47048	110	140	0·79 ± 0·01	2·31 ± 0·02	0·809 94 ± 0·000 37
47049	61	140	0·44 ± 0·01	1·28 ± 0·02	0·808 36 ± 0·000 51
47050	75	110	0·68 ± 0·01	1·98 ± 0·02	0·817 04 ± 0·000 48
47051	130	100	1·28 ± 0·01	3·76 ± 0·04	0·838 64 ± 0·000 48
47052	290	58	4·87 ± 0·05	14·4 ± 0·1	0·942 90 ± 0·000 58
47053	130	100	1·27 ± 0·01	3·75 ± 0·04	0·872 51 ± 0·000 51
47054	155	82	1·91 ± 0·02	5·61 ± 0·06	0·893 31 ± 0·000 50
			Forty Mile Well		
47057	170	260	0·65 ± 0·01	1·89 ± 0·02	0·753 13 ± 0·000 31
47057 (bt)	800	8	100·5 ± 2	426 ± 8	5·492 1 ± 0·005 1
47055	160	235	0·68 ± 0·01	1·97 ± 0·02	0·754 29 ± 0·000 35
47055 (bt)	750	6·5	114·6 ± 2	534 ± 10	6·967 3 ± 0·006 9
47056	210	260	0·80 ± 0·01	2·30 ± 0·02	0·760 55 ± 0·000 29
47056 (bt)	930	18	51·8 ± 1·0	182 ± 4	2·883 5 ± 0·003 3
47058	165	130	1·29 ± 0·01	3·76 ± 0·04	0·793 75 ± 0·000 32
47059	165	120	1·38 ± 0·02	4·03 ± 0·04	0·801 05 ± 0·000 34
			Red Rock		
47060	330	280	1·18 ± 0·01	3·42 ± 0·04	0·785 68 ± 0·000 41
47060 (bt)	1 250	37	34·1 ± 0·07	112 ± 2	2·055 9 ± 0·002 1
47063	275	145	1·90 ± 0·02	5·55 ± 0·06	0·833 22 ± 0·000 44
47061	275	140	1·96 ± 0·02	5·73 ± 0·06	0·835 61 ± 0·000 38
47061 (bt)	1 200	27	44·9 ± 0·9	152 ± 3	2·502 5 ± 0·002 6
47064	285	135	2·11 ± 0·02	6·17 ± 0·07	0·848 21 ± 0·000 35
47064 (bt)	1 100	17	65·4 ± 1·0	240 ± 5	3·466 7 ± 0·003 5
47062	190	85	2·24 ± 0·02	6·56 ± 0·07	0·860 71 ± 0·000 40
			Roadside Bore		
47080	125	260	0·47 ± 0·01	1·37 ± 0·02	0·754 63 ± 0·000 31
47081	165	340	0·49 ± 0·01	1·42 ± 0·02	0·755 83 ± 0·000 35
47079	135	265	0·51 ± 0·01	1·48 ± 0·02	0·758 50 ± 0·000 46
47076	115	235	0·51 ± 0·01	1·48 ± 0·02	0·758 86 ± 0·000 29
47077	120	235	0·51 ± 0·01	1·48 ± 0·02	0·758 61 ± 0·000 31
47075	110	150	0·74 ± 0·01	2·15 ± 0·02	0·782 08 ± 0·000 39
47074	115	145	0·80 ± 0·01	2·32 ± 0·03	0·788 50 ± 0·000 36
			Dog Rocks		
47089	45	470	0·099 ± 0·002	0·286 ± 0·004	0·712 48 ± 0·000 21
47084	50	485	0·101 ± 0·002	0·292 ± 0·004	0·713 13 ± 0·000 25
47088	50	470	0·105 ± 0·002	0·303 ± 0·004	0·713 98 ± 0·000 24
47082	50	440	0·112 ± 0·002	0·324 ± 0·005	0·714 40 ± 0·000 32
47083	55	500	0·112 ± 0·002	0·324 ± 0·005	0·714 39 ± 0·000 30
47086	80	285	0·279 ± 0·004	0·81 ± 0·01	0·732 65 ± 0·000 29
47085	100	265	0·37 ± 0·01	1·07 ± 0·01	0·742 27 ± 0·000 41
47087	110	205	0·54 ± 0·01	1·56 ± 0·02	0·760 14 ± 0·000 38
			Tommy Bore		
47066	71	560	0·127 ± 0·002	0·367 ± 0·005	0·717 36 ± 0·000 33
47070	86	630	0·137 ± 0·002	0·396 ± 0·005	0·716 31 ± 0·000 34
47067	70	500	0·140 ± 0·002	0·41 ± 0·01	0·718 58 ± 0·000 28
47069	90	630	0·143 ± 0·002	0·41 ± 0·01	0·715 91 ± 0·000 26
47072	88	585	0·151 ± 0·002	0·44 ± 0·01	0·719 11 ± 0·000 37
47071	90	590	0·153 ± 0·002	0·44 ± 0·01	0·717 20 ± 0·000 29
47068	87	480	0·181 ± 0·003	0·52 ± 0·01	0·720 44 ± 0·000 37
47073	95	425	0·224 ± 0·003	0·65 ± 0·01	0·727 87 ± 0·000 41
			Mica Bore		
47065 (musc)	240	35	6·82 ± 0·07	20·7 ± 0·2	1·236 50 ± 0·000 55

* This sample has been omitted from the regression analysis—see text.
(musc)—separated muscovite.
(bt)—separated biotite.

two sample points. In this case the age listed has not been computed by the program and no error limits have been given. No regression analysis data is given for the Tommy Bore samples since the data do not define an isochron. Biotite ages have been calculated for samples from Red Rock and Forty Mile Well, and these are given in Table 13.

DISCUSSION OF RESULTS

ROADSIDE BORE

In the general vicinity of Roadside Bore, amoeboid shaped bodies of granitoid intrude banded gneiss. In places, a protoclastic foliation and banding are developed in the granitoid at the contact with the gneiss. This margin effect diminishes in intensity and becomes very weak about two hundred metres from the contact. The sample site (lat. 25°58′30″, long. 118°11′50″) 3 km northeast of Roadside Bore, is in the granitoid within three hundred metres of such a contact.

Seven samples were collected from within a radius of 150 m. They include 47074, 47076, 47077, 47081 which are coarse-grained to medium-grained, seriate in part, pink, chloritic (after biotite) granite; 47074 and 47076 are weakly banded. Other phases include pegmatite (47075); leucogranite (47080); and a more biotite-rich phase containing biotite schlieren (47079). In thin section, the dominant granite type has microperthitic microcline, quartz, plagioclase, and minor biotite or chlorite after biotite.

This granite gives an isochron of 2 461 ± 92 m.y. The only alteration is dusting of plagioclase and breakdown of biotite into chlorite. The weak foliation is probably syntectonic to the granite intrusion. Therefore the recorded age is likely to be a magmatic event.

The initial $^{87}Sr/^{86}Sr$ ratio of 0.7058 ± 0.0021 is relatively high for a granite with an age of 2 460 m.y. (Faure and Powell, 1972, p. 45). This could be due to one of three factors: metamorphic equilibration on a whole-rock scale; contamination of a granite magma by crustal material rich in ^{87}Sr; or a derivation from reconstituted older crustal rocks. There is no evidence of substantial recrystallization so that metamorphic equilibration is not likely. Neither is there evidence for contamination of the magma by extraneous crustal material. We therefore suggest that the granite is derived from partial melting of the older banded gneiss sequence.

TABLE 10. REGRESSION DATA FOR THE WHOLE ROCK SAMPLES IN TABLE 9
(DATA FROM TOMMY BORE HAVE NOT BEEN TREATED)

Regression	Number of samples	(a) MSWD	Age (m.y.)	R_i	Model
Rocky Bore	5	5·0	2 608 ± 771	0·709 3 ± 0·003 3	1
			2 603 ± 149	0·709 5 ± 0·006 5	(b) 2
			2 619 ± 213	0·708 7 ± 0·010 7	3
Errabiddy	2		783	0·830 6	....
	3	0·03	744 ± 214	0·785 4 ± 0·009 5	1
	4	50·3	725 ± 20	0·796 7 ± 0·001 2	1
		-	764 ± 207	0·794 9 ± 0·006 2	2
			712 ± 77	0·797 4 ± 0·008 1	3
Forty Mile Well	5	4·2	1 557 ± 53	0·710 2 ± 0·002 0	1
			1 550 ± 122	0·710 4 ± 0·004 3	2
			1 561 ± 100	0·710 0 ± 0·004 1	3
			1 561 ± 100	0·710 0 ± 0·004 1	(b) 4
Red Rock	5	10·8	1 604 ± 56	0·706 3 ± 0·004 0	1
			1 596 ± 165	0·706 9 ± 0·011 8	(b) 2
			1 619 ± 227	0·705 1 ± 0·017 9	3
Forty Mile Well and Red Rock (combined)	10	6·8	1 560 ± 17	0·709 9 ± 0·000 9	1
			1 554 ± 44	0·710 2 ± 0·002 0	(b) 2
			1 602 ± 54	0·709 5 ± 0·003 3	3
Roadside Bore	7	0·57	2 461 ± 92	0·705 8 ± 0·002 1	1
Dog Rock	8	0·74	2 573 ± 52	0·702 3 ± 0·000 5	1

(a) mean square of weighted deviates.
(b) preferred model.

DOG ROCKS

This site (lat. 25°55'45", long. 118°15'30") is 2.5 km south of Dog Rocks within a body of granodiorite and adamellite, and is 2 km south of an intrusive contact with banded gneiss. Near the contact, the granitoid is strongly foliated and has pink and grey banding. These banded phases occur sporadically throughout the granitoid body, and a penetrative foliation is locally developed. Eight samples were collected within a radius of about 50 metres. The dominant rock (samples 47089, 47088) is a grey, medium-grained to coarse-grained biotite granodiorite containing oligoclase and minor microcline. Sample 47082 is similar, but has pink microcline phenocrysts. The remainder of the suite is made up of: foliated, pink and grey banded granitoid (47084, 47083), a cross-cutting pegmatite (47086), a leucogranite dyke (47085), and a medium-grained, pink, biotite granite similar to granite near Roadside Bore (47087).

These granitoids provide an age of 2 573 ± 52 m.y. and this is considered to be a magmatic age. Little alteration is present, but some phases have a strongly developed foliation and/or weak banding. The foliation is strongest near contacts with the older gneiss and decreases in intensity away from the contact. The foliation and banding have a swirling flow-like appearance in some places.

The fabric is considered to be related to the intrusion of the granitoid, and was caused by the magma, in a crystal-mush state, pushing against the older gneiss. No later stage deformation or metamorphism is needed to explain the foliation development, and the age recorded is probably a magmatic event. The initial ratio of 0.7023 ± 0.0005 is consistent with either a direct mantle derivation or partial melting of the base of the crust.

ROCKY BORE

In the vicinity of Rocky Bore, a number of bodies of granitoid of various textural types, ranging from even-grained to seriate, to porphyritic, intrude a north northeast-trending complex of banded gneiss and migmatite. The Rocky Bore body is seriate to porphyritic containing scattered prolate megacrysts of microcline aligned in a northerly direction. Petrographically, it is a biotite-microcline-quartz granite containing subordinate plagioclase. Grain size is 2-4 mm, and quartz has crystallized as sub-grains 0.5-1.0 mm across. Biotite has been recrystallized as have the margins of most other grains. Some biotite has been chloritized. The body was sampled on the eastern margin (lat. 25°46'50", long 117°08'00").

Five points from Rocky Bore give an isochron of around 2 600 m.y. (Table 10). This probably records the intrusion of the granite, and therefore gives a younger limit on the age of the migmatite. The date also falls within the range of major batholithic granitic activity elsewhere in the Yilgarn Block. The quality of the isochron, moreover, precludes the possibility of major Proterozoic events having affected the rock, as happened at Errabiddy. One point (47042) lies well above the isochron and has not been used in the regression analysis. This rock, which is a leucocratic clot of quartz, microcline and plagioclase bounded by a recrystallized sheared margin, presumably acted as a sink of radiogenic strontium liberated from the surrounding, biotite-bearing rock during a later, minor thermal event.

The initial strontium ratio of 0.7093 is too high for a directly mantle-derived granite of that age; therefore, it probably represents anatexis of crustal material. This is supported by the nature of the contact between the granite and the surrounding migmatite. The contact is gradational from massive granite, which develops a migmatitic-style foliation and banding and passes into migmatite with a complex foliation over a distance of several hundred metres. The style of the contact is suggestive of an autochthonous anatectic origin.

ERRABIDDY

A migmatite complex similar to that at Rocky Bore was sampled 10 km west-southwest of Errabiddy homestead, (lat. 25°29'50", long. 117°03'00") with a view to determining directly the age of the metamorphism which produced the migmatite. The rock is a well-layered migmatite with abundant small-scale isoclinal folds, ptygmatic veining and other flow-style structures. The overall trend of metamorphic layering is north-northeast. The metamorphic component of the migmatite is granodiorite (marginal to adamellite) biotite gneiss, with abundant evidence throughout of post-crystallization events indicated by strained polygonized quartz, bent biotite, altered plagioclase, and exsolution of albite from anorthoclase to give perthite. The granitoid component is coarse-grained and leucocratic, and could involve two types—one seen as distinct bands and a possibly later variety occurring as amoeboid-shaped masses. The latter contains clots of biotite. Samples were taken at 3 points within a 200 m radius.

The nine samples analyzed do not form a single isochron (Fig. 25) and the data indicate a complex history.

The only meaningful way to view the results is in three groups, each corresponding to a sampling cluster. Thus 47046, 47 and 48 were collected from one point, the group consisting of 47049, 50, 51 and 52 from another and 47053 and 54 from the third. This grouping produces isochrons of 744 m.y., 725 m.y. and 783 m.y. respectively, and unrealistically high initial ratios. These ages are clearly related to a thermal agent later than the initial crystallization of the rock. The good alignment of the analyses at most of the other sampling localities suggests that restricted whole rock equilibration of this kind only occurred at Errabiddy. Such an event could reflect a period of rapid temperature decrease as a result of uplift, and hence closure of mineral lattices with respect to Rb and Sr. A short heating event at this time could have also occurred. The data is insufficient to distinguish between these two possibilities.

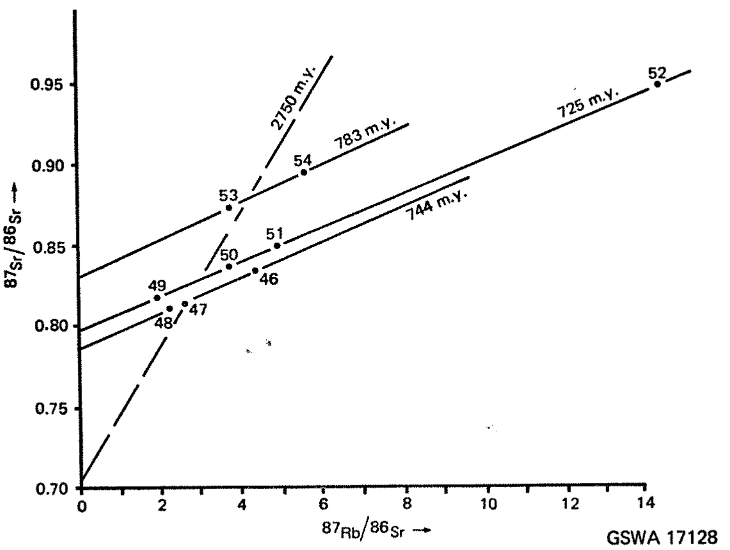

Figure 25 Isochron plot for whole-rock samples from Errabiddy. First three digits of sample numbers omitted. Reference isochron of 2 750 m.y. (R_i = 0.7075) shown by dashed line.

Geological evidence also suggests a complex history. The migmatite at Errabiddy probably was initially part of the same regional tectonic unit as seen at Rocky Bore (the "Archaean gneissic terrane" of Elias and Williams, 1977), but has been affected by Proterozoic tectonic and metamorphic events that formed the Gascoyne Province. Evidence from de Laeter (1976) and this paper indicates that the main metamorphic and intrusive events related to the Gascoyne Province occurred between 2 150 m.y and 1 550 m.y. ago, with a peak at 1 700-1 550 m.y. in the southern part of the province. The age of about 750 m.y. from Errabiddy however, is similar to the widespread mineral ages reported by de Laeter (1976) from the Gascoyne Province. No evidence of an older date, either Lower Proterozoic or Archaean, can be derived from the Errabiddy data. As geological evidence demands that the rocks are older than 750 m.y., then the 750 m.y. thermal event has caused the development of new 'isochrons' of smaller gradient across a much older isochron which would give the original age of the migmatite. Thus points lying above this reference isochron (shown as a dashed line in Fig. 25) would represent whole rock samples of lower than average mica content for their immediate location which soaked up, during the thermal event, radiogenic strontium from neighbouring rock volumes with higher mica contents. Therefore, the three new 'isochrons', although derived from whole rocks, can be considered as effective mineral isochrons of a rock which is mineralogically, and therefore isotopically, homogeneous over a larger volume. Had larger volumes of rock been isotopically analyzed, then the points on each of the new 'isochrons' could possibly be averaged to a single point, and the three resultant "average" points may define an older date representing the time at which strontium was homogeneous over the range in which all the samples were collected. Thus, the data available for Errabiddy do not give direct information on the original age of the migmatite.

The high initial strontium ratios given by the three 'isochrons' however could be a clue to the original age of the migmatite. If it is assumed that no rubidium or strontium metasomatism has occurred, i.e. that the rocks have behaved as a closed system since the migmatite was first formed, then knowing the approximate average Rb/Sr ratio of the migmatite, the rate of development of the $^{87}Sr/^{86}Sr$ ratio can be approximated. Assuming a reasonable value of 0.705-0.710 for the $^{87}Sr/^{86}Sr$ initial ratio for the migmatite at the time of formation, and averaging the strontium ratios prevailing 750 m.y. ago (given by the intercepts of the 750 m.y 'isochrons') to about 0.805 (Fig. 25), the time for the strontium ratios to rise from 0.705 or 0.710 to 0.805 can be calculated, and an estimate of the prehistory of the rock before 750 m.y. ago can be made. Whether any other metamorphic events have affected the rock during this prehistory is immaterial so long as the first assumption remains valid. Using the relationship defining the development of the $^{87}Sr/^{86}Sr$ ratio: (Faure and Powell, 1972, p. 12),

$$^{87}Sr/^{86}Sr = (^{87}Sr/^{86}Sr)_o + {}^{87}Rb/^{86}Sr\ (e^{t}-1)$$

where:—

$^{87}Sr/^{86}Sr$ = the ratio of strontium isotopes at t = 750 m.y.;

$(^{87}Sr/^{86}Sr)_o$ = the same at the time of initial crystallization of the migmatite;

$^{87}Rb/^{86}Sr$ = the ratio of these isotopes, approximated to a constant value over time, since the rate of decay of ^{87}Rb is very small;

t = the time between the initial crystallization of the migmatite and the last homogenization event (750 m.y. ago);

λ = the decay constant of ^{87}Rb ($1{\cdot}42 \times 10^{-11}\ yr^{-1}$)

The results for various values of $^{87}Rb/^{86}Sr$ and $(^{87}Sr/^{86}Sr)_o$ which are given in Table 11, show a possible prehistory of the order of 2 000 m.y. before the 750 m.y. thermal event, consistent with the Archaean age assigned to the migmatite by Elias and Williams (1977).

TABLE 11

TIME, IN MILLIONS OF YEARS, FOR DEVELOPMENT OF Sr RATIOS FROM ASSUMED INTIAL RATIOS (R_i), TO 0.805 AT 750 M.Y. AGO, FOR VARIOUS AVERAGE $^{87}Rb/^{86}Sr$ VALUES

$^{87}Rb/^{86}Sr$	Time required (m.y.)	
	R_i = 0·710	R_i = 0·705
3·5	1 885	1 983
3·0	2 195	2 309

RED ROCK

At Red Rock (lat. 25°20'35", long. 1117°59'10"), porphyritic adamellite with some even-grained phases forms part of a large body which intrudes reworked basement.

At Red Rock itself one sample (47060) of medium-grained biotite adamellite was taken. Most of the suite is taken from within a 50 m radius of a point 1 km southwest of Red Rock. Sample 47061 is porphyritic adamellite, and the remaining samples 47062 (aplite), 47063 (fine-grained leucocratic adamellite) and 47064 (fine-grained biotite adamellite) are from small dykes which intrude the porphyritic adamellite. The nearest outcrop of reworked Archaean gneiss to this locality is 3.5 km to the southwest.

An age of 1 600 m.y is recorded, and there is no evidence that this is other than a magmatic event. The samples do show thorough recrystallization but there is little metamorphic alteration other than saussuritization of plagioclase. The initial $^{87}Sr/^{86}Sr$ ratio of 0.7065 is, for a granitoid of this age, indicative of the incorporation of large amounts of older crustal material (Faure and Powell, 1972, p. 45). Anatexis of Archaean gneissic crust is regarded as the most likely origin of this granitoid.

FORTY MILE WELL

Another large body of relatively late-stage granitoid occurs near Forty Mile Well, 24.5 km northwest of Red Rock. In the sampling area, which is within a 200-metre radius of a point (lat. 25°14'30", long. 117°46'10") 2.2 km west of Forty Mile Well there is a complex admixture of coarse-grained, seriate adamellite, porphyritic adamellite, and fine-grained to medium-grained adamellite. Interrelationships suggest that these phases are co-magmatic. There are also some minor raft-like bodies of partly injected, banded gneiss and nebulitic migmatite which probably constitute older material. Samples 47055, 47056 and 47059 are foliated, medium-grained, seriate or porphyritic, biotite-oligoclase-microcline adamellite with muscovite; 47057 is fine-grained adamellite; and 47058 is a cross-cutting dyke rock.

These mixed adamellitic granitoids provide an isochron age of 1 557 m.y. which is considered to be the magmatic age. A probably anatectic origin, related to the partial melting at depth of older, gneissic crustal material is indicated by the high $^{87}Sr/^{86}Sr$ ratio (0.7102) for a granitoid of this age.

Both the Red Rock and the Forty Mile Well sample sites are part of a major granitoid batholith which was intruded along the northern margin of the Yarlarweelor Gneiss Belt (Elias and Williams, 1977). The difference in ages between granitoids from the two areas may be real, reflecting successive phases of intrusion and crystallization in a single magmatic event. Alternatively, the age difference may be regarded as within the limits of experimental error. Table 10 shows that by considering the preferred model age for the two localities, the age ranges indicated overlap completely. Even with the reduced error limits of the model 1 ages, there is still considerable overlap. The age can be better defined by combining the data from the two localities into a single isochron. Table 10 shows the results of this combination, an age of 1 554 ± 44 m.y. The preference for a model 2 isochron suggests that there is an age difference between the two localities, but the doubling of the number of points defining the isochron has resulted in considerably reduced error in both slope and initial Sr ratio. The age of 1 554 m.y. is therefore regarded as a more accure indication of the age of intrusion of this regional granitoid.

TOMMY BORE

In the Tommy Bore area, an elongate pluton of granodiorite is intruded along a shear zone between the layered sequence of the Trillbar Belt (Elias and Williams, 1977) and the reworked gneiss of the Yarlaweelor Gneiss Belt. The contact zones of this granodiorite are strongly foliated, and a penetrative foliation persists into the pluton for about 1 km. The sample site (lat. 25°32'10", long. 117°47'30") is 1 km south of a contact between granitoid and banded gneiss. Samples 47070, 47069, 47072 and 47071 are of medium-grained, biotite granodiorite containing abundant microcline. Samples 47067 and 47073 are from rafts of banded leucocratic gneiss; 47068 is a late stage pegmatite; and 47066 is from a dyke of fine-grained adamellite.

Because of the narrow range of $^{87}Rb/^{86}Sr$ (Table 9) no reliable isochron can be obtained from the Tommy Bore data, although four of the eight points form an approximate isochron at 1 420 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of about 0.71. This date is considered to be too unreliable to postulate a magmatic event of such a young age, and if it has any real meaning it may record a phase of activity along the shear zone which the granodiorite intrudes. There is ample evidence of post-intrusive activity within the granodiorite. It has a well-defined fabric defined by flattened quartz grains and aligned recrystallized biotite flakes. Quartz is completely recrystallized, plagioclase is saussuritized (often heavily), and in some samples there has been complete recrystallization of plagioclase grain boundaries. Continued or sporadic activity along the shear zone may well account for the fact that the strontium isotopes have been irregularly redistributed.

MICA BORE

Interfolding of reworked Archaean gneiss and Proterozoic supracrustal sediments occurs in the Mica Bore area. At the sample locality (lat. 25°28'50"", long. 118°05'30"), 3 km northeast of Mica Bore, quartz-mica schist, considered to be originally part of the Archaean basement, has been remetamorphosed and tightly folded, and a new axial planar fabric is developed. The new fabric is expressed by elongate, recrystallized quartz grains and aligned muscovite flakes. Muscovite therefore appears to have been completely recrystallized, and its model age would date this Proterozoic metamorphic event. Sample 47065 (musc) consists of muscovite separated from the whole rock.

For calculating the model age, some idea of the initial ratio can be obtained by considering Red Rock and Forty Mile Well granitoids which are thought to be derived from the older material in the Yarlarweelor Gneiss Belt. The R_i of these are 0.705 and 0.710, but at Mica Bore, the schists are unusually rich in muscovite, and were therefore probably originally richer in ^{87}Rb. This would cause a comparatively large increase in the ^{87}Sr content of the schist, and hence increase the $^{87}Sr/^{86}Sr$ of the muscovite at the time of recrystallization.

A reasonable range of R_i for muscovite is 0.70 to 0.74, and variations in model age within this range are shown in Table 12. This clearly establishes realistic limits for the age of metamorphism and basement reworking, and the preferred figure is 1 702 m.y.

TABLE 12. VARIATION OF MUSCOVITE MODEL AGE WITH INITIAL $^{87}Sr/^{86}Sr$ RATIOS, MICA BORE (SAMPLE 47065 (Musc.))

Initial Ratio	Model Age (m.y.)
0·70	1 802
0·71	1 769
0·72	1 763
0·73	1 702
0·74	1 672

GEOCHRONOLOGY IN RELATION TO PRECAMBRIAN TECTONISM

South of the Bullbadger Shear Zone and south of the Murchison Tectonic Lineament (Fig. 24), Archaean ages are recorded by granitoids which intrude gneissic terrain and greenstone belts, and there is no evidence of any Proterozoic activity. In this area, structural trends are generally oriented north to northeast, except where locally disturbed by intrusion of granitoids.

North of the Bullbadger Shear Zone and north of the Murchison Tectonic Lineament, Archaean structural trends are disrupted, and are generally easterly, but quite variable. Within this disturbed zone, which contains reworked Archaean gneiss and granitoid together with some metamorphosed supracrustal rocks, a dynamothermal event at about 1 700 m.y., and a thermal event at about 750 m.y. are recorded. The geochronological data presented here support the postulation (Elias and Williams, 1977) that the Bullbadger Shear Zone and the Murchison Tectonic Lineament provide an approximate boundary between the Yilgarn Block to the south and the Gascoyne Province to the north.

Within the Yilgarn Block on the Robinson Range Sheet, lithological, structural, and metamorphic contrasts suggest that the gneisses are older than the greenstone sequences. Both groups are intruded by granitoid bodies, such as the Rocky Bore and Roadside Bore granites, the R_i of which suggest derivation from older crustal rocks. It is proposed that partial melting of older gneissic rocks took place between 2 700 m.y. and 2 500 m.y. and the anatectic granitoids so produced were emplaced in rocks of lower metamorphic grade at higher levels in the crust.

Strontium isotope data for the Dog Rocks granodiorite (R_i = 0.702) is consistent with a direct mantle derivation for granitoid of this age (2 570 m.y.). It would, however, fit the partial melting hypothesis to suggest that the Dog Rocks granodiorite was derived from partial melting of upper mantle or lower crustal material during the same period of heating which was responsible for anatexis at higher crustal levels.

The emplacement of the Roadside Bore granite (2 460 m.y.) is the last recorded Archaean event in the area studied.

A period of Proterozoic orogenesis involving regional metamorphism, deformation and granitoid diapirism is thought to have taken place in the approximate interval of 1 800 to 1 650 m.y. This activity affected 'pre-Padbury Group' supracrustals and involved the tectonic and metamorphic reworking of the Archaean gneissic sequence. Geochronological evidence presented here suggests an Archaean age for the migmatite near Errabiddy. The preferred model age for the regeneration of muscovite at Mica Bore is 1 700 m.y., and this is probably related to the waning of the first Proterozoic metamorphic and tectonic event that affected this mobile region. Gneissic and granitic rocks from the central part of the Gascoyne Province record similar ages of 1 738 m.y. and 1 637 m.y. (de Laeter, 1976). Metamorphic rocks from the northwestern Gascoyne Province have a similar age of 1 693 ± 235 m.y. (Compston and Arriens, 1968).

The regional metamorphism of the Gascoyne Province is broadly contemporaneous with granitoid activity in the central part, but is significantly older than the granitoids in the eastern part, such as at Red Rock and Forty Mile Well (1 550 m.y.). The initial $^{87}Sr/^{86}Sr$ ratio data for these granitoids is consistent with an origin by partial melting of older crustal material. This process of magma generation seems to be the expression at a deeper crustal level of the first Proterozoic regional metamorphism, and the actual emplacement of these granitoids at a higher level in the crust did not occur until sometime after their formation. A subtle alternative is that these granitoids formed after the first regional Proterozoic metamorphism in an event which left little or no mark at higher crustal levels.

The intrusion of these later granitoid batholiths as diapirs is considered to be responsible for a second period of deformation during which the Padbury Group, along with the pre-Padbury metasediments and reworked Archaean gneissic terrain was folded in mantled gneiss domes (Elias and Williams, 1977). The Padbury Group was not affected by the first Proterozoic regional metamorphism and deformation, but the 'pre-Padbury Group' metasedimentary sequence was so affected.

It is concluded that the Padbury Group was not deposited at the time of the Proterozoic regional metamorphic event, so an older limit on the age of the Padbury Group is approximately 1 700 m.y. The Padbury Group was, however, deformed as a result of the nearby emplacement of the late granitoids, and the best estimate of the age of these (the combined Red Rock-Forty Mile Well isochron) is 1 554 m.y. The Padbury Group is therefore confirmed as a Lower Proterozoic supracrustal sedimentary sequence, as was first suggested by Barnett (1975), with an age of deposition sometime between 1 700 and 1 550 m.y.

A short heating event, widespread throughout the Gascoyne Province at about 800 m.y., may be responsible for the biotite mineral ages recorded from the Red Rock adamellite and Forty Mile Well adamellite (Table 13).

TABLE 13. MINERAL AGES CALCULATED FROM WHOLE ROCK SAMPLES AND THEIR RESPECTIVE SEPARATED BIOTITES (DATA FROM TABLE 9), FROM FORTY MILE WELL AND RED ROCK

	Sample	Age (m.y.)
Forty Mile Well	47055	818
	47056	826
	47057	783
Red Rock	47060	816
	47061	799
	47064	764

At Errabiddy whole rock isochrons also give a date of around 750 m.y. (Table 10). However, there is no petrographic evidence, in terms of alteration or recrystallization, for such a late stage metamorphism. Similar mineral ages (average 765 m.y.) have been reported by de Laeter (1976) from further west in the Gascoyne Province. If such a metamorphic event was so widespread throughout the Gascoyne Province at this time, its effects would be expected to be observed in Gascoyne Province rocks as well as in basal units of overlying Bangemall Group sediments. No such effects have been documented. It seems more likely that this 750-800 m.y. age reflects a period of rapid temperature decrease and hence closure of mineral lattices with respect to rubidium and strontium movement as a result of uplift. Present data suggest an overall decrease in mineral ages from east to west in the Gascoyne Province, but more data would be needed to confirm this.

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THE AGE OF THE SYENITIC ROCKS OF THE FITZGERALD PEAKS, NEAR NORSEMAN

by J. R. de Laeter* and J. D. Lewis

ABSTRACT

The Fitzgerald Peaks Syenite is one of a number of small alkaline intrusives occurring near the axis of the major greenstone belt of the Eastern Goldfields Province of the Yilgarn Block. Using a decay constant of 1.42 x 10^{-11} yr^{-1} a Rb/Sr age of 2 360 ± 96 m.y. (R_i = 0.7044 ± 0.002) is reported which excludes the possibility that this intrusion is related to the nearby Proterozoic Albany-Fraser Province. Because of petrographic and chemical similarities it is suggested that all the syenitic intrusions in the province have a similar age.

INTRODUCTION

Systematic regional mapping of the Eastern Goldfields Province of the Yilgarn Block has located a number of small syenitic and alkali-granite bodies. Most of the intrusions are found in a north-south zone about 70 km wide by 500 km long situated close to the axis of the major greenstone belt of the region (Libby, in press). With the possible exception of the Widgiemooltha dyke swarm the alkaline rocks appear to be the youngest magmatic phase in the province.

The Fitzgerald Peaks Syenite occurs at the southern end of the zone of alkaline intrusions and, with an area of 120 km², is the largest single body known. Prior to this study no direct evidence of the age of the Fitzgerald Peaks Syenite was available but its closeness to the Albany-Fraser Province, and the presence in this metamorphic belt of two small alkaline bodies, suggested the possibility of a Proterozoic age. The present paper reports an Archaean whole rock age for the Fitzgerald Peaks Syenite and discusses the implications of this for the regional geology of the Eastern Goldfields Province.

PREVIOUS GEOCHRONOLOGICAL WORK

A review of Archaean geochronology in Western Australia has been made by Arriens (1971) who has shown that the majority of granite ages in the Yilgarn Block fall within the range 2 700-2 500 m.y. These granites occupy at least 50% of the area of the block and form the framework within which the greenstone belts occur. Older ages of up to 3 100 m.y. were obtained from the gneissic belt which forms the western margin of the Yilgarn Block,

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and Proterozoic ages of about 2 200 m.y. for a series of minor acid intrusions and small granite bosses in the Southwestern Province.

In the Eastern Goldfields Province Turek (1966) obtained ages of about 2 700-2 600 m.y. for a variety of granites and shales in the vicinity of Kalgoorlie, but of particular interest are ages obtained from the Widgiemooltha dyke suite and a whole rock/mineral isochron for a single sample from the Fitzgerald Peaks. The Widgiemooltha dykes, an east-west trending swarm of very large dykes widely scattered throughout the Eastern Goldfields, were generally recognized at the time as being the youngest intrusions in the region and gave an age of 2 420 ± 30 m.y. This event, with the gold mineralization at 2 400 ± 30 m.y., marks the close of the Archaean in Western Australia. A single sample collected from the Fitzgerald Peaks, however, gave an apparent age of 1 670 m.y. on a whole rock/microcline isochron. However, as the associated initial $^{87}Sr/^{86}Sr$ ratio was 0.7473, and the rock was asumed to be Archaean, it was suggested that the age was spurious and that there had been a loss of radiogenic ^{87}Sr from the microcline.

To the east and northeast of the Fitzgerald Peaks a wide variety of Proterozoic ages have been found in the Albany-Fraser Province. Wilson and others (1960) dated muscovite from a pegmatite in the Fraser Range at 1 210 m.y. (K/Ar) and 1 280 m.y. (Rb/Sr) while Bunting and others (1976) found ages ranging from 1 725 m.y. to 1 289 m.y.

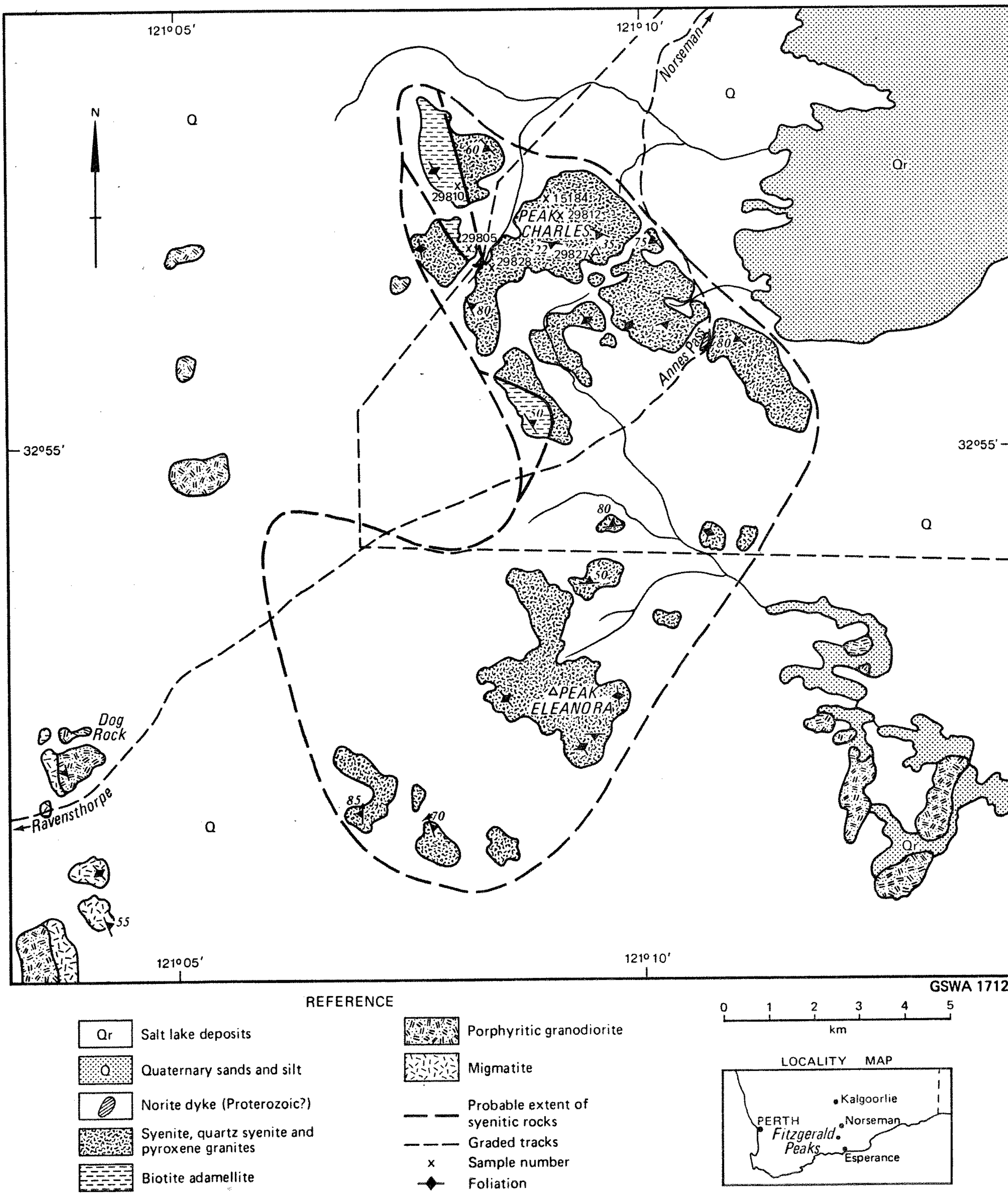

Figure 26 Geological sketch map of the Fitzgerald Peaks.

at the northern end of the belt. It was suggested by Bunting and others (1976) that the marginal rocks of the Yilgarn Block had been reworked and incorporated within the mobile zone along with the intrusion of younger granites. The presence of a riebeckite rhyolite at Bobbies Point with a model age of 1 190 m.y., close to an adamellite dated at 1 725 m.y., indicates the possibility that an alkaline magmatic phase associated with the formation of the mobile zone could also have been responsible for the intrusion of the Fizgerald Peaks Syenite.

GEOLOGY OF THE FITZGERALD PEAKS

The regional geology of the Lake Johnston area, which includes the Fitzgerald Peaks, has been described by Gower and Bunting (1972), while a more detailed account of the geology and petrology of the syenitic rocks has been given by Lewis and Gower (in press). Briefly, the Fitzgerald Peaks Syenite is located 96 km south-southwest of Norseman, near the southwest margin of a large Archaean batholith which occupies the eastern third of the Lake Johnston 1 : 250 000 sheet and covers an area in excess of 5 000 km². The principal rock type within the batholith is a porphyritic biotite-adamellite which grades into porphyritic biotite-granodiorite. Foliation is usually north-northwest, parallel to the trend of the Archaean greenstone belts, but 16 km south of the Fitzgerald Peaks the batholith is truncated by the Albany-Fraser Province and foliation in the granite is northeast, possibly reflecting a Proterozoic influence.

The Fitzgerald Peaks are a prominent group of hills rising over 300 m above the plain of the surrounding Archaean granite. Peak Charles, the highest of the group, is a conical hill of bare rock 658 m high. Geophysical evidence outlines a roughly crescent-shaped mass (Fig. 26) and although its margins are nowhere exposed it is presumed to be intruded into the surrounding granite. The rock is pink, medium-grained, and is distinctive in that it contains rare xenoliths of mafic rock in various stages of assimilation and the mafic mineral is a dark-green clinopyroxene. Commonly the rock type is a quartz syenite containing mesoperthite, 5-10% quartz and aegirine-augite. The proportion of quartz is variable, however, from almost nil to 20% thus giving a range from syenite to pyroxene-granite. In places biotite replaces aegirine-augite as the mafic mineral and the perthite has unmixed to give discrete oligoclase crystals, giving rise to biotite adamellite (Fig. 26). Chemically the two varieties are similar except for a slightly lower alkali content in the biotite adamellite (Lewis and Gower, in press). However, Libby (in press) suggests that the biotite adamellite is chemically intermediate between the syenitic rocks and the surrounding granitoids and possibly represents a mixture of the two.

MATERIALS USED

The samples analyzed in this study were all collected during the regional mapping of the Lake Johnston area and their locations are marked on Figure 26. The choice of sample was based on a preliminary determination of Rb and Sr to obtain as wide a range as possible. Six samples were finally analyzed, all from the Peak Charles area, and included two biotite adamellites, two leucocratic alkali granites and two samples which showed intermediate petrographic characteristics.

Specimen 29805 is typical of the biotite adamellite, being medium-grained with a normal granitic texture and mineralogy. Anhedral crystals of microcline, oligoclase (An_{12-15}) and quartz are the principal minerals with small flakes of interstitial olive-brown biotite distributed throughout the rock.

Accessory minerals include apatite, zircon, and magnetite with a little chlorite and fluorite and plentiful sphene. The sphene occurs as lozenges and amoeboid grains and is characteristic of all rock types in the Fitzgerald Peaks. The mineral is orange-brown in colour, often zoned, has relatively low birefringence and is sometimes metamict. Specimen 29828, from the main mass of Peak Charles, is essentially similar to 29805 except that green hornblende replaces biotite and there are a few relict grains of aegirine-augite altering to blue-grey arfvedsonite. The second biotite adamellite specimen, 29810, is a leucocratic variety in which much of the biotite has altered to chlorite and in which a little pumpellyite is present. The feldspar in this rock consists of albite/oligoclase (An_{8-14}) and perthite.

Specimens 15184 and 29812 are both coarse-grained leucocratic alkali granites containing about 80% mesoperthite and 20% quartz with accessory magnetite and sphene. In both specimens the sphene is metamict and partly converted to rutile. Specimen 15184 also contains a little accessory fluorite. Mesoperthite forms large anhedral grains with complex lobate margins. The proportion of exsolved albite (An_{5-10}) varies from about 30% to 90% and occurs as untwinned oriented spindles or broad bands and patches which show poorly developed polysynthetic twinning. The overall texture suggests hypersolvus crystallization.

Specimen 29827 is a medium-grained quartz-poor alkali granite which contains relicts of aegirine-augite altering to arfvedsonite with a few flakes of red-brown biotite. The feldspar is predominantly a mesoperthite with broad bands of exsolved albite, but in part this has broken down to discrete grains of microcline and albite. Orange-coloured sphene, apatite and zircon are common and there is a little secondary carbonate.

EXPERIMENTAL PROCEDURES

The experimental procedures for Rb/Sr analyses used in this study were essentially the same as those described by Lewis and others (1975). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project was 0.7102 $\pm$ 0.0001, normalized to a $^{88}Sr/^{86}Sr$ value of 8.3752. The value of 1.42 x $10^{-11}yr^{-1}$ was used for the decay constant of ^{87}Rb (Steiger and Jäger, 1977). It should be noted that this is the first time this value for the decay constant has been used by the laboratory, as in earlier publications a value of 1.39 x $10^{-11}yr^{-1}$ has been adopted.

RESULTS

The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios, as well as the calculated $^{87}Rb/^{86}Sr$ ratios are given in Table 14. Errors accompanying the data are at the 95 per cent confidence level. The Rb and Sr concentrations in each sample are also listed. However these concentrations are only accurate to $\pm$7 per cent and the Rb/Sr ratios may not correspond exactly with the ratios which would be derived from the separate Rb and Sr values listed.

The data listed in Table 14 have been regressed using the least squares programme of McIntyre and others (1966). The age and initial ratio of the Fitzgerald Peaks Syenite, assuming experimental variation only, is 2 356 $\pm$ 25 m.y. and 0.70446 $\pm$ 0.00073 respectively. However, the mean square of weighted deviates (MSWD) is greater than expected from experimental variations alone. A more realistic estimate of the age and initial ratio would be 2 360 $\pm$ 96 m.y. and 0.70436 $\pm$ 0.00225, which is the model 4 age based on the assumption that there is some variation in age and initial ratio in the data itself, in addition to experimental variation. This assumption is supported by the inclusion in the isochron of the adamellite samples which may be mixtures of the alkali magma and older granitic material.

Table 15 also lists the regression data based on a decay constant for ^{87}Rb of 1.39 x $10^{-11}yr^{-1}$. This allows for a better comparison between the new and old data and gives a preferred age of 2 411 $\pm$ 98 m.y. for the Fitzgerald Peaks Syenite. This age will be used in the following discussion.

DISCUSSION

The confirmation of an Archaean age for the Fitzgerald Peaks Syenite places the intrusive event with several other late Archaean events in the Eastern Goldfields Province. If an affinity with other alkali intrusives throughout the province is accepted then it is possible that the age of the Fitzgerald Peaks rocks dates a period of minor but widespread alkaline activity in the Eastern Goldfields Province. The Archaean age also eliminates the possibility that the Fitzgerald Peaks Syenite is directly associated with igneous activity during the formation of the Proterozoic Albany-Fraser mobile zone. However, as Bunting and others (1976) have suggested, part of the mobile zone may be reworked Archaean material and it is possible that the small alkaline bodies within the zone and to the south of Fitzgerald Peaks may be remnants of Archaean intrusions.

TABLE 14. ANALYTICAL DATA FOR THE FITZGERALD PEAKS SYENITE

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
29828	45	385	0·116 ± 0·001	0·337 ± 0·003	0·715 31 ± 0·000 51
29805	140	415	0·336 ± 0·003	0·973 ± 0·01	0·738 63 ± 0·000 47
29827	170	330	0·516 ± 0·006	1·50 ± 0·02	0·754 86 ± 0·000 42
29810	147	125	1·18 ± 0·01	3·46 ± 0·03	0·824 60 ± 0·000 53
29812	125	65	1·91 ± 0·02	5·60 ± 0·06	0·889 98 ± 0·000 59
15184	200	85	2·33 ± 0·03	6·90 ± 0·07	0·940 97 ± 0·000 71

TABLE 15. REGRESSION DATA FOR THE FITZGERALD PEAKS SYENITE

	Age (m.y.)		Intercept
	$\lambda = 1{\cdot}42 \times 10^{-11}yr^{-1}$	$\lambda = 1{\cdot}39 \times 10^{-11}yr^{-1}$	
Model 1 MSWD = 13·59	2 356 ± 26	2 407 ± 26	0·704 46 ± 0·000 73
2	2 376 ± 103	2 427 ± 105	0·703 96 ± 0·001 39
3	2 347 ± 97	2 398 ± 99	0·704 70 ± 0·005 25
4*	2 360 ± 96	2 411 ± 98	0·704 36 ± 0·002 25

* preferred age.

The possibility of a Proterozoic age for the intrusion of the Fitzgerald Peaks Syenite rested on a correlation between a single point whole rock model age of 1 190 m.y. for the Bobbies Point riebeckite rhyolite (Bunting and others, 1976) and the whole rock/mineral age of 1 670 m.y. obtained by Turek (1966) for a single sample from Peak Charles. The field relations and petrology of this specimen are not known, however, and it cannot be determined with certainty whether the specimen was truly part of the alkaline suite. Turek himself suggested that the age he had obtained was spurious and thought that there had been a loss of radiogenic ^{87}Sr from the microcline. This remains one of a number of possible explanations for the obvious failure of Turek's analysis (GA 1461, Fig. 27) to conform with the simple and coherent pattern of our results.

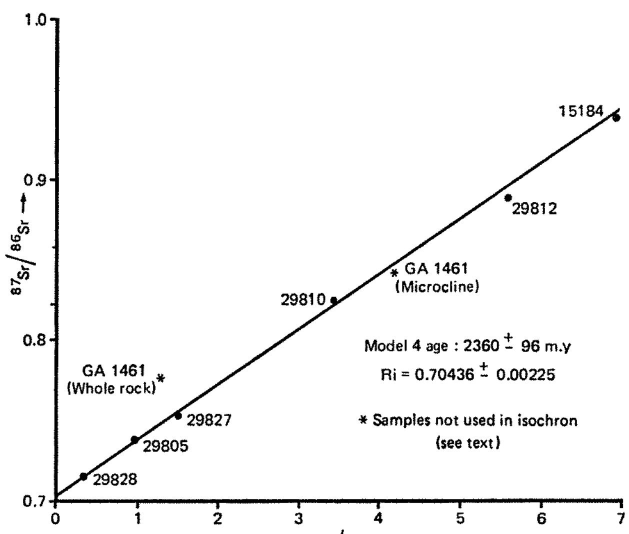

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Figure 27 Isochron plot of six whole rock analyses from the Fitzgerald Peaks Syenite.

In the southern part of the Eastern Goldfields Province the age of 2 411 ± 98 m.y. for the Fitzgerald Peaks Syenite places it with the Widgiemooltha dyke suite (2 420 ± 30 m.y.) and gold mineralization (2 400 ± 30 m.y.) (Turek 1966).

The small norite body in Anne's Pass, then, appears to be a member of the major dyke suite intruded shortly after the syenite.

Libby (in press) has shown that petrographically and chemically the Fitzgerald Peaks intrusion is similar to a number of other quartz-poor alkaline intrusives distributed over a distance of more than 500 km along the axis of the major greenstone belt of the region. In particular the rocks contain a distinctive mesoperthite, aegirine-augite or arfvedsonite, and an orange-coloured sphene. It seems possible, therefore, that the formation of this rock-type occurred at a similar time throughout the province, that is at 2 411 ± 98 m.y. The only comparable age determination in the northern part of the area is 2 480 ± 30 m.y. for the Mount Boreas Granite, 300 km north of Kalgoorlie (Bunting and Williams, 1976). This type of granite—potash-rich and fluorite-bearing—is both chemically and mineralogically distinct from the syenites but it does contain a similar orange-coloured sphene, unlike the older granites and gneisses. Mount Boreas-type granite intrusions are widely distributed throughout the same area as the smaller syenitic bodies, and, although in some localities it probably intrudes the syenite, both types are thought to be the youngest intrusive rocks of the area. The Fitzgerald Peaks age determination thus confirms the close association in time of the two rock types.

In conclusion, the final phase of Archaean magmatic activity in the Eastern Goldfields Province of the Yilgarn Block, during the period 2 480-2 400 m.y., appears to have begun with the intrusion of small bodies of quartz-poor alkaline rocks and larger bodies of quartz and potash-rich granites. This was followed by major fracturing of the crust and the intrusion of the east-west Widgiemooltha dyke suite and, finally, by widespread gold mineralization.

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A MONZONITIC PLUTON NEAR LAKE SHASTER

by W. G. Libby and S. L. Lipple

ABSTRACT

A mildly alkaline hornblende-biotite-andesine-microcline monzonite is exposed at Lake Shaster, Western Australia, about 70 km east-southeast of Ravensthorpe, in the Proterozoic Albany-Fraser Province. Small amounts of nepheline and/or olivine appear in the C.I.P.W. norm of several samples but not in the mode. One sample has 0.04 per cent normative quartz. Quartz appears in the mode of several samples.

Chemical trends fail to establish that the monzonite is a product of simple differentiation either from a parent magma of nearby calc-alkaline acid volcanics or from a parent magma of Archaean quartz-poor felsic alkaline plutonic rocks of the Eastern Goldfields Province.

INTRODUCTION

A small syenite body was described in the explanatory notes for the Ravensthorpe 1:250 000 geological sheet (Thom and others, 1977). Chemical and additional petrographic data suggest that the term *monzonite* is more appropriate than *syenite*. Further description of the pluton seems appropriate in the light of increasing interest in silica-saturated and slightly over-saturated granitic rocks in the area (Lewis and Gower, 1978; Libby, 1978; and Lewis and de Laeter, 1978).

The monzonite is exposed at the northern margin of Lake Shaster (Lat. 33° 52' S, Long. 120° 44' E), about 70 km east-southeast from Ravensthorpe. Lake Shaster is a large (about 3 km by 6 km) ephemeral salt lake

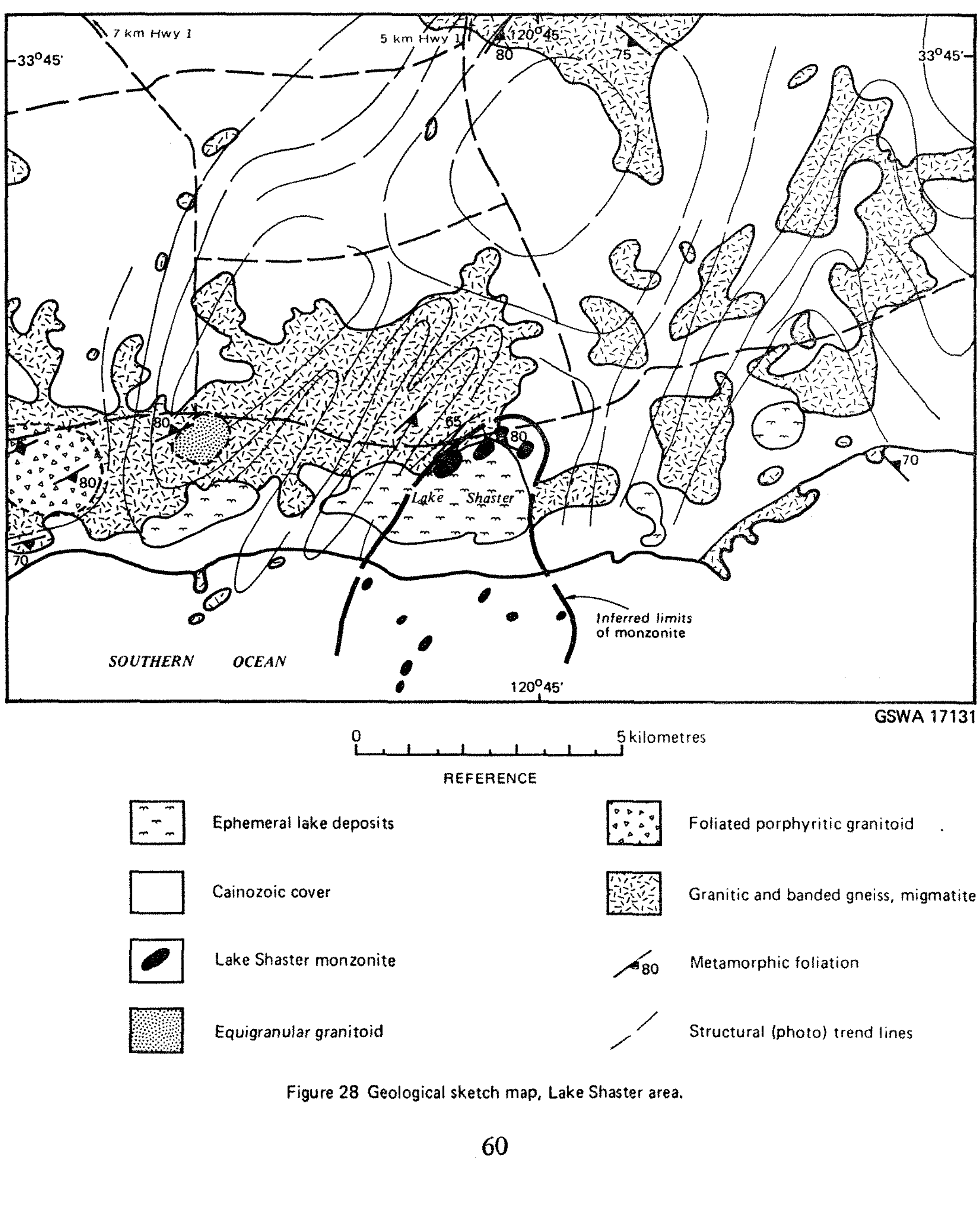

Figure 28 Geological sketch map, Lake Shaster area.

surrounded by low, gently undulating, heath-covered sandplain, and separated from the Southern Ocean by about 0.5 km of coastal dune and beach sand. Several islets in the ocean to the south of Lake Shaster may also be part of the monzonite stock. Access to Lake Shaster is by good gravel roads southward from Highway 1.

REGIONAL GEOLOGY

The regional geology has been described by Thom and others (1977) and is illustrated in the accompanying geological sketch map (Fig. 28). The monzonite is a rounded mass, 5 to 6 km in diameter, situated in a large box-shaped fold formed by enclosing gneiss. The gneiss is well foliated and banded, and ranges from adamellitic to granodioritic, with rare amphibolitic layers. Banding is fine, 1 to 3 cm in width. The metamorphic gneiss and migmatitic country rock are part of the middle Proterozoic mobile belt defined as the Albany-Fraser Province by Daniels and Horwitz (1969). Thom and others (1977) consider that metamorphic rocks of the Albany-Fraser Province were generated by the reworking of Archaean rocks of the formerly more extensive Yilgarn Block. The monzonite pluton is on strike with abundant metamorphosed amphibolite, ultramafic rock and sedimentary rock, probably remnants of an Archaean greenstone terrain (Fig. 28).

West of Lake Shaster several northeast-trending, east-dipping isoclinal folds separate the monzonite body from an oval mass of poorly-foliated biotite adamellite and nebulitic migmatite. The adamellite is fine to medium-grained, dominantly even grained with rare biotite wisps and a few small feldspar phenocrysts but otherwise homophanous. Mineral foliation is defined by alignment of biotite, quartz and feldspar, and varies from weak to prominent. The mass is considered to form a dome with poorly foliated homogeneous adamellite or nebulitic migmatite in the core becoming increasingly foliated toward the margin, passing gradually into gneiss.

A third discrete pluton is exposed over an area of about 1 km by 3 km, about 9 km west of Lake Shaster (Fig. 28). It consists of a strongly and coarsely porphyritic cream-coloured, strongly foliated granite which appears to intrude the surrounding migmatites.

The relation of the two nearby homogeneous granitoids to the monzonite at Lake Shaster is unknown, but they illustrate that homophanous granitoids punctuating the regional gneisses are common in this part of the province.

FIELD CHARACTERISTICS

The monzonite at Lake Shaster forms relatively prominent, smoothly rounded, well-jointed outcrops adjacent to the northern shore of Lake Shaster. The rock is a fresh, massive, homophanous, coarse-grained biotite-hornblende monzonite. Feldspar grains have a uniform pink colour. Phenocrysts are numerous and laths are commonly 2.5 to 3 cm long. Foliation formed by alignment of feldspar, hornblende, biotite and phenocrysts is mainly weak to indetectable, but locally is moderately developed parallel to the regional foliation. Close examination of outcrops identified only sparse amounts of quartz, which is fine grained and bluish. No xenoliths or schlieren were observed. Several thin (less than 10 cm) pegmatite veins strike 100° to 115° and dip 75° north.

Numerous granitoid rocks which are exposed up to 3.5 km offshore in the Southern Ocean, south from Lake Shaster, although not visited, are probably also monzonite. The outcrops exhibit a similar, non-directional, smooth photo-pattern to that of the rocks identified as monzonite. This photo-pattern is in marked contrast to the prominently banded pattern of the adjacent gneiss and migmatite.

Contacts between the monzonite and enclosing gneiss are obscured by superficial sand deposits. However, the contrast in composition and degree of foliation between gneiss and monzonite, and homogeneity of the monzonite suggest the monzonite is younger than the gneiss.

The monzonite also contrasts with the porphyritic, probably Proterozoic, adamellite which is located west from Lake Shaster and is described above. The adamellite has a distinctive colour, texture and composition, includes abundant quartz and mafic schlieren, and is strongly foliated.

PETROGRAPHY

Thin sections were cut from seven samples: 28345 B, C, and D; 29577 B; and 29606 A, B, and C. Brown biotite is the dominant mafic material in all samples but dark green hornblende is also abundant. Microcline is the dominant felsic mineral, constituting about two thirds of the feldspars, the remainder being sodic andesine. A few sections have obvious but minor intergranular quartz (less than 1 per cent), whereas others have little, if any, visible quartz apart from that in the ubiquitous myrmekite. Black opaque grains, probably magnetite, are common in all samples, as is sphene. Accessory zircon and apatite are several times more abundant than average for granitoids of the Yilgarn Block or the Albany-Fraser Province. Allanite is a prominent accessory in all but two of the samples, approaching one per cent in the thin section of sample 29577 B. The allanite, confirmed by x-ray diffraction, is largely metamict but a few grain cores show some optical crystallographic character. Plagioclase extinction angles on (010) in sections cut normal to crystallographic a-axis indicated compositions between An_{30} and An_{35} in all samples.

All samples are allotriomorphic granular; however (001) faces are developed on biotite, and crystal faces are partially developed on zircon, apatite and allanite. All samples are inequigranular and some have coarse insets of microcline. Microcline, especially where coarse-grained is finely perthitic.

CHEMISTRY

Four samples from two localities were analyzed for major elements by chemical methods. The results, together with C.I.P.W. norms, are listed in Table 16. Analyses were performed by the Western Australian Government Chemical Laboratories. Both sample localities are near the presumed northern margin of the monzonite body; one locality (samples 28345 B, C and D) is at the northern margin of Lake Shaster, the other is about 1 km to the northeast.

TABLE 16. MAJOR ELEMENT ANALYSIS

Oxide (%)	28345 B	28345 C	28345 D	29577 B
SiO_2	59·0	59·9	59·4	59·9
Al_2O_3	19·5	18·6	19·0	18·9
Fe_2O_3	1·9	1·7	1·6	2·0
FeO	2·11	2·17	2·28	1·93
MgO	1·1	1·2	1·2	1·1
CaO	2·54	2·06	2·08	2·17
Na_2O	3·10	3·22	3·15	3·36
K_2O	9·1	9·7	9·8	9·0
H_2O^+	0·50	0·40	0·43	0·51
H_2O^-	0·11	0·12	0·12	0·16
CO_2	0·08	0·08	0·07	0·13
TiO_2	0·43	0·47	0·46	0·59
P_2O_5	0·20	0·26	0·26	0·19
MnO	0·06	0·06	0·06	0·07
Total	99·7	99·9	99·9	99·9
C.I.P.W. Norms				
Q	0·00	0·00	0·00	0·04
C	0·65	0·00	0·17	0·43
Or	53·48	57·03	58·15	53·25
Ab	26·23	26·12	23·35	28·43
An	10·79	7·80	8·18	8·70
Ne	0·00	0·61	1·79	0·00
Di	0·00	0·18	0·00	0·00
Wo	....	0·09	....	....
En	....	0·05	....	....
Fs	....	0·03	....	....
Hy	1·69	0·00	0·00	3·72
En	1·05	....	....	2·64
Fs	0·64	....	....	1·08
Ol	2·02	3·46	3·80	0·00
Fo	1·20	2·02	2·08	....
Fa	0·81	1·44	1·73	....
Mt	2·78	2·49	2·29	2·85
Il	0·82	0·89	0·87	1·12
Ap	0·47	0·62	0·62	0·45
Cc	0·18	0·18	0·16	0·30

The composition of analyzed samples is remarkably uniform, in keeping with the uniform petrographic and field characteristics of the rock.

The silica percentage (averaging about 59.5) is abnormally low for a granitoid rock, and potash percentage (about 9.5) is above average. This combination results in C.I.P.W. norms showing a rock very close to silica saturation, again consistent with petrographic observation. Normative quartz (0.04 per cent) is present in a single sample (29577 B), normative olivine appears in three samples (28345 B, C and D) and normative nepheline is present in two samples (28345 C and D). Neither olivine nor nepheline was observed petrographically. Normative ablite:anorthite ratios suggest anorthite contents in the range An_{23} to An_{29}. These are consistent with a-normal extinction angle determinations of An_{30} to An_{35} if some albite is occult in potash feldspar, both in solid solution and, as observed, in perthitic exsolution.

The appearance of nepheline in the norm of some samples qualifies the monzonite as a marginally alkaline rock in the classification of Curry (1976, p.1) even though the silica deficiency seems to be taken up in the mafics.

The monzonite shows little chemical affinity either with analyzed quartz-rich granitoids elsewhere in the region (Thom and others, 1977) or with silica-saturated to weakly oversaturated alkaline granitoids which constitute a part of the granitic suite of the nearby Archaean Yilgarn Block (Gower, 1974; Bunting and Williams, 1976; Lewis and de Laeter, 1978; Lewis and Gower, 1978; and Walker, 1978).

In a plot (Fig. 29) of weight per cent total alkalies against weight per cent SiO_2 the monzonite lies on a trend established by the Yilgarn Block alkaline suite (after Libby, 1978), clearly distinct from a typical calcalkaline trend (Southern California Batholith, Larsen, 1948). Analyses of granitoid rocks from the Ravensthorpe sheet (Thom and others, 1977), though more limited in compositional range than the Californian data, tend to follow the calcalkaline trend of the Californian rocks, distinctly divergent to the alkaline trend of the rocks from the Eastern Goldfields Province and the monzonite at Lake Shaster (Fig. 29). However, in a plot of agpaitic index against solidification index (Fig. 30) with data after Libby (1978) the monzonite plots well clear of the trend of alkaline rocks of the Eastern Goldfields Province. Thus there is no reason, on the basis of these indices, to believe that the monzonite is part of a simple differentiation series related to the Proterozoic granitoids of the area, to the Archaean granitoids of the area, or to the nearby Archaean alkaline rocks. The monzonite may, of course, have been derived from one or another of these suites by secondary differentiation, contamination, or by metasomatic modification of its original composition.

The monzonite is rich in potash. Not only is the absolute K_2O per cent high, but Figure 31 shows that the K_2O:Na_2O ratio in the monzonite is substantially greater than in the agpaitic Archaean alkaline rocks of the area.

PETROGRAPHIC SYSTEMATICS

In the course of study of samples for the Ravensthorpe mapping project, Libby originally identified the monzonite as syenite (Thom and others, 1977). Closer petrographic work on additional samples and chemical analyses completed after the earlier publication suggests that a more appropriate name for the rock is monzonite, though the composition is near the boundary between the monzonite and syenite fields. Available thin sections probably are inadequate to establish the plagioclase:microcline ratio in the body; indeed, the volume per cent of plagioclase derived by point count of three samples, 29577 B, 28345 B and C (34.8, 45.0 and 22.3 per cent respectively) is quite variable, suggesting that the composition of bulk rock is not accurately portrayed by the sections. However, on average the point count supports a monzonitic plagioclase:microcline ratio. The density-adjusted volume per cent of An + Ab in total normative feldspar gives a more stable result, with suggested plagioclase percentages of 40, 36, 34 and 40 per cent, respectively, for samples 28345 B, C, and D and 29557, thus placing the rock, by analysis of norms, firmly in the monzonite field. However, as in the calculation of plagioclase composition from norms, an unknown proportion of the normative albite is in fact resident in alkali feldspar.

In summary, the rock is an andesine (about An_{33}) monzonite with 34 to 38 volume per cent plagioclase and 62 to 66 volume per cent microcline.

CONCLUSIONS

The monzonite at Lake Shaster has a composition not previously reported from other granitic bodies in the area. Chemical trends give no reason to believe that the monzonite is a product of the direct line of magmatic development which has formed associated Proterozoic granitoids, nearby Archaean granitoids, or the Archaean alkaline suite of the

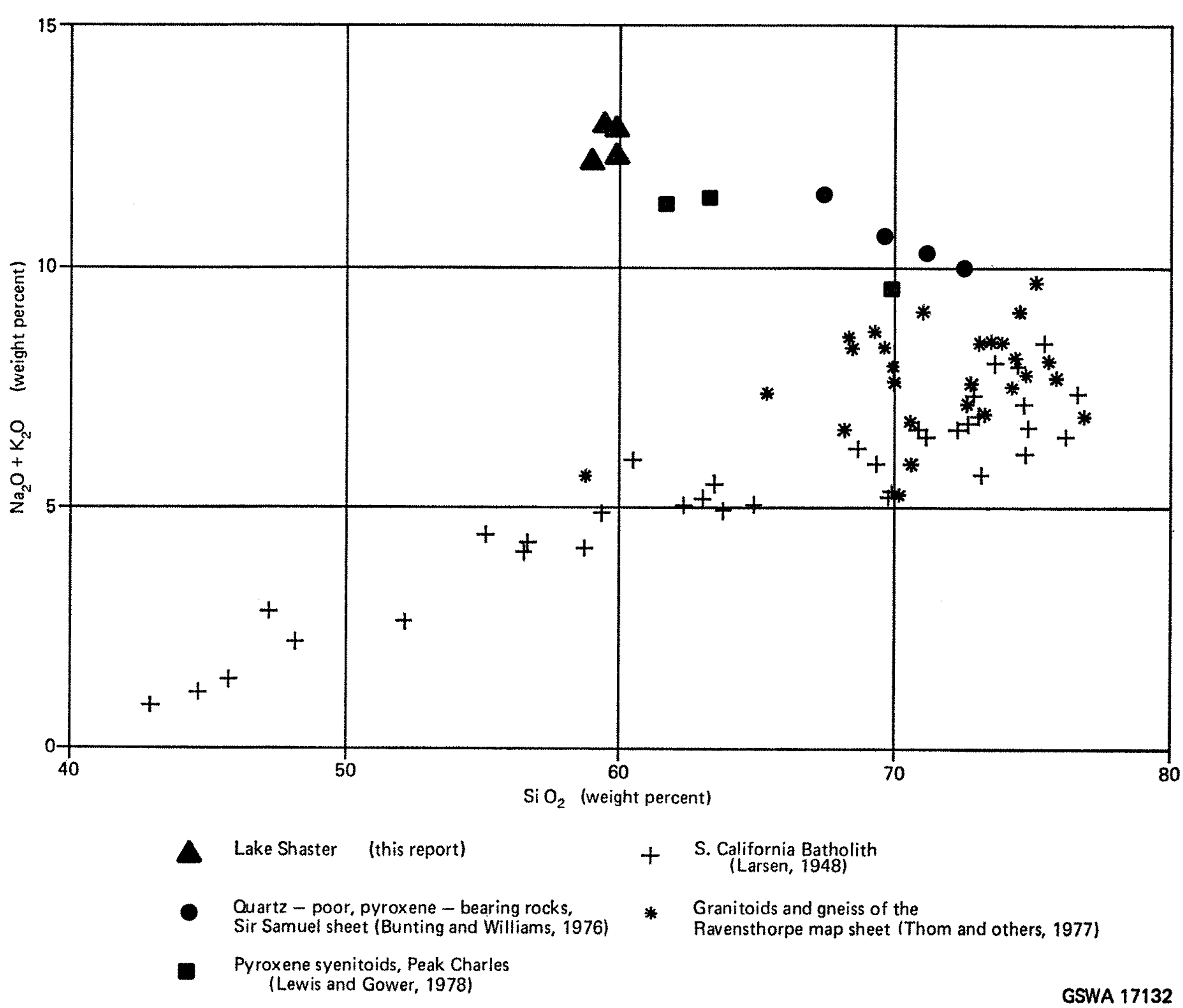

Figure 29 Plot of silica versus alkalis.

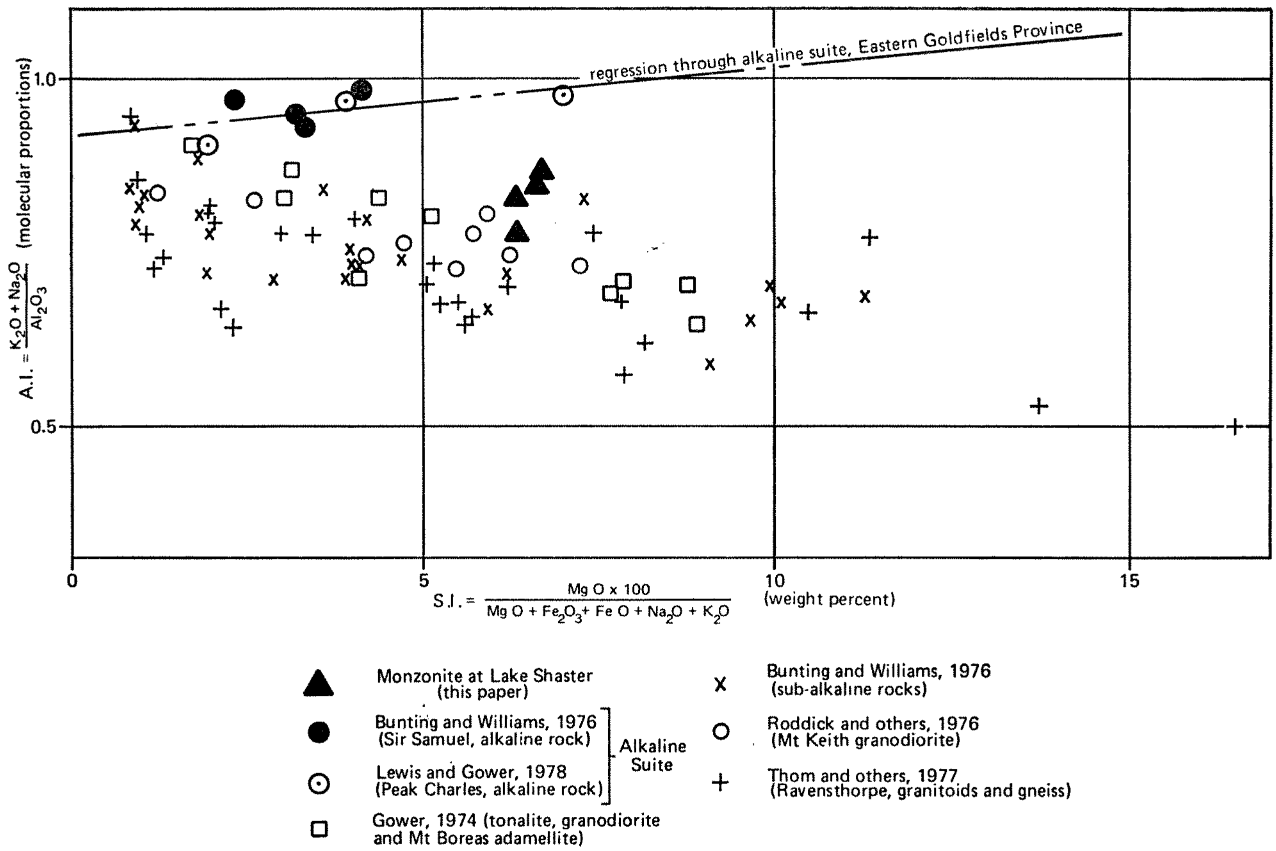

Figure 30 Agpaitic index (A.I.) versus solidification index (S.I.) for Lake Shaster monzonite, two suits of alkaline rock and various granitic rocks from the Eastern Goldfields Province.

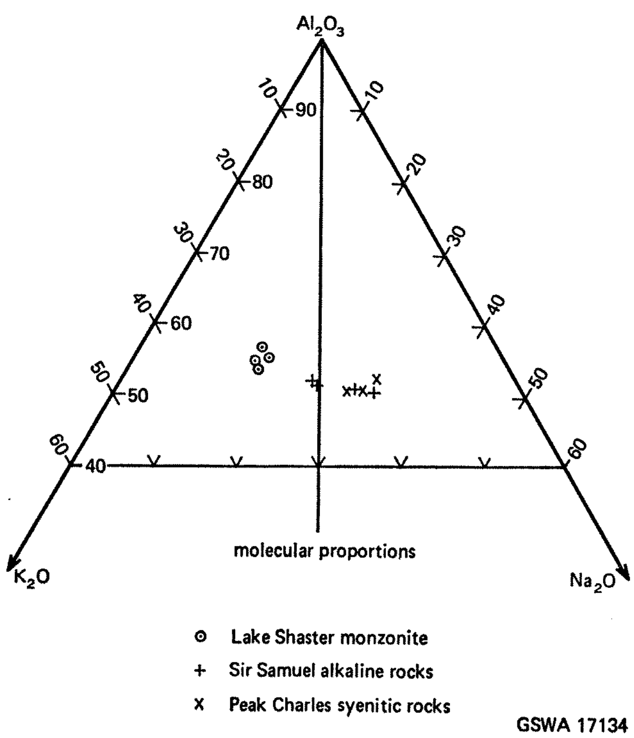

Figure 31 Molecular proportions of Al_2O_3, K_2O and Na_2O in various alkaline granitoids of Western Australia.

Eastern Goldfields Province. However, development from these units by secondary differentiation, contamination, or metasomatic processes is not eliminated.

Miaskitic alkaline affinities are suggested by the alkali and alumina-rich, silica-poor character of the rock, together with abundant zircon and apatite. Despite the apparent homogeneity of the samples examined, syenites undersaturated in silica may be associated with the pluton at a different structural level or at surface level beneath superficial deposits which mostly conceal the pluton.

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PETROLOGICAL EVIDENCE FOR AN UNUSUALLY HIGH ARCHAEAN GEOTHERMAL GRADIENT IN THE WONGAN HILLS AREA, WESTERN AUSTRALIA

by D. F. Blight

ABSTRACT

The mineral assemblage, microcline + andalusite + fibrolite + muscovite + biotite + quartz ± garnet, present in Archaean metapelitic rocks of the Wongan Hills, Western Australia, suggests that physical conditions operating during metamorphism were about 200 MPa pressure at a temperature of about 660°C. This implies an unusually high geothermal gradient of 70°C/km. This high geothermal gradient may well have been caused by the temperature effect of a nearby adamellite body.

INTRODUCTION

During the course of petrological investigations of rocks collected during the regional mapping of the 1 : 250 000 Moora sheet, a mineral assemblage was encountered from which the pressure and temperature of metamorphism could be estimated. This assemblage occurs in diamond drill core donated by Otter Exploration N.L. from their DDH 3 in the southern part of the Wongan Hills (lat. 30° 35′ 19″ S, long. 116° 38′ 25″ E). The Wongan Hills are located approximately 150 km northeast of Perth anl cover an area approximately 20 km long and 6 km wide.

REGIONAL GEOLOGY

The rocks of the Wongan Hills, which have been described by Carter, Low and Lipple (in prep.), constitute part of a belt of Archaean supracrustal rocks. They are composed of metamorphosed and deformed mafic and felsic volcanics intercalated with sediments ranging from banded iron-formations to highly aluminous types. Porphyritic and even-grained Archaean granitoids intrude this sequence. The structure of the area is complex; at least two tectonic events are evident. Presumed Proterozoic dolerite dykes intrude faults and northeast trending fractures. Carter and others (in prep.) suggest a tentative correlation of these Wongan Hills rocks with the "greenstone belts" of the Murchison and Eastern Goldfields Provinces rather than with the Jimperding Metamorphic Belt, some 40 km to the south, previously described by Wilde (1974).

MINERALOGY

The rocks examined from DDH 3 are predominantly metasediments with minor interlayered meta-ultramafics. The metasedimentary assemblages observed are:

(i) microcline (perthitic) + fibrolite + andalusite + muscovite + biotite + quartz ± almandine, with minor tourmaline and sulphide;

(ii) cordierite (altered) + garnet + quartz + biotite + sulphides; and

(iii) quartz + grunerite + sulphides.

The meta-ultramafic assemblage observed is:

(iv) garnet + grunerite + opaques (with minor muscovite and quartz).

Assemblage (i) contains "reaction" textures, which enable a rough estimate to be made of pressure-temperature conditions operating during metamorphism. Rocks of assemblage (i) are composed of large (up to 3.0 mm in size) poikiloblastic crystals of microcline with weakly embayed grain boundaries. The small (0.15 mm) inclusions within the microcline are predominantly quartz, although there is some biotite and muscovite. Between non-abutting microcline grains are ragged (0.4 mm) muscovite flakes and/or laths of biotite or equigranular polygonal mosaics of small (0.2 mm) quartz grains. Scattered throughout the rock are clumps (up to 10 mm) of fibrolite. Fibrolite also occurs as long needles within the microcline and around and within muscovite. In thin section 49162 (Fig. 32a) muscovite can be seen altering to fibrolite via the reaction: muscovite + quartz ⇌ fibrolite + K-feldspar + H_2O. Garnet, when it forms, occurs as porphyroblasts up to 5 mm in size. Fine-grained tourmaline and opaques are scattered throughout the rock. All specimens examined contained retrograde chlorite. In one thin section (49167-3) retrograde muscovite developing from andalusite can be observed (Fig. 32b).

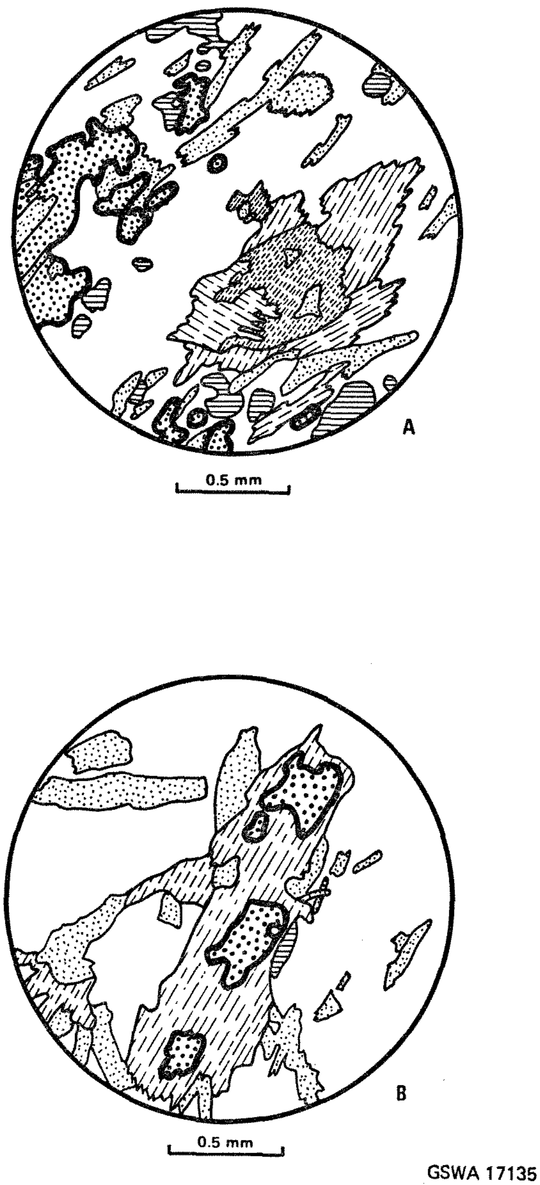

Figure 32 Line drawings from photomicrographs.
The minerals are andalusite (heavy stipple) biotite (light stipple), muscovite (hatched), fibrolite (dense hatching), quartz (horizontal lines) and microcline (clear). a. 49162 b. 49167-3.

The rock has a strong fabric defined by biotite, and more rarely fibrolite, and the orientation of inclusion trails within the microcline. In parts, this strong fabric is very weakly folded indicating at least two phases of deformation. More commonly, the fibrolite, especially when associated with muscovite, has random orientation suggesting a post-tectonic development. A weak compositional layering, possibly relict sedimentary bedding, is also present.

APPLICATION OF EXPERIMENTAL DATA TO WONGAN HILLS ROCKS

From the assemblage (i) it is possible to place constraints on the pressure-temperature conditions of metamorphism provided that P_{H_2O} (water pressure) = P_{Tot} (total pressure). The rocks at Wongan Hills are thought to satisfy this requirement for the following reasons:

(i) the abundance of hydrous phases;

(ii) the breakdown of muscovite to fibrolite liberates water which should fill available pore space, and unless mass removal of this water from the system takes place the water pressure should be close to, if not the same as, the load pressure; and

(iii) there are no carbonates in the area which could give rise to CO_2, which in turn would reduce the partial pressure of the water in the fluid phase.

Touret (1971), through examination of fluid inclusions within rocks belonging to the sillimanite-muscovite-biotite subfacies of the amphibolite facies from Norway, came to a similar conclusion.

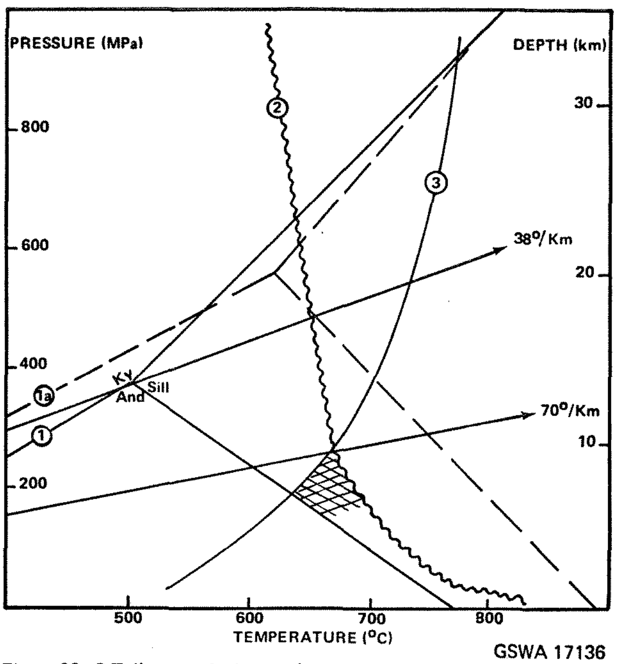

Figure 33 P-T diagram of relevant phases

Curve 1. Andalusite-kyanite-sillimanite (Holdaway, 1971).

Curve 1a. Andalusite-kyanite-sillimanite (Richardson and others, 1969). (note that this andalusite-sillimanite boundary is in the region of a 200°C overstep from that proposed by Holdaway, 1971).

Curve 2. Quartz + albite + orthoclase + H_2O $\rightleftharpoons$ liquid (Winkler, 1967).

Curve 3. Muscovite + quartz $\rightleftharpoons$ K-feldspar + Al_2SiO_5 + H_2O (Winkler, 1967). Note: 100 MPa = 1 kb.

With reference to Figure 33, in which all curves are drawn for the condition of $P_{H_2O} = P_{Tot}$, thin section 49162 has co-existing andalusite and sillimanite (fibrolite) and also shows the reaction muscovite + quartz $\rightleftharpoons$ fibrolite + K-feldspar + H_2O. Thus, using the alumino-silicate phase diagram of Holdaway (1971), as suggested by Anderson and others (1977), it could be argued that provided $P_{H_2O} = P_{Tot}$, this assemblage formed under conditions corresponding to the intersection of curves 1 and 3, namely 630°C and 200 MPa.

The metastable/stable co-existence of two or more alumino-silicate phases has long been recognised. Fleming (1973, in prep.) has suggested, on textural criteria, that fibrolite may develop from andalusite within the andalusite stability field. In a study of rocks from South Australia, he develops a series of exchange reactions involving biotite for micro-subsystems closed to aluminium to explain the appearance of fibrolite and andalusite and their associated textures. On the other hand, Holdaway (1971) suggests that to form fibrolite from andalusite requires 200°C or more of overstepping, while to form fibrolite from muscovite would require an overstepping of the order of only 10°C. Thus, in such cases rock containing andalusite and fibrolite would be in the sillimanite field: the andalusite is metastable.

Holdaway's (1971) hypothesis is preferred for rocks from the Wongan Hills. Examination of textures shows that the fibrolite develops from muscovite (Fig. 32a) *without* the involvement of biotite. Furthermore, if the fibrolite present in these rocks had formed in the andalusite stability field, the resulting geothermal gradient would be even higher than that suggested by this study (Fig. 33).

Assemblage (i) is most likely a disequilibrium assemblage in which the fibrolite developed from muscovite on the high temperature side of curve 3 in the sillimanite stability field (Fig. 33).

Further constraints may be placed upon the pressure-temperature conditions of metamorphism by curve 2 (Fig. 33), which indicates the beginning of melting of a hydrous granite. No evidence for melting was observed in metamorphic rocks of granitoid composition from the Wongan Hills, either in field observations (e.g. no migmatites, Lipple, pers. comm.) or by microscope examination (compare with Mehnert, Busch and Schneider, 1973). Thus these rocks have formed on the low-temperature side of curve 2.

The presence of andalusite requires a geothermal gradient of 38°C/km or more (Fig. 33), and consequently these rocks must have formed on the low-pressure side of such a geothermal gradient.

From the above-mentioned observations, the estimated pressure-temperature conditions of metamorphism of rocks from the Wongan Hills are 140-240 MPa and 640-680°C (shaded area in Fig. 33).

This implies that the rocks from the Wongan Hills were metamorphosed under an unusually high geothermal gradient of 70°C per kilometre. This high gradient may, in part, be due to an Archaean geothermal gradient, which may have been as high as 40-50°C/km (Stewart, 1977), but is more likely to be due to the presence of an external heat source nearby, such as an igneous body. Such a body, in the form of an equigranular, medium to coarse-grained biotite adamellite, crops out approximately 1 km south of DDH 3 (Carter, Low and Lipple, in prep.). This body may well have locally provided the heat to impart the apparently anomalous geothermal gradient, and presumably was responsible for the breakdown of the muscovite to fibrolite.

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HIGH-GRADE RETROGRESSIVE METAMORPHISM AND MINERAL CORONA DEVELOPMENT IN BASIC ROCKS OF THE COLLIE AREA, WESTERN AUSTRALIA

by D. F. Blight

ABSTRACT

Gneisses in parts of the Collie 1:250 000 Sheet were sporadically metamorphosed to the granulite facies by heating and dehydration associated with the intrusion of dolerite dykes. The dykes were emplaced near the end of a period of major tectonic activity while the regional temperature was still high. As the contact-heated gneisses and associated dolerites cooled to a regional temperature corresponding to the amphibolite facies, hornblende, garnet and epidote coronas were locally generated, especially where preferred solution paths facilitated chemical transfer.

INTRODUCTION

During the course of regional mapping and the geological investigations of proposed dam sites on the Collie 1:250 000 Sheet, a few isolated rocks with mineral assemblages indicating granulite facies metamorphism were collected. A more comprehensive sampling and petrological programme was initiated to examine the extent of these granulite facies rocks and to attempt to determine the cause of their occurrence. Because of the extensive development of a laterite profile on the Darling Plateau, fresh rock is generally only exposed along stream-incised valleys. Thus, the two areas around which this investigation was centred are:

(1) along the banks of the Brunswick River south of the Mornington Fire Tower (lat. 33°12'S, long. 115°57'E), and

(2) along the banks of the Collie River near Mount Lennard (lat. 33°20'S, long. 115°53'E).

The area studied is part of a north-trending, probable Archaean, polytectonic gneiss belt (possibly a mobile zone), which grades eastward into a relatively undeformed porphyritic adamellite. Numerous coarse-grained dolerites intrude this sequence. A description of these rocks from Collie Sheet is detailed below.

GNEISSES

The gneisses, which commonly show indications of two deformative events, and which are commonly layered, have a granoblastic, equigranular, polygonal to interlobate texture. As in other high-grade metamorphic terrains, acidic rocks dominate the more basic ones. The majority of the rocks collected showed mineralogical assemblages indicative of the amphibolite facies. In basic rocks the assemblages noted were plagioclase + hornblende + opaques ± quartz ± sphene ± clinopyroxene; and in acid rocks the assemblages were quartz + plagioclase + microcline + biotite ± hornblende ± apatite ± opaques. No evidence was found which might suggest that the amphibolite-facies rocks are downgraded granulites.

Some of the rocks examined contained hypersthene, whose appearance in basic rocks marks the incoming of the granulite facies (Binns, 1969). The majority of granulites from the area are leucocratic. These range in composition from granodiorite to quartz diorite and have the mineral assemblage quartz + plagioclase + biotite + hypersthene + opaques and minor apatite. A few basic granulites were noted (e.g. 48465); these have a disequilibrium assemblage of plagioclase + hypersthene + clinopyroxene + hornblende + garnet + opaques, some of these minerals forming as coronas.

From field and petrological examination, the granulite facies assemblages were found to be very localised, occurring within a regional amphibolite facies terrain. Furthermore, when the locations of the granulite-facies rocks were examined closely it was found that they occurred adjacent to, or nearby (less than 100 m), the coarse-grained dolerites which intrude the region.

DOLERITES

These basic intrusive igneous rocks have a relict subophitic texture overprinted by a static metamorphism. The apparent, primary igneous mineralogy, still partly discernible in thin sections, was labradorite + clinopyroxene + orthopyroxene + opaques and sparse apatite. The subsequent, static, retrograde metamorphism produced diverse minerals, which are commonly manifest as reaction coronas.

CORONITES

Rocks containing minerals with coronas, referred to as coronites, develop from static metamorphism of the basic assemblage (both dolerites and granulites). Hornblende associated with varying amounts of opaques and vermicular quartz, is produced from both types of pyroxenes (Fig. 34); the alteration progressed from the rims of the pyroxene grains inward. This alteration of pyroxene can be seen in all stages: in some cases, hornblende occurs as corona shells about the pyroxene. These hornblende coronas have partly replaced adjacent plagioclase grains; the replacement is apparently greater where the coronas have formed about orthopyroxene. The iron liberated by this reaction commonly forms opaques, frequently as oriented reticulated masses (Fig. 34a) in the cores of hornblende masses, especially when the whole pyroxene grain has altered to hornblende. It may be that these opaques formed from the alteration of hypersthene, a more iron-rich pyroxene, but in any case, the shape of these reticulated opaques is presumably the result of the crystallographic control that the host pyroxene exerts on the exsolution of the opaques. In some thin sections, the presence of microscopic blebs and rods of exsolved opaques imparts a dusty appearance to the pyroxenes. Rarely, some recrystallization has taken place within the pyroxene core so that the hornblende seems to have formed from a secondary pyroxene.

Thin coronas of garnet and varying amounts of vermicular quartz commonly occur around the hornblende masses and shells (Fig. 34b). The coronas abut plagioclase grains, which are zoned progressively from labradorite in the core to andesine adjacent to the garnet. A similar zoning of plagioclase has been noted in coronites studied by Griffin and Heier (1973) and by Starmer (1969). Plagioclase laths are commonly cloudy in the cores, but clear in the less calcic rims.

The garnet corona development within a rock tends to occur in patches or in elongate trails (Fig. 34c). Whether these elongate trails are a linear or planar feature is not known. Rarely, the garnet is present as coronas directly around pyroxene grains.

In two samples (52401 and 52402) the corona structures are augmented by discontinuous patches of epidote-quartz symplectite between the garnet and plagioclase.

GENESIS OF CORONITES

Coronites have been studied since the early work of Sederholm (1916), and the general consensus has been that they are formed by subsolidus metamorphic reactions rather than by magmatic reactions. It is now generally accepted that they result from deuteric alteration during the cooling of an igneous rock or a high temperature metamorphic rock. Griffin and Heier (1973), who have given a most comprehensive account of coronites, emphasise that such cooling must take place " . . . at *moderate to high pressures* in order that the rock should pass through the P-T curve(s) of the appropriate reaction(s) at temperatures high enough to allow reasonable reaction rates" (Author's italics).

Coronas similar to those described above have been observed in basic rocks from Uganda (Hepworth, 1964; de Waard, 1967), Scandinavia (Starmer, 1969; Griffin and Heier, 1973), Spain (Hubregtse, 1973) and New Zealand (Blattner, 1976).

De Waard (1967) suggests that the development of the hornblende and garnet coronas about orthopyroxene occurs in response to the reaction:

$$\text{Opx} + \text{Alb} + \text{An} + H_2O \rightleftharpoons \text{Hbd} + \text{Gnt} + \text{Qtz}$$

Hepworth (1964), on the other hand, suggests that in many cases the orthopyroxene alters to hornblende and garnet via a phase of secondary clinopyroxene. The coronites from Collie and New Zealand show that the hornblende appears to develop directly from both orthopyroxene and clinopyroxene, and Hepworth admits that the generation of a secondary clinopyroxene is not always evident in the Ugandan rocks.

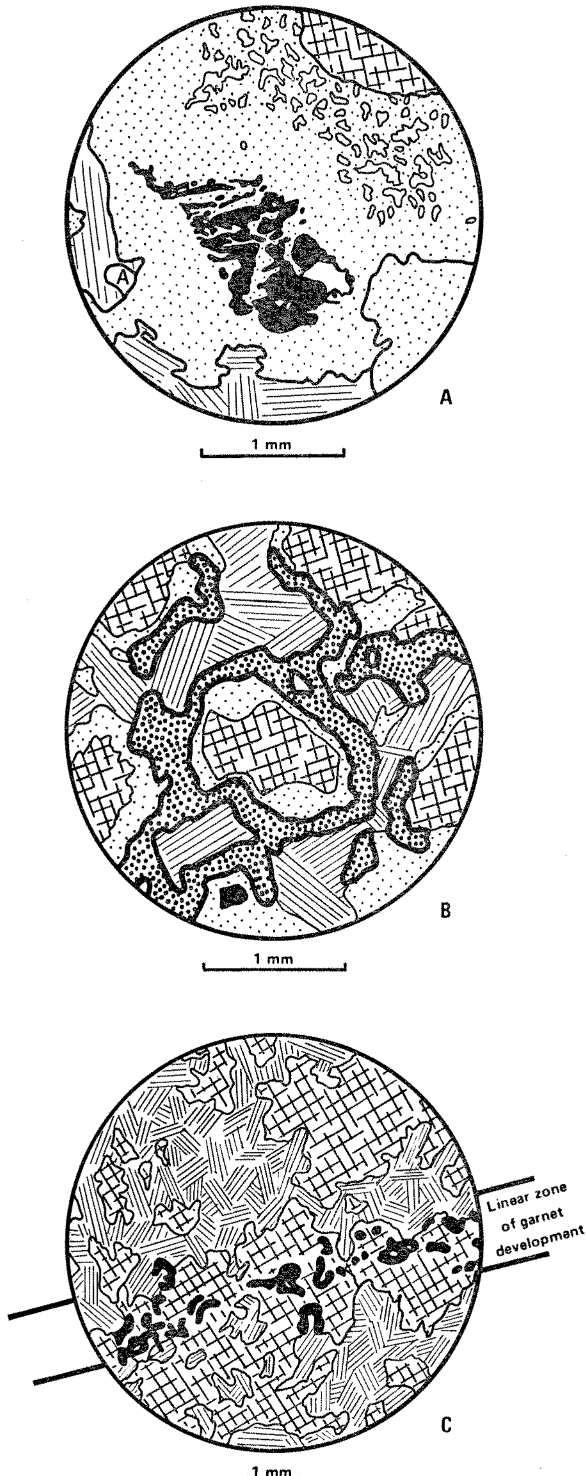

Figure 34 a Hornblende-quartz rim about clinopyroxene core with "crystallographic" controlled exsolved opaques. (50367C)
(Key : cross hatching - clinopyroxene, light stipple - hornblende, dense stipple garnet, hatching - plagioclase, solid - opaques, clear - quartz, A - apatite).
Figure 34 b Garnet corona about hornblende with clinopyroxene core; garnet abuts plagioclase (50370A)
(Key : same as Fig. a).
Figure 34 c Linear zone of garnet corona developed (50370A)
(Key : cross hatching - pyroxene and hornblende, solid - garnet, hatching - plagioclase).

The coronites from Collie provide a range of textures which suggest that the formation of garnet coronas passes through an intermediate stage. Hornblende is produced first, from which the garnet forms, rather than the hornblende and garnet forming at the same time. Thus, two reactions are postulated for the ultimate formation of the hornblende-garnet coronas:

(1) Cpx/Opx + Plag ⇌ Hbl + Qtz + Fe oxides

(2) Hbl + Plag ⇌ Gnt + Qtz + Fe oxides

These two reactions can be combined to give the overall reaction:

(3) Cpx/Opx + Plag ⇌ Hbl + Gnt + Qtz

The variation in textures seen in the rocks from Collie show the first of these two reactions frozen in various stages of completion (e.g. Fig. 34d shows reaction (1) and Fig. 34b shows reactions (1), (2) and (3)). Where pyroxene is mantled directly by garnet with no intervening hornblende it is assumed that hornblende generated by reaction (1) is all used up in the production of garnet by reaction (2). Blattner (1976) also came to a similar conclusion and postulated similar reactions to (1) and (2) above to produce hornblende and garnet mantles about pyroxene.

The production of the epidote-quartz symplectites is a result of the reaction:

(4) Plag + Gnt + Fe oxides + H_2O ⇌ Epid + Qtz

which is nearly independent of temperature above about 200 MPa water pressure (Winkler, 1967, p. 113).

Without the aid of chemical analyses it is impossible to write balanced equations for reactions (1) and (2). Furthermore it is possible that during the corona development the system was chemically open. Evidence for an open system is two-fold. Firstly, within the same thin section, the amount of quartz produced by the alteration of pyroxene to hornblende, and hornblende to garnet, is variable. This can be accounted for if SiO_2 were allowed to migrate out of the system. Secondly, the patchy development of the garnet coronas is very similar to that described by Blattner (1976). He attributes this fact to the formation of garnet along a system of joint planes within the host rock (metadiorite) by means of cation migration along channels thus created by the joints. Elements were lost to these channels, " . . . Na (and K) preferentially, and Al least so". Thus, it is possible that the production of hornblende and garnet coronas in coronites of the Collie area involved fluid phases which facilitated the movement of ions and enabled Ca, Na, Al, and Si to be removed from the system.

Figure 35 is an idealized sketch showing a possible cooling path for the dolerites and basic granulites. Corona development takes place as this cooling curve intersects each

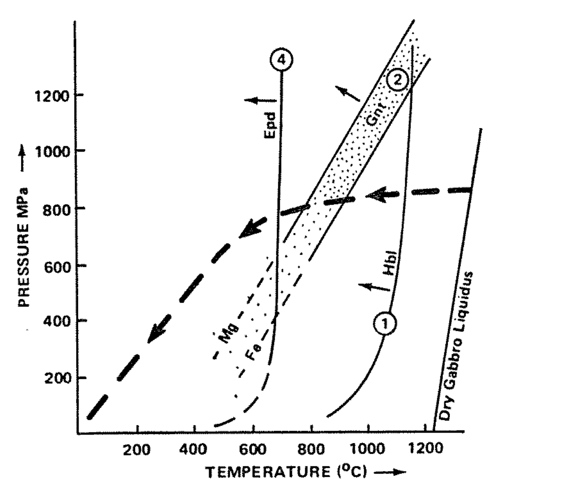

Figure 35

Idealized sketch of probable cooling path for the dolerites and basic granulites

(1) First appearance of hornblende for $P_{H_2O} = P_{Tot}$ (Touret, 1971)

(2) First appearance of garnet (Green and Ringwood, 1967)

(3) First appearance of epidote for $P_{H_2O} = P_{Tot}$ (approximate position from Winkler, 1967)

Passing through these curves gives rise to successive coronas of hornblende, garnet and epidote.

particular upper-stability-limit curve of the appropriate mineral. While these particular stability curves may not be strictly appropriate for this particular system (e.g. P_{H_2O} of the system may not be the same as P_{Tot}) the gross features will be comparable.

The similarity of the basic granulites to the metamorphosed dolerites, both in the development of the coronites and in their close spatial relationship, suggests that the localised occurrence of the granulite-facies assemblage of the Collie area is a result of rocks under amphibolite facies conditions being locally heated by adjacent dolerite dykes into P-T conditions suitable for the development of granulite facies mineralogy.

CONCLUSIONS

Granulite facies rocks were sporadically developed in parts of the Collie 1:250 000 Sheet (between Collie and Bunbury, and between Collie and Harvey), in response to the deep seated (pressure between 500 and 1 000 MPa) intrusion of dolerite dykes towards the end of a major tectonic event. The heat of the dykes dehydrated rocks which were under amphibolite facies conditions, and these elevated temperatures locally produced "contact" granulite facies assemblages.

As the rocks slowly cooled to amphibolite-facies conditions in order to equilibrate with the surrounding material, hornblende, garnet and epidote coronas developed. With this temperature fall, hydrous fluid phases capable of carrying cations moved along preferred solution paths facilitating the garnet development and giving rise to the sporadic, patchy, and linear occurrence of the garnet.

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DISCOCYCLINID FORAMINIFERS FROM WESTERN AUSTRALIA

by A. E. Cockbain

ABSTRACT

Nearly a dozen discocyclinid species have been previously recorded from the Giralia Calcarenite (Carnarvon Basin). Re-examination of the original material does not confirm this taxonomic diversity. Two species, both previously recognized, are described and illustrated from the Giralia Calcarenite on the basis of matrix-free specimens; they are *Discocyclina* cf. *discus* and *Asterocyclina* cf. *stella*. *A.* cf. *hornibrooki* and *D.* sp. are described and illustrated from the Werillup Formation (Bremer Basin).

INTRODUCTION

Discocyclinid foraminifers have long been known to occur in Eocene rocks in Western Australia, and nearly a dozen species have been recorded in the literature. The purpose of this note is to review the previous identifications and to illustrate, for the first time, oriented thin sections cut from matrix-free specimens. Localities mentioned in the text are shown in Figure 36.

PREVIOUS RECORDS

Chapman and Crespin (1935) recorded and illustrated the first discocyclinids (and first positively identified Eocene rocks) from Western Australia. Their samples came from two localities in the Giralia Calcarenite, one on the east flank and one on the west flank of the Giralia anticline. The species identified were:

Asterocyclina cf. *stellata* (d'Archiac)
Actinocyclina cf. *aster* Woodring *(sic)*
Discocyclina dispansa var. *minor* Rutten
D. douvillei (Schlumberger)
D. pratti (Michelin)

Further records of discocyclinids from the Giralia Calcarenite in the Giralia anticline were given by Condon and others (1956), based on identifications by Edgell (1952). The following species were identified but not figured:

Asterocyclina stella Gümbel
A. stellaris (Brunner)
Discocyclina cf. *chudeaui* (Schlumberger)
D. discus (Rutimeyer)
D. fritschi (Douville)
D. cf. *turnerensis* Vaughan

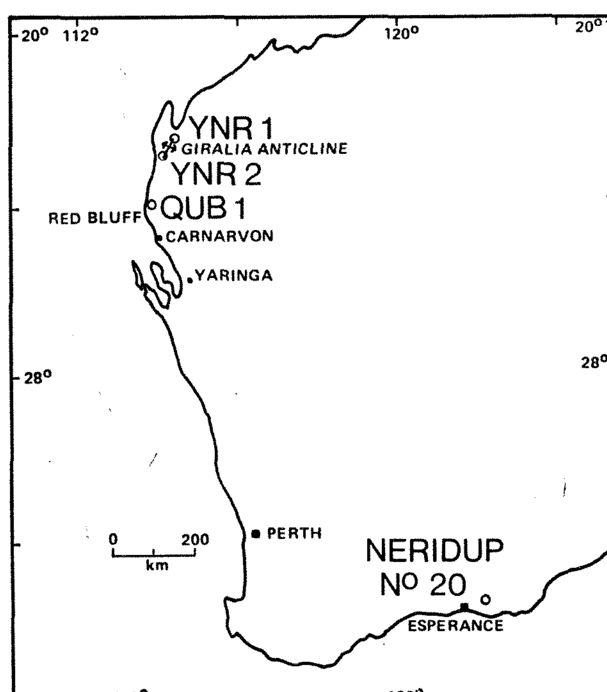

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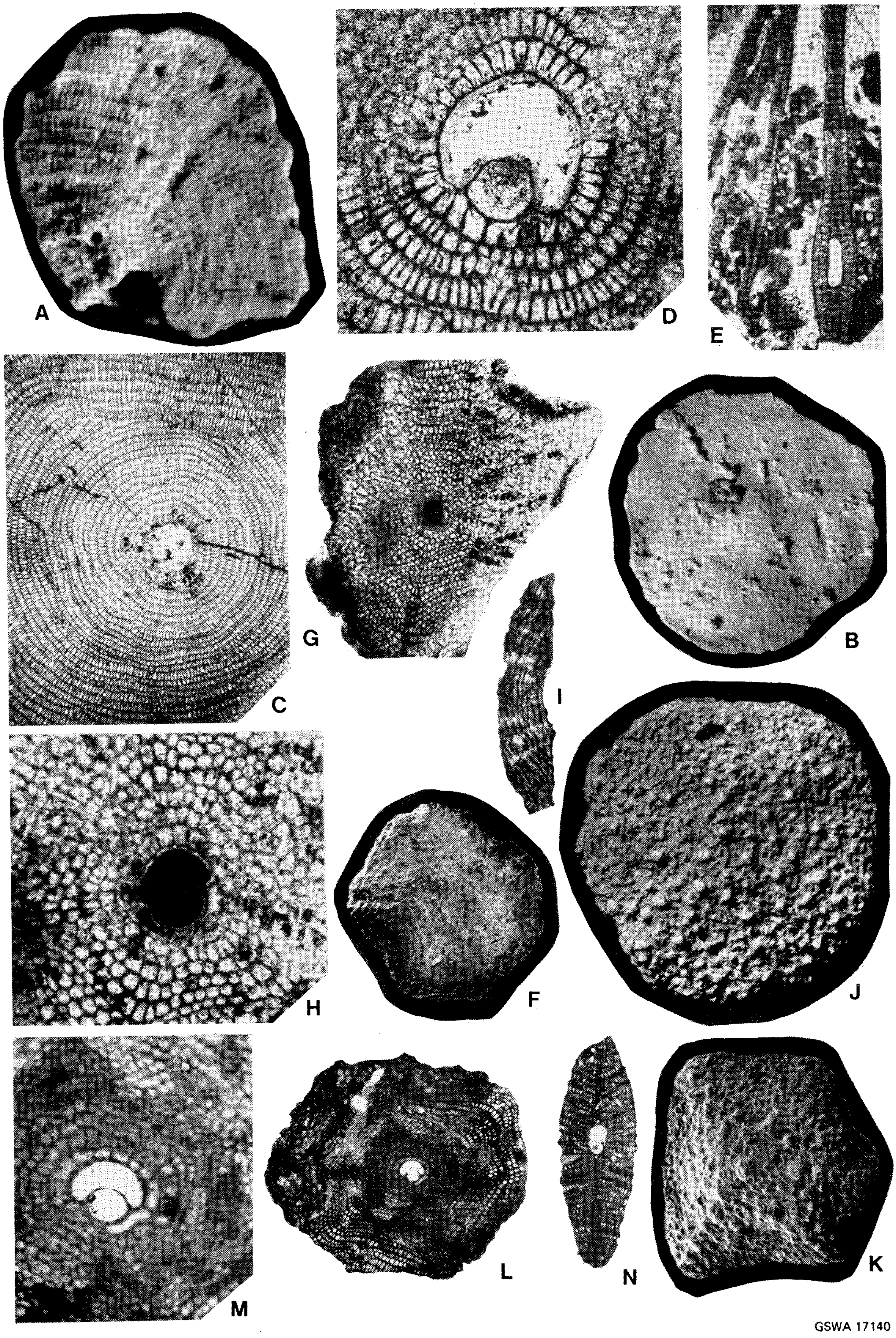
Figure 36 Locality map



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Konecki and others (1958) recorded *Asterocyclina* cf. *aster* and *Discocyclina* sp. (identified by Crespin) from the Giralia Calcarenite near Yaringa North (now called Yaringa) homestead. Both *Discocyclina* and *Asterocyclina* have been identified from Red Bluff (Crespin, 1955) from the same formation.

The only other discocyclinid record from Western Australia known to me is that of *Asterocyclina* from the Plantagenet Group in the Bremer Basin near Esperance (Cockbain, 1967).

RE-EXAMINATION OF GIRALIA ANTICLINE SPECIMENS

The original thin sections which Chapman and Crespin used to illustrate their paper are in the Commonwealth Palaeontological Collection housed in the Bureau of Mineral Resources in Canberra. Through the courtesy of the Bureau, I have been able to examine these slides. There are three slides with discocyclinids, and as can be seen from Chapman and Crespin's (1935, pl. 3, 4) illustrations, most of the specimens are axial sections with rare but poor equatorial sections (e.g. their pl. 4, fig. 8). All that can be confidently said from these thin sections is that discocyclinids including *Asterocyclina* are present.

Edgell's slides, on which Condon and others' (1956) faunal list is based, are also in the Bureau of Mineral Resources collection. However, a letter (July 1977) from the Bureau states that ". . . we cannot now identify the particular sections from which Dr Edgell identified the species . . .". I have examined some 30 thin sections from the Giralia Calcarenite in the Bureau collection which were used by Edgell. Most are randomly cut thin sections which show axial and equatorial sections of discocyclinids, a few of which can be recognized as *Asterocyclina.* Four slides are oriented sections of matrix-free *Asterocyclina,* one axial and three equatorial; three of them are labelled *'Asterocyclina aster'*, a name which does not occur in the published faunal list. *A. aster* is a North American species and similar forms from the Giralia Calcarenite are identified below as *A.* cf. *stella.*

MATRIX-FREE SPECIMENS

The difficulties of identifying larger foraminifers in random thin sections are well known. Indeed, Adams and Belford's (1974, p. 499) remarks on *Eulepidina* apply equally well to the discocyclinids. "The specific characters on which the numerous nominal species have been based need to be evaluated statistically on the basis of matrix-free material. Until this has been done it will not be possible to name specimens occurring in hard limestones satisfactorily". Matrix-free specimens of discocyclinids have been obtained from a number of samples and are described below. The localities from which the samples came are listed in Table 17.

SYSTEMATIC PALAEONTOLOGY

The systematics of discocyclinid foraminifers is in need of revision, and until this is done it is difficult to know how variable the various species are. Because of this, the species discussed below are placed in open nomenclature.

Discocyclina sp. cf. **D. discus** (Rutimeyer)
Figure 37, B, C, D, E

cf. 1850 *Orbitolites discus* Rutimeyer; p. 115, pl. 5 (not seen)

cf. 1958 *Discocyclina discus* (Rutimeyer): Neumann; p. 90, pl. 14, fig. 1-8; pl. 15, fig. 1, 2; pl. 27, fig. 3, 4; text-fig. 25.

Material: F9776 (6 sectioned specimens) from YNR1; F9774 (15 specimens, 5 sectioned) from YNR2; F9775 (8 sectioned specimens) from QUB1; all from Giralia Calcarenite, Middle and Upper Eocene.

Description: A flat thin discocyclinid ranging in diameter from 6 to 16 mm; maximum thickness 1.8 mm. The surface is smooth or finely pustulose. There is a low swelling at the centre of the disc in some specimens, and a slight pimple at the centre in others. The nucleoconch is eulepidine with the following dimensions:

Specimen No.	Protoconch		Deuteroconch		Nucleoconch overall length
	length	width	length	width	
F9774/2	180	155	230	425	415
F9774/3	....	....	....	450	450
F9774/4	....	....	....	475	490
F9774/5	....	....	....	750	575
F9775/4	155	200	300	455	455
F9775/5	175	180	250	415	430
F9775/6	....	....	....	....	500
F9776/3	....	....	....	....	615
F9776/4	190	275	315	575	540

All measurements in μm

TABLE 17. LOCALITY DATA

Fossil Locality No.	Latitude south	Longitude east	Locality	Formation	Collector and GSWA Fossil No.
			Yanrey 1:250 000 map sheet		
YNR 1	22° 37′	114° 17′	Giralia anticline, east flank; north end	Giralia Calcarenite (base)	W. J. E. van de Graaff, 1975 F9394, F9776
YNR 2	22° 55′ 30″	114° 02′	Giralia anticline, west flank; near Cardabia No. 10 bore	Giralia Calcarenite (middle); type section	J. Backhouse, D. J. Belford, 1969; F9774
			Quobba 1:250 000 map sheet		
QUB 1	24° 02′	113° 25′ 30″	Red Bluff	Giralia Calcarenite (near top)	P. D. Denman, A. E. Cockbain, 1977; F9775, F9778
			Esperance 1:250 000 map sheet		
....	33° 40′	122° 17′	Neridup No. 20 borehole; 72 km east of Esperance	Werillup Formation	F6425 (30·5 m), F6427 (35 m), F9777 (35 m)

Figure 37 A - *Discocyclina* sp., Werillup Formation, Neridup No. 20 bore, 35 m, exterior (worn), F9777; x40.
B, C, D, E - *Discocyclina* cf. *discus,* Giralia Calcarenite from localities YNR2 and QUB1. B - exterior, F9774/6 (YNR2); x4.
C - equatorial section, F9774/3 (YNR2); x20.
D - equatorial section, F9775/5 (QUB1); x60.
E - axial section, F9775/3 (QUB1); x20.
F, G, H, I - *Asterocyclina* cf. *stella* Giralia Calcarenite from locality YNR1.
F - exterior, F9394/23; x20. G, H - equatorial section, F9394/1; G, x20; H, x60. I - axial section, F9394/4b; x30.
J, K, L, M, N - *Asterocyclina* cf. *howchini* Werillup Formation, Neridup No. 20, 30.5 and 35 m. J - exterior, F 6425/2 (30.5m); x20.
K - exterior, F 6427/14 (35m); x20. L, M - equatorial section, F6427/1 (35 m); L, x20; M, x60. N - axial section, F6427/4 (35 m); x20.

Periembryonic chambers are slightly larger than the other equatorial chambers. The primary auxiliary chambers (i.e. those adjacent to the wall separating the protoconch from the deuteroconch) are similar in size to the other periembryonic chambers. There are 3-4 periembryonic chambers in contact with the protoconch.

Lateral chambers are difficult to make out; there seem to be no more than 10 layers on either side of the equatorial layer in the centre.

Remarks: The overall test shape and appearance of the nucleoconch recall *D. discus;* however in that species the nucleoconch is very much larger. Discocyclinids with a nucleoconch of comparable size with the Giralia form (e.g. *D. sella*) do not have the same arrangement of periembryonic chambers. Those with similar periembryonic chambers (e.g. *D. dispansa*) have a fat test.

Discocyclina sp.
Figure 37A.

Material: F9777, Werillup Formation, Plantagenet Group; Upper Eocene; Neridup No. 20 borehole, 35 m.

Remarks: One worn fragment of a large lenticular foraminifer, which when complete would have had a diameter of around 10 mm, has the typical discocyclinid pattern of equatorial chambers. The genus has not been recorded previously from the Plantagenet Group.

Asterocyclina sp. cf. **A. stella** (Gümbel)
Figure 37 F, G, H, I.

cf. 1861 *Hymenocyclus stella* Gümbel; p. 543 (not seen)

cf. 1958 *Asterodiscus stella* (Gümbel): Neumann; p. 112, pl. 28, fig. 1-6, text-fig. 36.

Material: F9394 (22 sectioned specimens) from YNR1; F9778 (one microspheric form, questionably assigned to this taxon) from QUB1; Giralia Calcarenite, Middle and Upper Eocene. Specimens are frequently ferruginized and it is difficult to make adequate sections showing internal features.

Description: Lenticular forms from 1.3 to 3.8 mm in diameter and between 0.5 and 0.75 mm in thickness. They may be circular or polygonal in outline and the surface is pustulose. The nucleoconch is bilocular to slightly nephrolepidine with the following dimensions:

Specimen No.	Protoconch		Deuteroconch		Nucleo-conch overall length
	length	width	length	width	
F9394/1	140	150	105	225	250
F9394/4a	150	155	95	200	265
F9394/5	....	140	....	210	240
F9394/8	....	180	....	215	245
F9394/9	....	100	....	140	195
F9394/10	180	190	150	275	315

All measurements in μm

The periembryonic chambers are difficult to make out. They seem to completely encircle the nucleoconch, with the primary auxiliary chambers being more tangentially elongated than the other chambers. Lateral chambers are distinct and up to 10 layers occur on either side of the nucleoconch.

Remarks: The preservation of the nucleoconch and surrounding chambers makes identification difficult. The specimens most closely resemble *A. stella* with which they are compared.

Asterocyclina sp. cf. **A. hornibrooki** Cole
Figure 37 J, K, L, M, N.

1967 *Asterocyclina* sp. Cockbain; p. 68

cf. 1967 *Asterocyclina hornibrooki* Cole; p. 6, pl. 1, fig. 1-12; pl. 2, fig. 1, 5, 6, 8, 10.

Material: F6425 (about 50 specimens), F6427 (about 50 specimens, 12 sections); Werillup Formation, Plantagenet Group, Neridup No. 20 borehole, 30.5 m and 35 m respectively.

Description: The specimens are all small (from 1.1 to 3.2 mm in diameter), lenticular (up to 1.4 mm thick), with no clear differentiation into umbo and flange. Some are circular in outline, others somewhat polygonal. The surface is pustulose. The nucleoconch is nephrolepidine with the following dimensions:

Specimen No.	Protoconch		Deuteroconch		Nucleo-conch overall length
	length	width	length	width	
F6427/1	100	125	80	230	195
F6427/2	165	195	115	275	275
F6427/13	140	190	115	290	260

All measurements in μm

The periembryonic chambers completely encircle the nucleoconch in one specimen; in another they seem to be interrupted at the base of the protoconch where the second ring of equatorial chambers is in contact with the nucleoconch wall. Lateral chambers are distinct and there are up to 10 layers on either side of the nucleoconch.

Remarks: The specimens most closely resemble the New Zealand species *A. speighti* and *A. hornibrooki* (Cole, 1962, 1967). In *A. hornibrooki,* the periembryonic chambers completely encircle the nucleoconch, while in *A. speighti* they are interrupted and the first complete ring of equatorial chambers is the third according to Cole (1962, p. 347), although his illustrations are not clear and this feature may be variable. The lateral layers of chambers of the Neridup specimens are more in accord with those of *A. hornibrooki* (which has 8-15 layers) rather than *speighti* (with 16-17) and are less regularly arranged than in *A. speighti.* How variable these characters are is uncertain. For the present these specimens are compared with *A. hornibrooki.*

DISCUSSION

The large number of discocyclinid species previously recorded from the Giralia Calcarenite is not confirmed by this study, although admittedly only a small amount of material has been examined. Only two species can be identified from matrix-free material and both have been recorded previously. The species *D.* cf. *discus* and *A.* cf. *stella* are compared with forms which are predominantly European in their distribution and occur in Middle and Upper Eocene rocks (Neumann, 1958).

The Werillup Formation is of Late Eocene age and *A. hornibrooki* is known from rocks of this age in New Zealand (Cole, 1967). The presence of a New Zealand species of *Asterocyclina* in the Esperance area is in agreement with the evidence of the other benthonic foraminifers, which Backhouse (1970) points out are similar to those recorded by Dorreen (1948) from the west coast of the South Island. The occurrence of *Discocyclina* in the Esperance area is the most southerly record of the genus known to me.

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ACACIELLA cf. *AUSTRALICA* FROM THE SKATES HILLS FORMATION, EASTERN BANGEMALL BASIN, WESTERN AUSTRALIA

by Kathleen Grey

ABSTRACT

The stromatolite group *Acaciella* Walter, previously known only from the Late Proterozoic and Cambrian in Australia, occurs in the late Middle Proterozoic Skates Hills Formation in the eastern part of the Bangemall Basin. The Western Australian form closely resembles *Acaciella australica* (Howchin) from the Late Proterozoic Bitter Springs Formation of the Amadeus Basin in central Australia.

INTRODUCTION

Stromatolitic carbonates are an important feature of the western and northern facies of the Bangemall Basin. Although stromatolites are abundant, taxonomic diversity is low, the main forms present being *Baicalia capricornia* and *Conophyton garganicum australe,* both recorded by Walter (1972). Carbonates are less common in the eastern facies, but a stromatolitic dolomite, containing a form not known from the western and northern facies, occurs near the top of the Skates Hills Formation, a basal unit in the Madley and Trainor 1 : 250 000 Sheet areas (Williams and others, 1976).

The Skates Hills Formation consists of a succession of conglomerate, interbedded sandstone, shale, and siltstone capped by a dolomitic unit containing several stromatolitic biostromes. Samples of cumulate and columnar stromatolites were collected from three localities during regional mapping by A. T. Brakel and R. E. J. Leech (Fig. 38). Samples (F9828 and F9829) from locality TRN1 consist of cumulate forms only, but extremely well-preserved columnar specimens were collected from localities TRN2 (F9830 and F9831) and TRN3 (F9832).

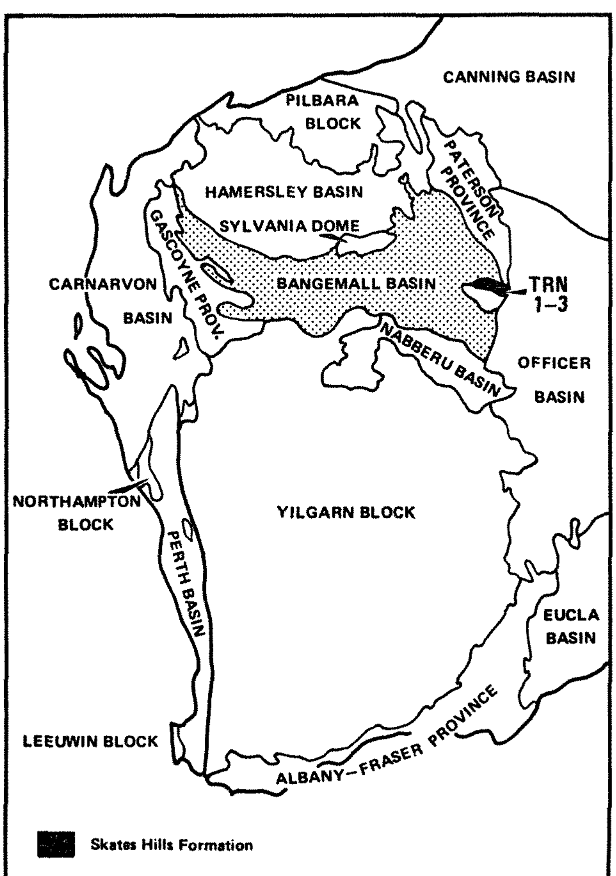

Figure 38 Regional setting of the Bangemall Basin showing stromatolite localities in Skates Hills Formation

Because only relatively small samples were collected it is difficult to determine the diversity shown by the columns. However, the material which is available shows the characteristics of the group *Acaciella* Walter. Columns are nearly straight, parallel and subcylindrical, with numerous low bumps, some cornices and peaks, and small areas of wall occurring infrequently. The Skates Hills specimens are similar to the type-form *Acaciella australica* (Howchin), described from the Amadeus Basin by Walter (1972), but show more frequent bridging, and, from the specimens available, show less diversity of column shape than *Acaciella australica.*

AGE

The age-range of *Acaciella* is from less than 1 000 m.y (Late Riphean) to Early Cambrian (Preiss *in* Walter, 1976, p. 369). The precise age of the Skates Hills Formation is uncertain. Geochronological ages for the Bangemall Group have been obtained from only three sources. A poor Rb/Sr isochron of about 1 080 m.y. was obtained from the Mount Palgrave felsic rocks by Compston and Arriens (1968). These authors also obtained a Rb/Sr age of 1 080 ± 80 m.y. from shale in the Curran Formation. The stratigraphic relationship of the Skates Hills Formation to these occurrences is not clear.

More recently, Gee and others (1976) reported a Rb/Sr age of 1 098 ± 42 m.y. from an altered rhyolite from the lower part of the Bangemall Group near Tangadee. The rhyolite occurs in the Coobarra Formation (Brakel and Muhling, 1976), which underlies the Backdoor Formation. The Backdoor Formation is considered by Williams and others (1976) to be a possible facies equivalent of the Skates Hills Formation. The maximum age of the Skates Hills Formation is therefore less than about 1 100 m.y. No minimum age has been determined, but it is probably in the region of 1 000 m.y.

Acaciella australica occurs in the Loves Creek Member of the Bitter Springs Formation. Radiometric dating of basement rocks indicates a maximum age of 1 076 ± 50 m.y. (Majoribanks and Black, 1974) for the onset of sedimentation in the Amadeus Basin, and the actual age

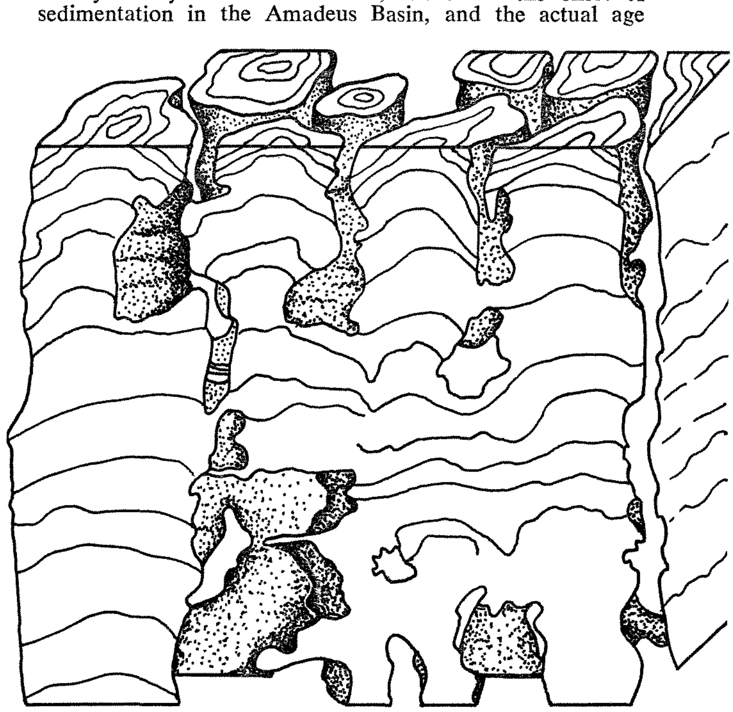

Figure 39 Three-dimensional reconstruction of part of specimen F9830 *Acaciel* cf. *australica.*

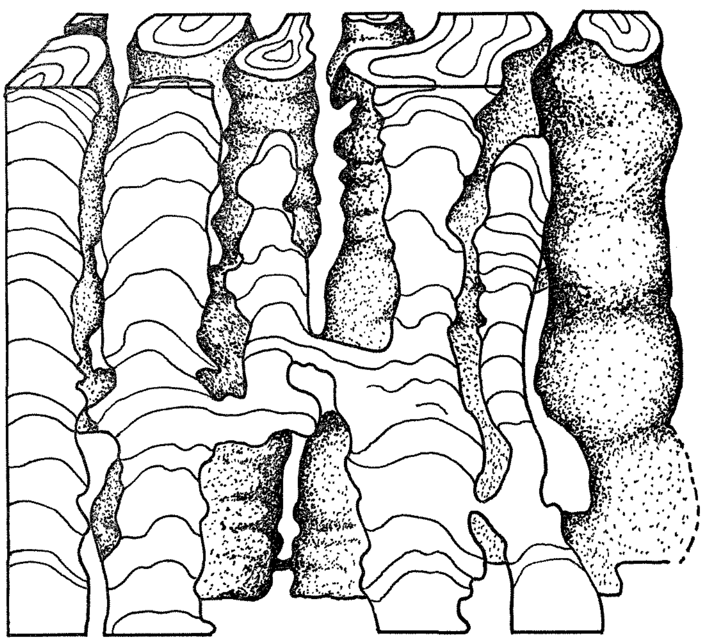

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Figure 40 Three-dimensional reconstruction of part of specimen F9830 *Acaciella* cf. *australica*

is probably much less than this (for discussion see Walter, 1972). Thus *Acaciella* cf. *australica* probably occurs in slightly older rocks in the Bangemall Basin than does *Acaciella australica* in the Amadeus Basin.

SYSTEMATIC DESCRIPTION

Group *ACACIELLA* Walter 1972

Acaciella sp. cf. *A. australica* (Howchin)
Figs 39-41

Material: Five specimens from three localities in the Trainor 1 : 250 000 Sheet area.

Mode of occurrence: At locality TRN1 interbedded dolomite and calcareous siltstone overlie shale. Three thin units of well-bedded dolomite contain cumulate stromatolites. The sequence is capped by a ripple-marked sandstone. Two specimens of cumulate stromatolites were collected from this locality.

Two specimens of well-preserved, columnar stromatolites were collected from locality TRN2. The stromatolite horizon apparently forms an extensive biostrome (Fig. 41a) approximately 6 m in thickness, and occurs near the top of a finely crystalline and laminated dolomite, which overlies a fine-grained sandstone and is capped by a siltstone. The dolomite contains irregular chert nodules up to approximately 15 cm in length.

Stratiform stromatolites occur below the columnar forms, with banding up to approximately 2 cm thick, but usually less than 1 mm. The column development and lateral variation were not recorded. The biostrome is probably stratiform, although some lensing may occur, and extends laterally for several hundred metres (Fig. 41a).

At locality TRN3 approximately 10 m of grey-pink dolomite with beds of columnar stromatolites is overlain by interbedded siltstone and dolomite, with sandstone at the top of the sequence. The small sample collected from this locality shows elongation of the tops of columns into ridges resembling ripple marks. A similar sequence occurs at a nearby locality, where the stromatolite bed is thinner. No samples were obtained from this locality.

Column shape and arrangement: The origin of the columns could not be determined in hand specimen. Both flat-laminated and cumulate stromatolites occur and columns probably arise from the cumulate forms. Columns tend to be perpendicular, relatively straight, and closely and regularly spaced. Width varies from 10 to 25 mm and in transverse section columns are usually rounded-polygonal to occasionally lobate, although in F9832 the tops of the columns form elongate ridges.

Most of the columns are discrete, but massive bridging and rare coalescence occurs. Small-scale bridging is common, and peaks, cornices, and irregular bumps of variable size are present. The smaller columns may terminate as steeply convex domes. The termination of larger columns is not known because the top of the biostrome is eroded.

Branching: Branching is almost exclusively α parallel, and occasionally β parallel. The origin of the branches cannot be determined from the hand specimen, but branches may increase slightly in width from the point of divergence.

Margin structure: Columns lack walls except for occasional development, usually in the area of bumps. Laminae generally terminate abruptly at column margins.

Lamina shape: Laminae are smooth, gently convex to rarely steeply convex, occasionally rectangular to rhombic, and rarely wavy.

Microstructure and texture: Microlaminae are variable in regularity and thickness, but tend to be continuous across the columns. In addition to light and dark microlaminae, white, vermiform patches are present. Macrolaminae are present but are not readily distinguished.

Dark microlaminae consist of fine-grained (less than 5 μm), equigranular, polygonal to interlobate, xenotopic dolomite. Microlaminae are from 50 to 500 μm in thickness and have smooth, parallel boundaries. They tend to thin towards column margins. Pigmentation is in the form of small specks of probable organic material, and the presence of oxides of iron which give a patchily pink colour to some laminae.

Light microlaminae are similar to the dark microlaminae, although grains are larger (10 to 30 μm) and xenotopic to hypidiotopic. Microlaminae range from 60 to 500 μm in thickness.

White, vermiform patches are more irregular, and sometimes thicker than the light and dark microlaminae. The patches anastomose frequently and the upper margin is markedly irregular. Grain size is extremely small, and determination of the mineralogy was not possible, although clay minerals are most probably present.

Interspace fillings: Interspaces are from 5 to 15 mm wide and are filled with fine-grained altered micrite containing large intraclasts of dolomite. Pink staining with iron oxide is common, but banding of the material in the interspaces is poorly developed. Layers of very fine-grained, altered micrite indicate periods of relative quiescence between periods of intraclast deposition. Intraclasts lie at a high angle to the bedding and are from 1 to 10 mm long and up to 4 mm thick. They are probably eroded fragments of algal mat. Relief of the columns was seldom greater than 5 mm and the frequent bridging suggests that for much of the time it was probably less than this.

Secondary alteration: Walter (1972, p.117) considered *Acaciella australica* from Katapata Gap to be primarily dolomitic, and this also seems to be the case with the Skates Hills specimens. Small veins of secondary calcite cross-cut the dolomitic laminae and occasional concordant stylolites are present. Some column margins are also stylolitic.

COMPARISONS

In gross morphology (mode of occurrence, column shape, branching and margin structure) there is a close resemblance to specimens of *Acaciella australica* (Howchin). Bridging may occur more frequently in the specimens from Skates Hills, columns appear more regular and there are minor differences in microstructure. Since *Acaciella australica* is a somewhat variable form, these differences may well be encompassed within the range of known variation. However, the samples collected from Skates Hills represent only a small portion of what is probably a fairly extensive biostrome. Until more material is available for the variation to be studied, the Skates Hills specimens are referred to as *Acaciella* cf. *australica.*

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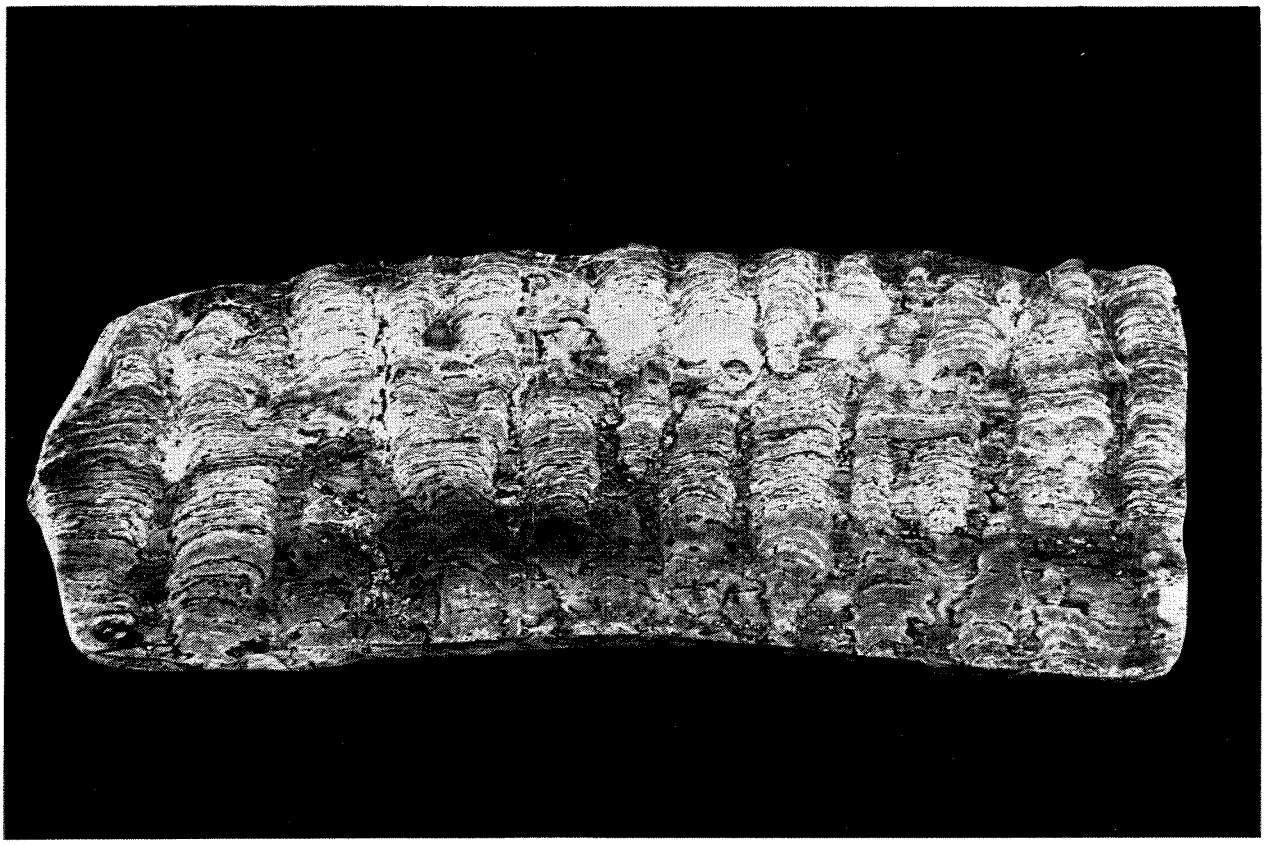
Figure 41a View of stromatolitic bioherm at locality TRN 2 showing tops of columns.

41b Polished section of part of specimen F9830. *Acaciella* cf. *australica,* showing columns.

A

2 CM



B

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LIVING STROMATOLITES IN THE NORTHERN GREAT SANDY DESERT, WESTERN AUSTRALIA: A MODERN ANALOGUE FOR PROBABLE TERTIARY DEPOSITS IN THE AREA

by R. W. A. Crowe, A. N. Yeates* and Kathleen Grey

ABSTRACT

Living freshwater stromatolites occur in the Canning Basin at McDonaldson Spring on the Mount Bannerman Sheet area. They are growing in water moderately rich in bicarbonate. Three growth forms are recognized: encrusting laminar, domal, and club-shaped columnar. The structures are calcareous, and the carbonate is believed to have been precipitated around algal filaments, in addition to being trapped and bound by the algae. Fossil stromatolites are also present in the adjoining probable Tertiary Lawford Beds, and similarities between the modern and fossil forms suggest similar depositional processes and environments. This means that rocks in the area, formerly regarded as calcrete of unspecified origin, are now thought to have been deposited biogenically.

INTRODUCTION

During regional mapping of the Canning Basin in 1973 living stromatolites were discovered in the headwaters of a spring-fed creek on the edge of the Great Sandy Desert in the northwestern part of the Mount Bannerman 1:250 000 sheet area in northern Western Australia (Yeates and others, 1975).

Stromatolites, formed by blue-green algae, are present in most of the springs and extend for a short distance downstream. The structures occur in pools and in places form barriers which produce small waterfalls. Such stromatolitic structures, though fairly common, have not been widely reported in Australia although they have been described elsewhere (see Golubic, 1973, for discussion).

The probable Tertiary rocks which form the reservoir for the springs in the area consist largely of limestone. Following the terminology of Goudie (1972) such terrigenous limestones of unknown and/or variable origins are normally referred to as calcrete, but in this area parts of the limestone contain structures suggesting a biogenic, algal origin. This paper describes the living stromatolites that occur in one of the springs—McDonaldson Spring—and suggests that they may represent an analogue for the origin of parts of the probable Tertiary deposits in the area.

SETTING

The northwestern part of the Mount Bannerman 1:250 000 Sheet and adjacent areas are underlain by gently dipping calcareous shale, mudstone and fine-grained quartz wacke of the Permian Liveringa Group and Noonkanbah Formation (Veevers and Wells, 1961; Yeates and others, 1975).

The Permian deposits are overlain by beds of probable Tertiary age, the Lawford Beds (defined by Casey and Wells, 1964). The Lawford Beds consist mainly of limestone with associated chalcedonic limestone, poorly consolidated conglomerate, and ferruginous sandstone. The unit attains a maximum thickness of 25 m and crops out

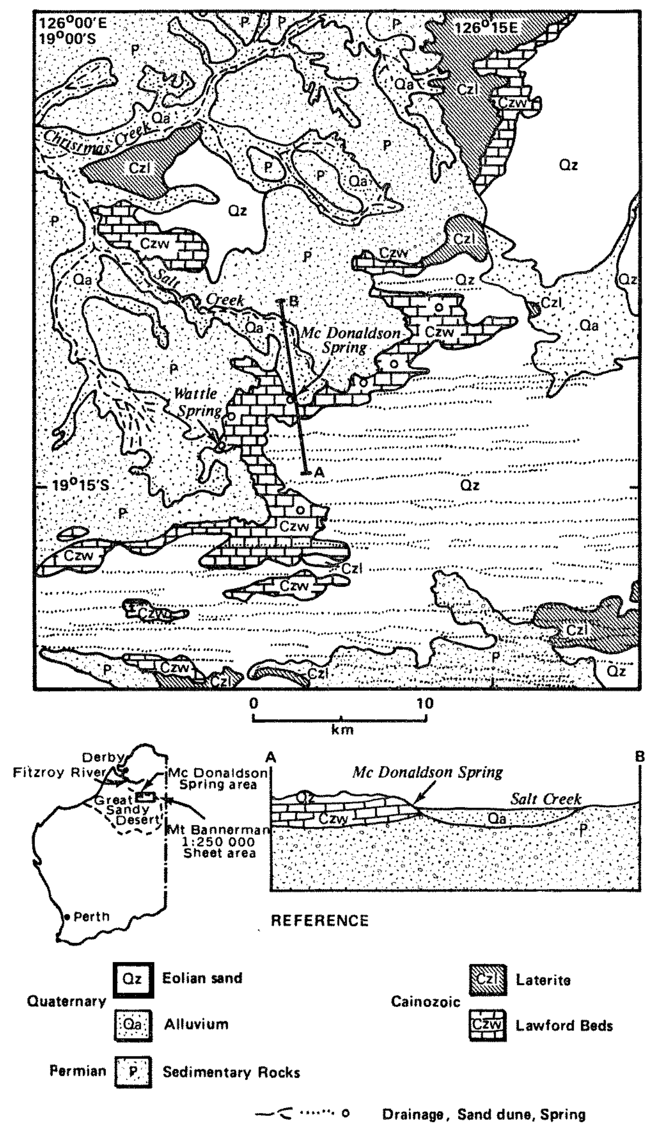


Figure 42
Simplified geological map, diagrammatic cross-section and drainage profile of the McDonaldson Spring area, and its location in Western Australia.

* Bureau of Mineral Resources, Canbarra; published with the permission of the Director.

along the banks of Christmas Creek (a major tributary of the Fitzroy River) and is believed to have been deposited by the ancestral Christmas Creek (Casey and Wells, 1964).

There is no direct evidence for the age of the Lawford Beds, but as the unit is lateritized and contains detrital laterite pisoliths within it, it is thought to be mainly Tertiary in age. This is when the main periods of lateritization are thought to have occurred in the northern and eastern parts of Western Australia (van de Graaff and others, 1977).

The Lawford Beds are overlain by laterite and by Quaternary deposits, which are mainly eolian sand (Fig. 42).

Due to the low porosity of the underlying argillaceous Permian rocks, the Lawford Beds act as a reservoir for a series of springs producing potable water. These occur where the headwaters of Salt Creek (so called because salt occurs in the banks of the lower reaches) have dissected the contact between the two units (Fig. 42). Stromatolites are present in the springs and extend for approximately 500 m downstream.

The best examples of the stromatolites occur at McDonaldson Spring (lat. 19°12'18"S, long. 126°08'24"E) in a narrow creek up to 2 000 m downstream from the spring. The spring waters flow for about 1 km before soaking into alluvial deposits of the main creek.

McDonaldson Spring lies in a semi-arid area which experiences erratic rainfall (annual average 375 mm), most of which falls in summer. Evaporation rates are high and the area has an average yearly temperature of 28°C, with average maxima of about 39°C in January and about 27°C in July. The average minima are about 24°C in January and about 9°C in July (Atlas of Australian Resources, 1973).

The spring usually flows all year but during the summer wet season a catchment area above the spring contributes floodwater to the creek. At such times the creek then discharges into Salt Creek and from there into Christmas Creek (Fig. 42). When sampled, the water at McDonaldson Spring was moderately rich in bicarbonate and mildly alkaline. It was not saturated in any dissolved salts (Table 18).

TABLE 18. ANALYSIS OF WATER SAMPLE FROM McDONALDSON SPRING
(Sample collected in September, 1973)

Specific conductivity (micromhos 20°C)	2 090
pH	8·0
Appearance	clear
Colour	colourless
Odour	nil

Mineral Matter	mg/litre	me*/litre
Total dissolved solids—		
By evaporation	1 450	
By conductivity x 0·7	1 470	
Sodium chloride (calculated from chloride)	630	
Total hardness (calculated as $CaCO_3$)	481	
Total alkalinity (calculated as $CaCO_3$)	438	
Calcium	51	2·54
Magnesium	86	7·07
Sodium	304	13·2
Potassium	61	1·56
Iron (Fe in solution)	<0·05	
Boron	0·8	
Fluoride	2·3	
Bicarbonate	534	8·75
Carbonate	nil	nil
Sulphate	213	4·81
Chloride	382	10·8
Nitrate	27	0·44
Silica	50	0·44

* Milli-equivalents

DESCRIPTION OF STROMATOLITES

MORPHOLOGY

Three main varieties of stromatolite morphology are represented at McDonaldson Spring. These are: encrusting laminar, domal, and club-shaped columnar. Domal forms frequently develop from encrusting laminar forms, usually forming above small irregularities in the laminae, or above fenestrae. Club-shaped columnar forms (Fig. 43a) arise from domal forms and these may branch and form further club-shaped forms. Encrusting laminar types are common in pools or areas of slow-moving water. In faster-moving water domal and club-shaped columnar types are more common, and are abundant in waterfalls and old waterfall barriers.

Domal forms are between 5 and 10 cm in diameter and are approximately 10 cm in height. The club-shaped columns develop from the domal forms on short 'stalks' which swell upwards and outwards to give the club-shaped appearance (Fig. 43b). Columns vary in diameter from a few millimetres up to 30 mm, although the majority are approximately 10 mm. Branches arise from the larger columns and are also approximately 10 mm in diameter. The flattened tops of some columns appear to be erosional features. The columns resemble abiogenically formed cave popcorn (Thrailkill *in* Walter, 1976), but in the case of the McDonaldson Spring structures blue-green algae are directly involved in their formation. The most abundant micro-organism in the McDonaldson Spring mats is *Phormidium* sp., a cyanophyte characterized by single narrow trichomes within a thin sheath (M.R. Walter, pers. comm.).

All three forms of McDonaldson Spring stromatolites range from finely laminated to unlaminated (massive). Finely laminated forms are common; massive fabric is only rarely developed. The mat which forms the stromatolites is soft and is underlain by a thin gelatinous layer. Lithification occurs only a few millimetres below the surface.

FABRIC AND MICROSTRUCTURE

Fenestrae are abundant and in some instances are quite large, often reaching up to 5 mm in length and occasionally as large as 25 mm. Although many of the fenestrae seem to have developed as a result of the decomposition of enclosed algal material, and the bridging of undulations on the stromatolitic surfaces by algal mat, the presence of truncated laminae in some of the cavities suggests that weathering and/or solution, may be a factor. Many of the cavities are lined with a thin layer of micrite.

Three types of fabric are common in the McDonaldson Spring stromatolites. Striped laminated fabrics, according to Monty (Walter, 1976), constitute a large part of many of the stromatolites and are particularly common in the finely laminated and columnar forms. These laminae contain interlocking, elongate crystals formed around radial filaments of *Phormidium*. Frequently the boundaries of the laminae are defined by a layer of horizontal filaments, or by a thin layer of micrite, indicating a phase of chemical precipitation which may mark a temporary cessation of algal growth.

The second type of fabric tends to occur in domal stromatolites and gives rise to coarse laminae. The fabric consists of a coarse reticulum of calcified algal filaments. Laminations result from the alternation of horizontally growing filaments with layers of erect bundles.

The third type consists of patches of massive fabric, which are probably the result of the deposition of calcium carbonate as a replacement of mucilaginous film associated with diatoms. Diatom frustules occur in the massive fabric patches and also in some of the fenestrae. They are similar to the massive cryptalgal diatomaceous mats associated with massive fabric which have been described from the Bahamas by Monty (Walter, 1976).

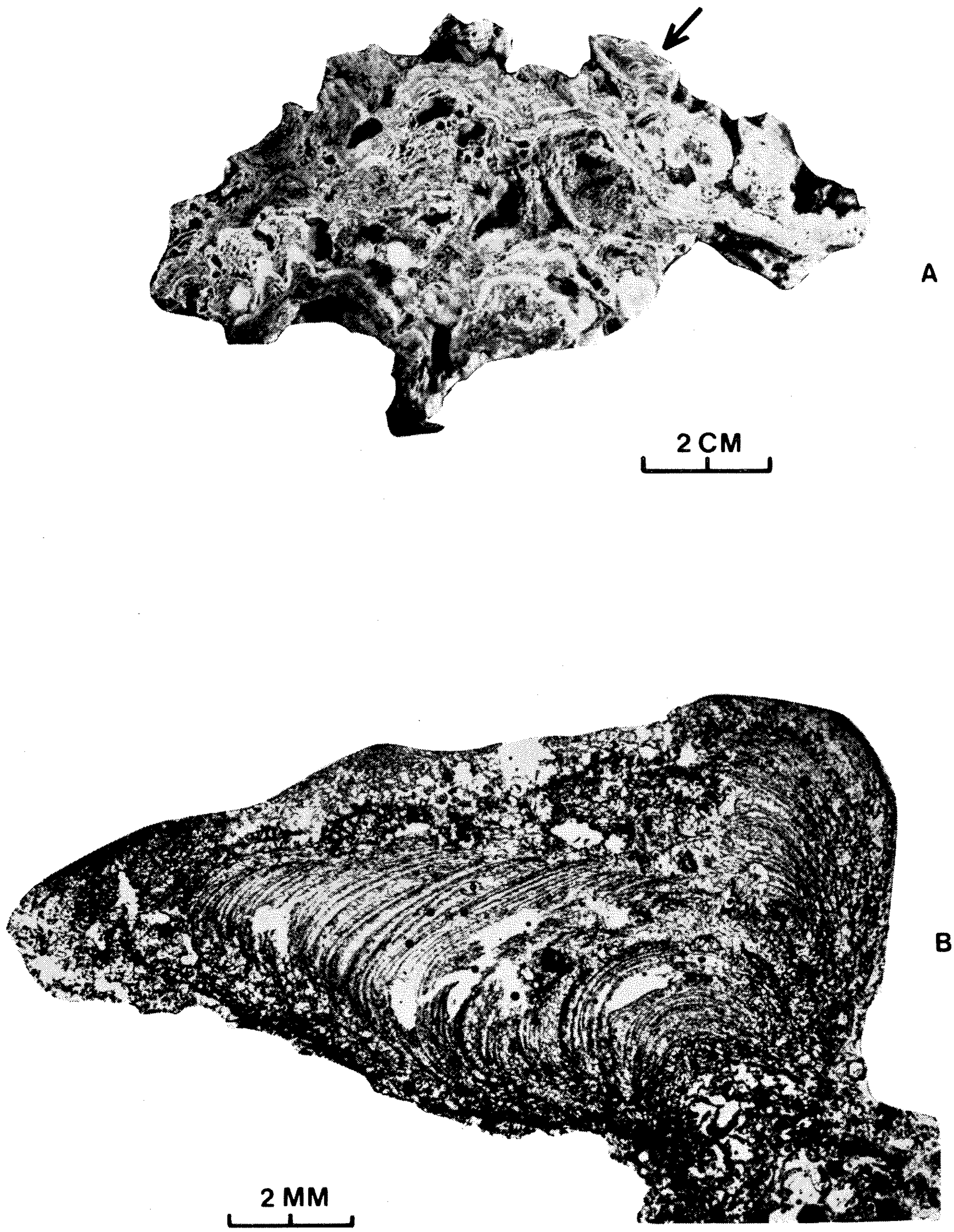
Precipitation of calcium carbonate around algal filaments and the replacement of mucilaginous film by carbonates are regarded as being more important than the trapping and binding of detrital grains in the formation of the stromatolites.

Fragments of plants and small organisms, encrusted with carbonate, are incorporated in the stromatolites. Some of the latter may have grown in association with the algal mat; others may have been washed in after death. Small patches of detrital quartz occupy cavities between the stromatolitic laminae, and small lateritic pebbles occur infrequently.

LITHIFICATION

The stromatolites at McDonaldson Spring are cemented by calcium carbonate. Carbonate lithification of algal structures can be either inorganic or biogenic, or a combination of both, and it is often difficult to distinguish which of these processes is taking place.

Precipitation of $CaCO_3$ from emerging groundwater is a common phenomenon with complex chemical controls. Precipitation often occurs within or around algal structures which have a large surface area in contact with $CaCO_3$-rich water. Precipitation is particularly common where the water is well aerated, such as in waterfalls (Golubic, 1973).



GSWA 17146

Figure 43a F.9835 cross-section of stromatolite showing domal and club-shaped columnar forms (specimen is 10.2 cm long). Specimen was collected from a waterfall face, McDonaldson Spring, Great Sandy Desert.
43b Photomicrograph of detail of club-shaped stromalolite. (Part of specimen F.9835 indicated by arrow).

Biogenic precipitation of $CaCO_3$, on the other hand, can be caused by changes in the pH due to the respiratory processes of the organisms involved. In algae, the process of photosynthesis (which utilizes C and O) can cause the changes necessary to bring about precipitation of carbonate.

Golubic (1973) believes that precipitation of carbonate in the upper part of a river flow is predominantly inorganic and that only lower downstream, where the water gains equilibrium with the atmosphere, does biogenic precipitation become more important. Because the stromatolites at McDonaldson Spring occur near the source of the spring it is suggested that the precipitation of calcium carbonate is dominantly inorganic although some biogenic precipitation may also occur. The dominant role of inorganic precipitation is supported by the occurrence of leaves and twigs in the stream which appear to have been recently fossilized, probably since the preceding flood.

FOSSIL ALGAL STRUCTURES IN THE LAWFORD BEDS

Fossil algal structures also occur in the Lawford Beds, which are probably of Tertiary age. They occur at a locality several hundred metres upstream from the spring in compact and well-lithified rock. The structures, consisting of undulating cryptalgal laminae, are very similar to the living encrusting laminar types described above, suggesting that deposition of this part of the Lawford Beds occurred in a similar environment.

CONCLUSIONS

The occurrence of stromatolites in McDonaldson Spring constitutes one of the few records of freshwater stromatolites in Australia. It is probable that the micro-environment largely controls the distribution of the various growth forms. Encrusting laminar types occur in slow-moving water and in pools, whereas the club-shaped, columnar, and domal types occur in waterfalls and appear to be restricted to faster-moving, well-aerated water. Old waterfall barriers are mainly composed of the latter types.

Most of the structures are composed of calcium carbonate, which is thought to have been precipitated around algal filaments from the spring water. Trapping of sediment also occurs but is of less significance.

The occurrence of cryptalgal structures in the probable Tertiary Lawford Beds and the similarities of these structures to the modern encrusting laminar forms, suggest that at least part of the Lawford Beds, formerly regarded as calcrete of unspecified origin, were laid down in quiet water fed from springs, and are of stromatolitic origin.

ACKNOWLEDGEMENTS

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PSEUDOVELOCITY APPLICATIONS IN THE CARNARVON BASIN

by I. R. Nowak

ABSTRACT

Pseudovelocity (synthetic sonic) logs may be generated from short-normal resistivity logs using the relation $TT^1 = A + (B)R_a^{-1/c}$ where TT^1 is the pseudotransit time, R_a the apparent resistivity, and *A, B* and *C*, empirically established constants. Pseudovelocity data can be a valuable aid to seismic interpretation in areas where resistivity logging is abundant and continuous velocity logging scarce. The method has been applied in the Carnarvon Basin in Western Australia where resistivity and sonic information from several bores has provided a formula from which a pseudovelocity model has been obtained for the petroleum exploration well Dirk Hartog 17B. Sources of error, limitations, and possible improvements to the method are discussed.

INTRODUCTION

Interest in pseudovelocities was initiated by M. Megallaa (G.S.W.A.; Sedimentary Division) who has recently been assessing seismic data from the Carnarvon Basin. An area of particular signficance centred around an isolated petroleum exploration well Dirk Hartog 17B, on Dirk Hartog Island, west of Shark Bay (Fig. 44). This well was completed in 1957, and wire-line logging operations did not include the sonic facility.

The interpretation of seismic reflection requires a knowledge of the vertical distribution of velocity to the depth of interest. The most commonly used and accurate way of obtaining this is from sonic logs of bores in the area. The sonic log is a recording of the time required, versus depth, for a compressional sound wave to traverse one foot* of formation. This 'interval transit time' is the reciprocal of the seismic velocity of the relevant formation. Sonic information is also useful for porosity determinations in sandstone and limestone sections, where the total travel time over any section is the sum of the travel time through the fluid-filled pores and that through the solid matrix (Table 19, equation (a)).

The sonic log is often omitted in wildcat or development wells and in wells drilled before about 1960. Therefore, a method for providing data equivalent to that normally obtained from a sonic log would be very useful. Almost invariably the suite of logs from any well includes the short-normal (406.4 mm or 16 inch) resistivity log which can be transformed, within limits, to yield pseudosonic information.

VELOCITY RELATIONSHIPS

There have been various attempts to link the sonic velocity of a formation with depth, age, and electrical resistivity. An early empirical relationship was equation (b) (Table 19), but it was soon realized that the situation was far more complex than this formula suggests. Sonic velocity is basically dependent on the bulk elastic modulus, and therefore on matrix and fluid proportions; this implies that porosity is a key parameter. Relation (c) is well known, but the true formation resistivity is not reliably measured by the short-normal method which records an apparent resistivity (R_a). This apparent resistivity relates to that of the formation invaded by the mud filtrate such that equation (d) holds. Combinations of these relationships were considered by various workers seeking to relate R_a directly to velocity. Equation (e) was widely applied,

* The imperial foot (0.304 8 m) continues to be used internationally in well logging.

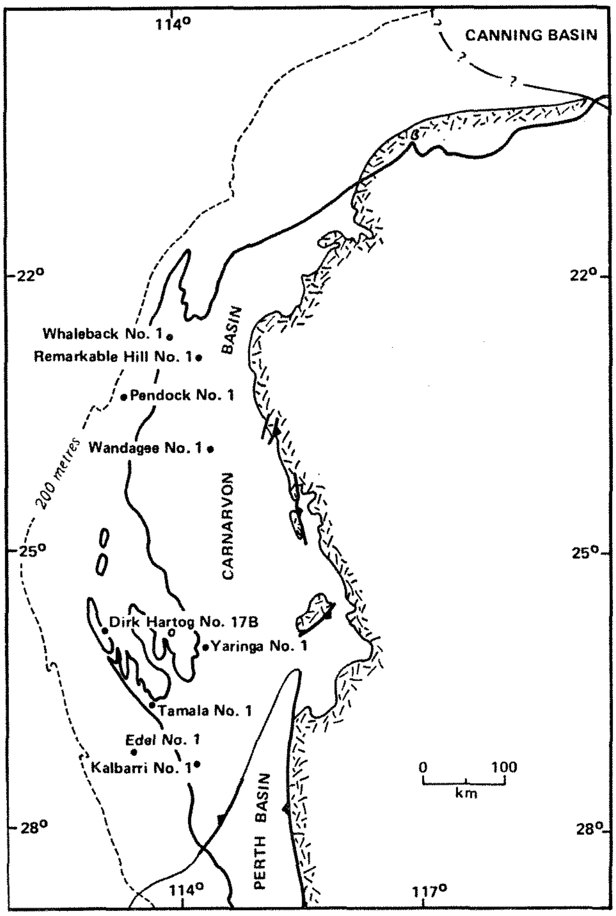

Figure 44 Carnarvon Basin, W.A. and relevant petroleum wells

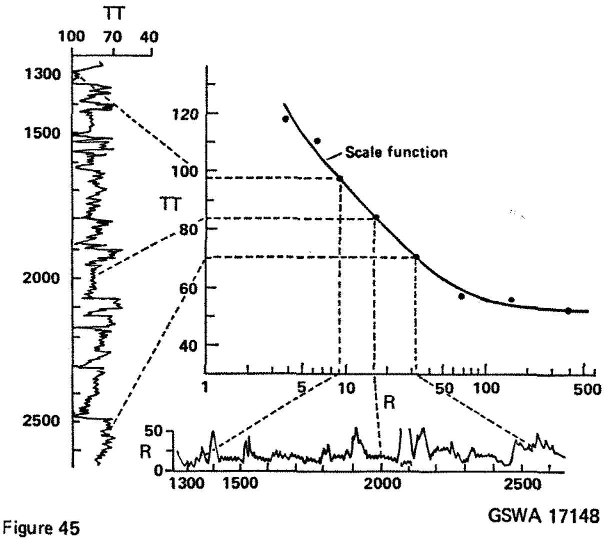

Figure 45

Sketch illustrating generation of scale-function curve. R (resistivity) in ohm-metres, and TT (transit time) in micro seconds per foot from specific depth interval form pair of values for each data point (after Kim, 1964)

especially in its inverse form where TT^1 is a pseudo interval-transit-time generated from observed resistivity values.

However, it became increasingly clear that neither depth nor age were major factors in controlling the sonic velocity of a formation, and that variation in lithology had the greatest influence.

DERIVATION OF THE SCALE FUNCTION

A group of researchers in the United States of America recently applied equation (e) to selected wells in the Illinois Basin (Rudman and others, 1975). When their work indicated that a resistivity-velocity transform which did not involve depth, was required, an empirical approach suggested by Kim (1964) appeared a likely avenue of inquiry. Comparisons of the overall form of sonic and short-normal logs for the same well show distinct similarities (Fig. 45) and suggest that there is a mathematical relationship between transit time and resistivity. The development of a practical relationship is amply described by Rudman and others (1975), and only an outline of the procedure is given here.

Relatively uniform (non-oscillating) portions of both logs at the same depth are selected, and their average values plotted on a semilog grid as in Figure 45. These values constitute one point on the plot, and additional values are produced from various sections over the length of the logs where relative stability is maintained. Sufficient points are established to enable a smooth curve to be constructed. This curve is then a predictive function because it specifies a transit time for any resistivity value. Note that, although each plotted point is associated with a particular depth, that depth is not identifiable from the curve.

A mathematical representation of this curve or 'scale function' is required, and theoretical considerations lead to the general equation: $TT^1 = A + (B)R_a^{-1/c}$ (Table 19, equation (f)). This form was derived by Kim who combined the sonic equation (a) and the resistivity formula (d) using porosity as the link. The constants A, B, and C are determined empirically and are not held to be physically significant parameters.

TABLE 19. RESISTIVITY AND VELOCITY EQUATIONS

(a) $TT^1 = \phi TT_f + (1-\phi)\,TT_m$
(b) $V = K(ZS)^{1/6}$
(c) $R_t/R_f = \phi^{-c}$
(d) $R_a/R_{mf} = \phi^{-c}$
(e) $V = K(ZR_a)^{1/6}$ or $1/V = TT^1 = 1/K(ZR_a)^{-1/6}$
(f) $TT^1 = A + (B)R_a^{-1/c}$ .... scale function

where:

TT	= Transit time in porous medium
TT_f	= Transit time in fluid
TT_m	= Transit time in matrix
ϕ	= Porosity
V	= Velocity
Z	= Depth
S	= Age
R_t	= True resistivity
R_a	= Apparent resistivity
R	= Resistivity of formation fluid
R_{mf}	= Resistivity of mud filtrate
TT^1	= Pseudotransit time

A, B, K, and C are constants

USE OF THE SCALE FUNCTION

Considering any particular well, e.g. Edel No. 1, an apparent resistivity (R_a) versus pseudotransit time (TT^1) curve may be established from field resistivity and sonic logs run in that well. In Figure 46, the curve has been carefully fitted by eye through a wide range of points. Values for the constants A, B, and C are determined (Rudman and others, 1975), and the predictive qualities of the scale function may then be applied to determine its validity. By means of the functions, a pseudosonic model is constructed from the known resistivity log, and this model is compared with the sonic log recorded in the field. Where a curve has been defined by a sufficient number of points, correlation is excellent: the differences between genuine (TT) and pseudo (TT^1) transit times are normally less than five per cent.

Having established accuracy of this order for any one well for which good data are available, Rudman and others (1975) then selected several wells from the Illinois Basin and produced R_a *versus* TT^1 plots for each. Then they simply calculated the arithmetic mean to arrive at their average scale function (ASF) to characterize the area concerned. When this ASF was re-applied to various wells, the TT^1/TT error was normally less than ten per cent. Obviously the ASF is not as applicable as the specific scale function of any well to that particular well. However, its use is realistic in the context of generating a pseudovelocity model for any given well in that area for which no sonic data are available.

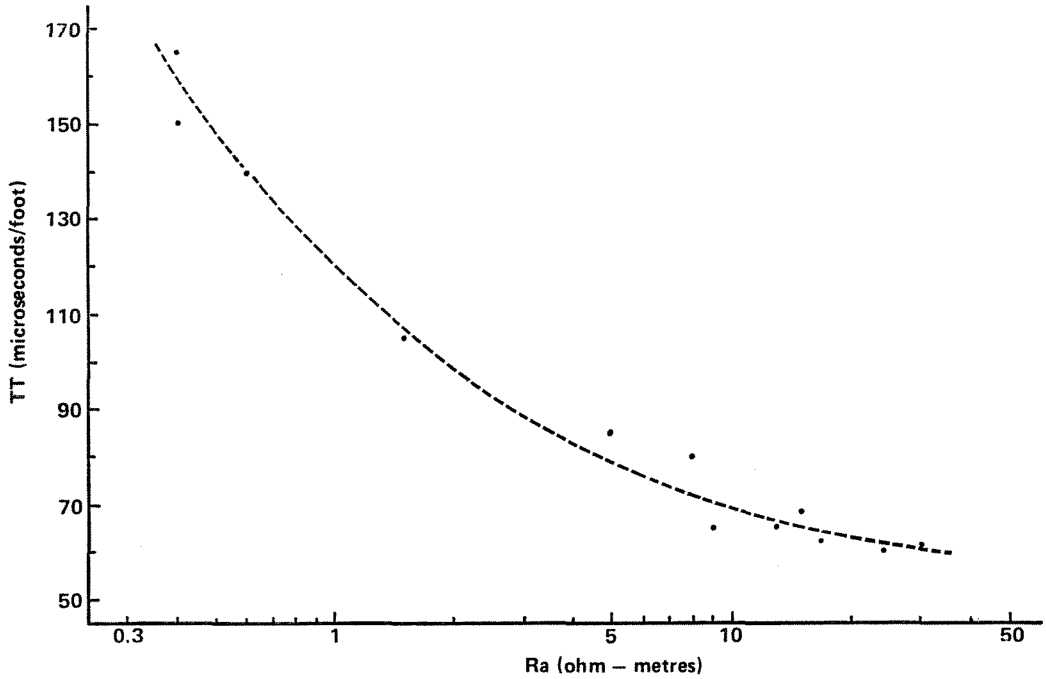

Figure 46 Example of a scale-function plot for a single well (Edel No. 1)

APPLICATION TO CARNARVON BASIN

The above concept, that an ASF may be established which characterizes the pseudosonic regime in a particular region, has been tentatively applied to the Carnarvon Basin (Fig. 44). Seven wells contributed and numerous R_a *versus* TT points were plotted on a single diagram. Readings were taken at relatively quiet intervals, to minimize errors, on both sonic and short-normal logs for each well. As this exercise involves generalizing at the scale of a basin, the plotting of points from several pairs of logs on the one diagram is essentially equivalent to plotting points for individual wells and then averaging the resulting curves. Moreover, the procedure used here is probably more accurate when information from some wells is scarce.

Again, a curve was constructed by eye (Fig. 47). Note that the data from Tamala No. 1 (circled) are judiciously ignored in the placement of the curve. This omission is justified because the Tamala values are clearly anomalous;

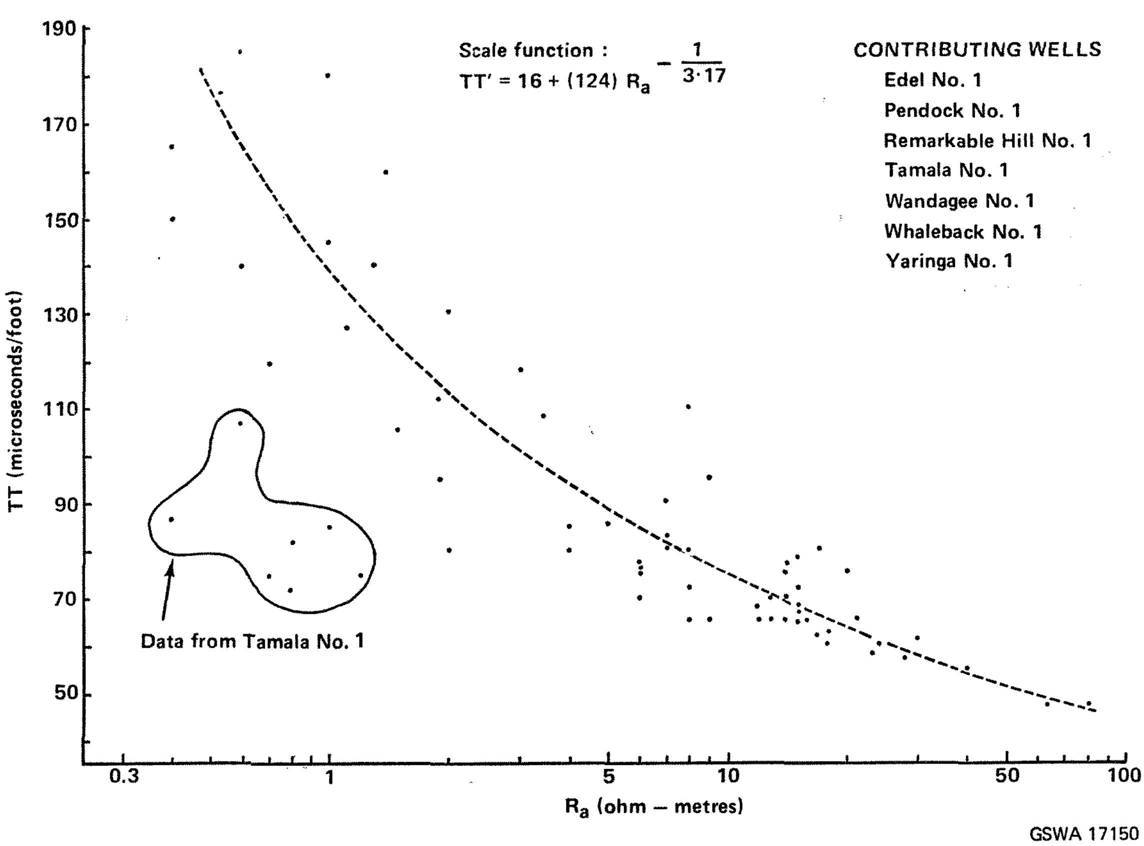

Figure 47 Scale function derived from R_a v TT points for seven wells in the Carnarvon Basin.

their inclusion would result in undue bias to the ASF. The constants of the scale function defining the curve were then calculated, and the following equation obtained:

$$TT^1 = 16 + (124)R_a^{-1/3.17}$$

This equation is considered to define the resistivity-velocity relationship for the entire Carnarvon Basin. As a check, the equation was used to generate pseudovelocity logs for those wells where sonic logs were recorded and TT^1 compared with TT. Continuous pseudosonic logs have not yet been generated by computer; however, for four wells, Edel No. 1, Remarkable Hill No. 1, Kalbarri No. 1, and Pendock No. 1, the entire resistivity log was divided into sections, each characterised by a reasonably stable R_a. Pseudotravel times were calculated by the scale function for each of these sections and added to give a total pseudotravel time from a selected upper datum to total depth of the well. Comparison with true total travel times from the sonic log for each well showed an average error of around eight per cent. Whilst of a slightly greater magnitude than had been hoped, it is reasuring that the error occurs in the one sense for two of the wells and in the opposite sense for the other two. Moreover, the likelihood of bias in the R_a to TT^1 transformation is further lessened as each pair of wells includes one from the northern and one from the southern group.

PENDOCK No. 1

Pendock No. 1 well is taken as an example of the above procedure. Plots have been made of travel time against depth, and also of interval velocity against depth—both standard presentations used in seismic interpretation. Although the diagram for Pendock No. 1 (Fig. 48) is somewhat simplified in that minor changes over thin sections of the sequence have been ignored, certain comparisons are significant. Firstly, the plots of pseudo data (the unbroken lines) derived from the resitivity information show the following features. Interval velocities are generally in the 2 130 to 2 740 m/s range from the upper hole to around 1 040 m below which depth a sharp increase occurs. This pattern is reflected in the pseudotravel time curve where the gradient is low for the upper 1 040 m, and then increases to total depth. Minor changes in gradient correspond to variations in interval velocity.

The dotted lines of Figure 48 summarise data obtained directly from the field-recorded continuous velocity (sonic) log. The genuine and pseudo plots of both interval velocity and travel time show excellent agreement and thus indicate a successful transformation. Note that the 400 to 800 m section accounts for most of the final percentage error. The travel-time curves diverge between 400 and 800 m and then are virtually parallel to total depth. Obviously, over this section, the scale function indicates a lower

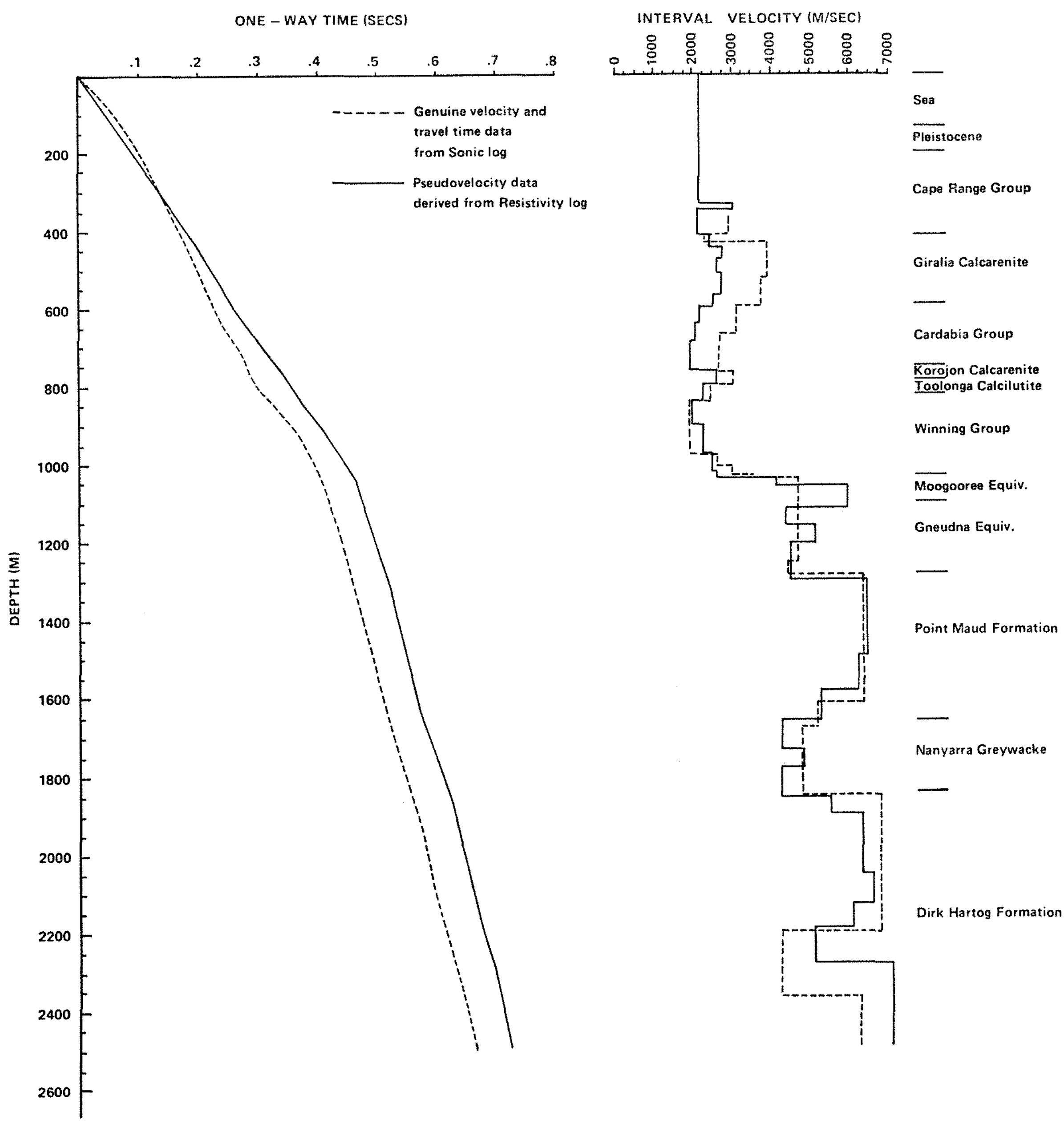

Figure 48 Comparison of sonic and pseudovelocity data for Pendock No. 1.

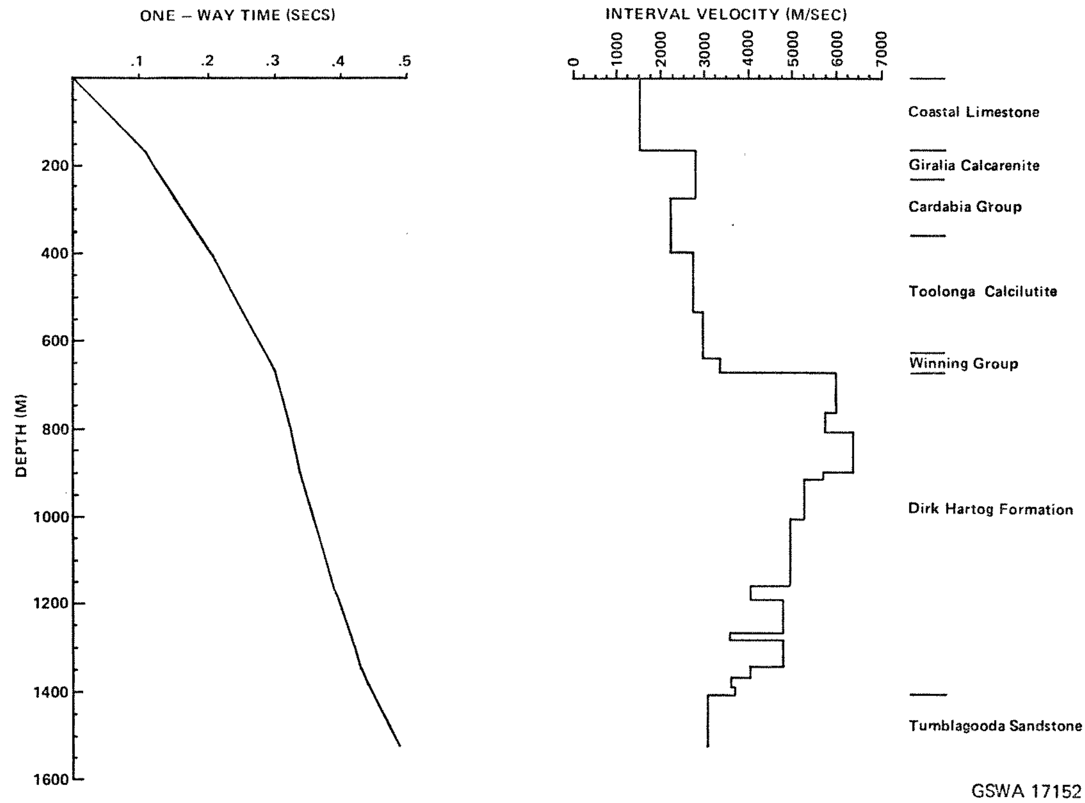

Figure 49 Pseudovelocity model proposed for Dirk Hartog No. 17B.

velocity from the resistivity data than is actually the case. Although the reason for this anomaly is not evident, it is noted that this section includes the Giralia Calcarenite and the Cardabia Group. These units should be carefully studied in other logs where pseudo and true travel times may be compared. A corrrection factor for this section may need to be empirically established.

From about 800 m down, the two interval-velocity curves vary with depth in relative harmony until the Dirk Hartog Formation is encountered; there the range of velocity variation in the genuine curve is somewhat greater than in the pseudo curve. Overall, however, it is considered that the disparity between the two sets of data in the example of Pendock No. 1 (and three other wells) is not excessive and that extension of the method is warranted.

DIRK HARTOG No. 17B

At this point, the purpose of this exercise can be fulfilled: that is, to generate a pseudovelocity model for a well which has never been sonically logged. The Dirk Hartog No. 17B petroleum exploration well was selected for initial attention because it was drilled in a locality where reliable velocity information is scarce. Using the basin scale function, the short-normal resistivity log was transformed to pseudovelocities as outlined above, and the resulting data presented, as for Pendock No. 1, in the form of travel-time and interval-velocity curves (Fig. 49).

Obviously no direct check can be made on the validity of these curves, but the pseudovelocity characteristics of certain formations can be compared with equivalents in other wells. For example, the velocities derived from the resistivity log for the Giralia and Cardabia sections are similar to those obtained in the relevant sections for Pendock No. 1. A further comparison between the Dirk Hartog and Pendock wells in the upper section of the Dirk Hartog Formation reveals a velocity of around 6 000 m/s in each case. Basically, then, there is a consistency of R_a values for the same stratigraphic unit in the logs from both Pendock and Dirk Hartog wells. Moreover, such equality needs to be sustained throughout the region in which a specific scale function is asumed to be valid.

CONCLUSION

An outline has been given of a recently proposed method for transforming short-normal borehole resistivity data into pseudovelocity information. A transforming scale function of the form $TT^1 = A + (B)R_a^{-1/c}$ can be used to generate a continuous pseudosonic log or, more simply, to approximate equivalent material from stable 'blocks' of the resistivity log. A specific scale function: $TT^1 = 16 + (124)R_a^{-1/3.17}$ has been formulated for part of the Carnarvon Basin. The validity of the function has been verified by counter checks against other wells in the basin, and then it was used to generate a pseudovelocity system for Dirk Hartog No. 17B; a well which has never been sonically logged. It is suggested that errors in total travel time over the length of a well should not exceed ten per cent. The pseudosonic information can be used as a guide to seismic interpretation in the vicinity of the wells and, as some insight is gained into the velocity characterisation of particular formations, as a guide to stratigraphy. Determination of porosity in limestone and sandstone sections should also be possible.

There are several restrictions to general application of the method, and these, and some suggested improvements, are discussed below.

(a) The use of logs from wells where the drilling mud resistivity was unusually high or low may be invalid. R_m for Tamala No. 1 was low at around 0.2 ohm-metres, whereas it was around 0.8 to 1.5 ohm-metres for the other bores.

(b) Pseudovelocities should not be generated for depths less than 150 m where resistivities are often anomalously high because of the presence of fresh water or only partial saturation.

(c) It may be necessary to apply a correction factor to certain stratigraphic units where resistivities are consistently anomalous (Rudman and others, 1976). The Giralia-Cardabia sequence may exhibit exceptionally high resistivities which would transform to erroneously low velocities.

(d) Rudman and others, (1976) note that the accuracy of the transformation may be improved if the final R_a *versus* TT^1 curve is defined by three distinct equations for three different sections of the curve rather than by the one scale function used here. Such a modification may have an effect on the Giralia-Cardabia anomaly.

(e) Investigation into changes to the mathematical form of the scale function and improved methods of curve-fitting are warranted.

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THE VALUE OF B-GA-RB DIAGRAMS IN DETERMINING DEPOSITIONAL CONDITIONS IN PROTEROZOIC ROCKS IN THE NORTHWEST OF WESTERN AUSTRALIA

by R. Davy, A. T. Brakel, and P. C. Muhling

ABSTRACT

Boron, gallium and rubidium data are summarized for 94 samples of sedimentary rock from the Hamersley and Bangemall Groups, and rocks underlying the Bangemall Group, of northwest Western Australia.

Interpretation of triangular diagrams for these elements supports near-shore deposition postulated for the Bangemall Group by regional sedimentary interpretation, though there is no complete agreement on the salinity of the depositional conditions. Interpretation of the diagrams for the older Proterozoic rocks is more tenuous though the conclusions deduced are compatible with available sedimentological evidence.

B-Ga-Rb diagrams can be of value in assessing the broad depositional condition of Proterozoic sedimentary rocks, supplementing sedimentological interpretation. The use of these elements is apparently not affected by weathering, diagenesis and low temperature recrystallization of phyllosilicates.

INTRODUCTION

Boron-gallium-rubidium (B-Ga-Rb) triangular diagrams have been tested for their value in supplementing sedimentological investigations of the depositional conditions of Proterozoic rocks of the northwest of Western Australia. The main rocks of interest were those of the Bangemall Group which contain stratabound low grade Pb-Zn mineralization, but other available data from Proterozoic rocks, namely rocks underlying the Bangemall Group, and rocks from the Hamersley Group, have been included.

Previous usage of these diagrams, originally proposed by Degens and others in 1958, has, with one exception, been restricted to Phanerozoic rocks where palaeontological evidence has assisted interpretation. The exception is a paper by Hickman and de Laeter (1977) on shale from Meentheena in the Pilbara of Western Australia.

The diagrams are based on the differential partitioning of B, Ga and Rb between clay minerals at the time of formation of the original sediment. The main clay minerals of interest are illite, supposedly more common in marine sediments, and kaolinite, more common in freshwater sediments. According to Degens and others (1957) marine sediments commonly contain larger absolute concentrations of B and Rb, and B/Ga ratios than do freshwater sediments, apparently reflecting a higher original illite/kaolinite ratio. B and Rb are collected preferentially in illite, where they replace Al and K respectively. Ga substitutes for Al in most minerals and is more concentrated in kaolinite than illite by virtue of the higher Al content of the former mineral; it is therefore normally more concentrated in freshwater sediments. The triangular diagrams allow for representation of relative abundances, obviating the need for the separation of pure clay minerals from the sediment which normally includes a varying proportion of quartz.

Tourmaline can also contribute B to sediments. In the present case modal estimation suggests that the contribution of B from this source is limited to less than 5 ppm except at one locality (Mount Palgrave) where for some samples the contribution may be 15 ppm.

A difference between the Proterozoic rocks and those studied by Degens and others (1957, 1958) is the degree of recrystallization of the Proterozoic rocks by post-depositional, mainly diagenetic, changes. The phyllosilicates* now present are muscovite and chlorite, and in rocks of the Hamersley Group, stilpnomelane. Kaolinite is only present as an alteration product in weathered samples.

STRATIGRAPHIC SETTING

Three main stratigraphic groups have been investigated:—

(i) Bangemall Group—approximate age 1 100 m.y.

(ii) pre-Bangemall Group rocks that occur as basement to the Bangemall Group—age uncertain, probably 1 600-2 000 m.y.

(iii) Hamersley Group—approximate age 2 200-2 400 m.y.

The stratigraphic succession of the Bangemall Group has been discussed by Brakel and Muhling (1976). Rock types sampled include black shale, siltstone, carbonated siltstone, silicified siltstone and chert. Mineralization occurs in the Kiangi Creek Formation (Glen Ross Shale Member) and in the Jillawarra Formation. Most samples were selected from these formations, with other samples from overlying formations.

The pre-Bangemall Group rocks, sampled from drill core only, include black, carbonated shales and siltstones, and quartz-magnetite-chlorite rocks with minor sulphide. The latter appear to have been ferruginous siltstones and shales metamorphosed to the greenschist facies level.

Hamersley Group samples were collected from the Dales Gorge Member (Trendall and Pepper, 1977), and include both shales and iron formation. One sample of iron formation from the younger Joffre Member was also collected.

CHEMISTRY

Analysis was carried out by the Western Australian Government Chemical Laboratories.

Values obtained are summarized as follows:

	No. of samples	B ppm	Ga ppm	Rb ppm	K_2O %
Bangemall Group rocks (oldest first)—					
Kiangi Creek Formation	25	10–215	<1–17	5–230	0·2–4·5
Jillawarra Formation, shales	22	30–155	3–32	60–375	1·1–7·4*
Jillawarra Formation, cherts	2	5–25	<2–4	6–65	N.D.†
Discovery Chert	11	2–20	<1–5	5–95	0·1–1·4▲
Ullawarra Formation	1	20	12	8	N.D.†
Curran Formation	3	70–120	16	160–180	3·0–3·6
Fords Creek Shale	1	350	18	170	3·8
Kurabuka Formation	1	30	8	57	N.D.†
Backdoor Formation[1]	11	10–210	<2–20	7–225	0·5–2·6°
Pre-Bangemall Group rocks—					
Unmetamorphosed	3	15–85	2–20	20–200	0·4–3·0
Metamorphosed	4	5–120	4–17	10–175	0·2–2·6
Hamersley Group rocks—					
Joffre Member iron formation	1	15	1	50	1·26
Dales Gorge Member, shale	6	30–100	2–6·5	45–135	1·47–4·21
Dales Gorge Member, iron formation	5	10– 30	≤0·5	5–30	0·13–0·37

* 17 samples only.
° 5 samples only.
† N.D. = not determined.
[1] Equivalent to Ullawarra Formation – Fords Creek Shale.
▲ 8 samples only.

* Determination, by X-ray diffraction analysis, by the Western Australian Government Chemical Laboratories.

In general the shales and siltstones have the highest values in all the above constituents. In most shales/siltstones B exceeds 40 ppm, Ga 12 ppm, Rb 60 ppm and K_2O 1.5%. Boron and Rb were always detected in the cherts and iron formation, commonly in the 10-30 ppm range for B, 5-70 ppm for Rb. Gallium, however, is commonly below detection in these rocks.

Relative behaviour of the trace elements is shown in the triangular plots—Figures 50-53 (Ga is multiplied by a factor of 10 following Degens and others, 1958, to enhance differences in distribution). A separate plot has been generated for chert samples, for most of which Ga is below detection (Fig. 54). The Ga figures for this plot have been assumed to be half the minimum detectable value.

Correlation coefficients, which indicate how the concentrations of elements vary with one another, show a high degree of significance between the constituents. In all formations with enough determinations Rb, Ga and K_2O correlate at the 99% probability levels. Boron also correlates with these constituents at the 99% level except at Mount Palgrave (Jillawarra Formation, seven samples in sub-group 676-689) where there has been lower greenschist facies metamorphism with the formation of authigenic tourmaline. The correlation here is significant at the 90% probability level. The high degree of correlation confirms the association of the trace elements with K_2O in the phyllosilicates, for there are no other K-bearing minerals.

DISCUSSION

The absolute proportions of the constituents depend to some degree on the provenance of the detritus and the waters which have contributed to the formation of the rocks. It was originally felt that a study of the relative proportions of the constituents was likely to provide more reliable information than the sole consideration of absolute values. In the event, the absolute values of B, Ga and Rb obtained from the shales and siltstones are in accord with values from previous literature summarized in Hickman and de Laeter (1977), encouraging belief that the study was viable.

EFFECTS OF WEATHERING AND METAMORPHISM

Data from a number of visibly weathered samples are included in the analyses, particularly from the Jillawarra and Kiangi Creek Formations. Their absolute values and plotted positions on the triangular diagrams are consistent with those for the fresh rocks. These observations support Degens and others (1957) who, after carrying out accelerated weathering tests, found these elements suitable for use in weathered as well as unweathered rocks.

All the rocks sampled here have been diagenetically altered and some have been metamorphosed. Diagenesis, involving low temperature recrystallization of phyllosilicates appears to have had no effect on the absolute values of the three elements considered even when authigenic tourmaline has been formed. At higher temperatures there is the suggestion of mobilization and loss of boron.

INTERPRETATION OF THE RESULTS

(a) Shales/siltstones

The triangular diagrams for shales/siltstones suggest deposition in environments which are variously marine, brackish or freshwater.

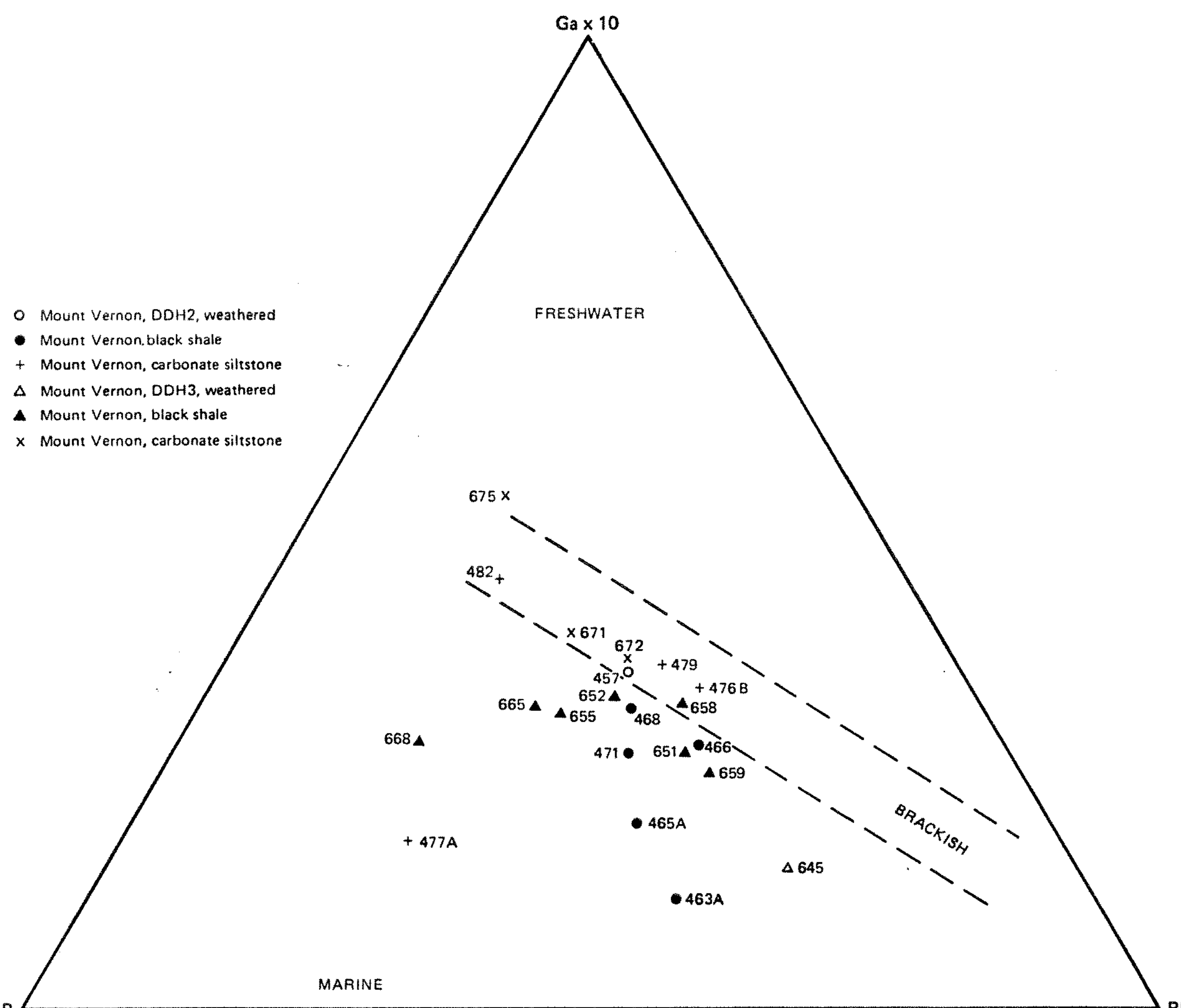

Figure 50 B-Ga-Rb diagram for shales from Glen Ross Shale Member, Kiangi Creek Formation, Bangemall Group

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(i) Bangemall Group

Interpretation is expressed below in tabular form:

Formation	Environment Based on Chemistry	Environment Based on Regional Mapping
Kurabuka Formation	freshwater	coastal lagoons
Fords Creek Shale	marine	marine shelf, usually below wave base
Curran Formation	brackish water	marine shelf, pro-delta
Ullawarra Formation	freshwater	marine platform (rare evaporites), very shallow in places
Discovery Chert	marine-brackish-freshwater	restricted basin, usually below wave base, probable sabkhas around edge
Jillawarra Formation	marine-brackish-freshwater	marine shelf below wave base except for rare shoals
Kiangi Creek Formation	marine-brackish	barrier bar and beach
Backdoor Formation	marine-brackish-freshwater	marine shelf usually below wave base

The geochemistry suggests that conditions ranging from fresh to brackish-deltaic to marine were present within many formations. For example, at Mount Palgrave the Jillawarra Formation (Fig. 51) is inferred to have had a brackish water to marine origin; in the Mount Vernon Syncline its origin appears to have been freshwater; whilst at Maroonah there is an apparent cycle from fresh-brackish water to marine and back to freshwater (samples 711 to 717) from the bottom to the top of the sequence.

Though there are differences of interpretation between the conclusions drawn from geochemistry and those from sedimentological considerations, the clustering of the chemical data in the vicinity of the brackish water zone suggests that sedimentation took place in shallow water as opposed to deep sea deposition. Differences in interpretation are mainly whether the waters were fresh or saline. Apparent freshwater deposition in sediments considered to be of marine origin can be explained by periodic freshwater flushing of the Bangemall embayment. Both sedimentological and chemical findings indicate that the Bangemall Basin was a zone of subsidence with sedimentation almost balancing downwarp, maintaining the whole area in the vicinity of sea level.

(ii) The pre-Bangemall Group rocks

The chemistry of the unmetamorphosed rocks suggests a brackish water origin (Fig. 53). Microscopic scour and fill structures suggest deposition in shallow water. The stratigraphic and sedimentological significance of these rocks has not yet been established, but future workers should consider this chemical evidence as part of their overall interpretation.

Superficially, the metamorphosed equivalents are of brackish to clearly freshwater origin. However, the B values of 517 and 520 (Fig. 53) are so low that mobilization and loss of B is suspected.

(iii) Hamersley Group

A marine origin for the Dales Gorge Member shale is suggested by the geochemistry, but these rocks are characterized by low absolute Ga values (Fig. 53). The

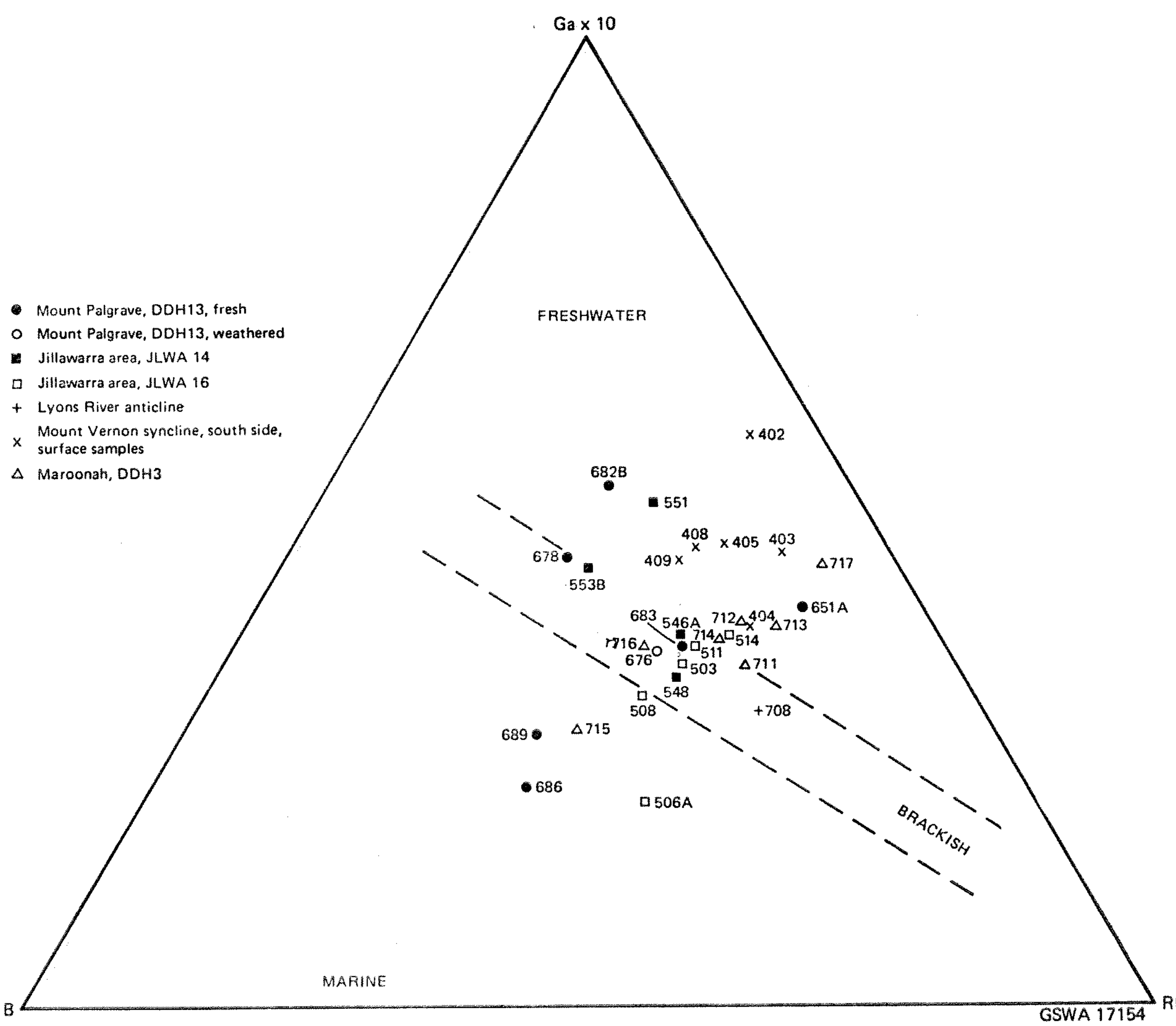

Figure 51 B-Ga-Rb diagram for rocks from the Jillawarra Formation (shales and siltstones), Bangemall Group

origins of the associated iron-formation rocks are still in debate, with opinions divided amongst marine (Trendall and Blockley, 1970; Garrels and others, 1973) and lacustrine (Eugster and Chou, 1973; van der Wood, 1977).

(b) Cherts and iron formation

The value of the triangular diagram for the cherts and iron formation is inherently low, with low absolute values of all trace elements. Where Ga is below detection the plotted point is a stylized estimate of the true position. Notwithstanding this potential for error, the Dales Gorge and Joffre iron formations plot as marine (like the Dales Gorge shales), and the cherts from the Bangemall Group show a scatter about brackish water deposition analogous to their more shaly equivalents.

IMPLICATIONS OF INTERPRETATION

The use of B-Ga-Rb diagrams, prior to the work of Hickman and de Laeter (1977), has been restricted to rocks no more than 450-500 m.y. old. Use of these diagrams for indicating depositional conditions in the Proterozoic carries with it the implication that the oceanic composition and the conditions of transport and deposition of the various constituents have not changed appreciably from the Proterozoic to the present day. Interpretation on this basis is reasonable for the Bangemall Group since there is substantial agreement that the oceanic composition has been close to that of the present for 1 000-1 500 m.y. (MacKenzie, 1975; Holland, 1976; Maynard, 1976).

Interpretation for the older rocks is more subject to doubt. Data for rocks underlying the Bangemall Group are limited, with no adequate external evidence for the conditions of deposition, and the Dales Gorge Shale, whilst indicating marine deposition, is anomalous in its Ga content. The freshwater deposition of the Hardey Sandstone shale deduced by Hickman and de Laeter (1977) does not assist in an assessment of the oceanic conditions extant at that time.

CONCLUSIONS

It is concluded that B-Ga-Rb diagrams can be of value in assessing the depositional conditions of Proterozoic sedimentary rocks, supplementing rather than displacing lithological and sedimentological indicators of deposition. The use of these elements is apparently not impeded by weathering, diagenesis, and low temperature recrystallization of phyllosilicates. However, increased temperatures of metamorphism may be reflected in a loss of boron.

These diagrams for the Bangemall Group are consistent with near-shore deposition postulated previously from the sedimentological and palaeontological studies made in the course of regional mapping, though there is no complete agreement on the salinity of the depositional conditions.

The value of these diagrams for older Proterozoic rocks is more tenuous, but the conclusions deduced are compatible with such sedimentological evidence as is known.

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This study could not have been carried out without the chemical and mineral analyses performed by members of the Western Australian Government Chemical Laboratories.

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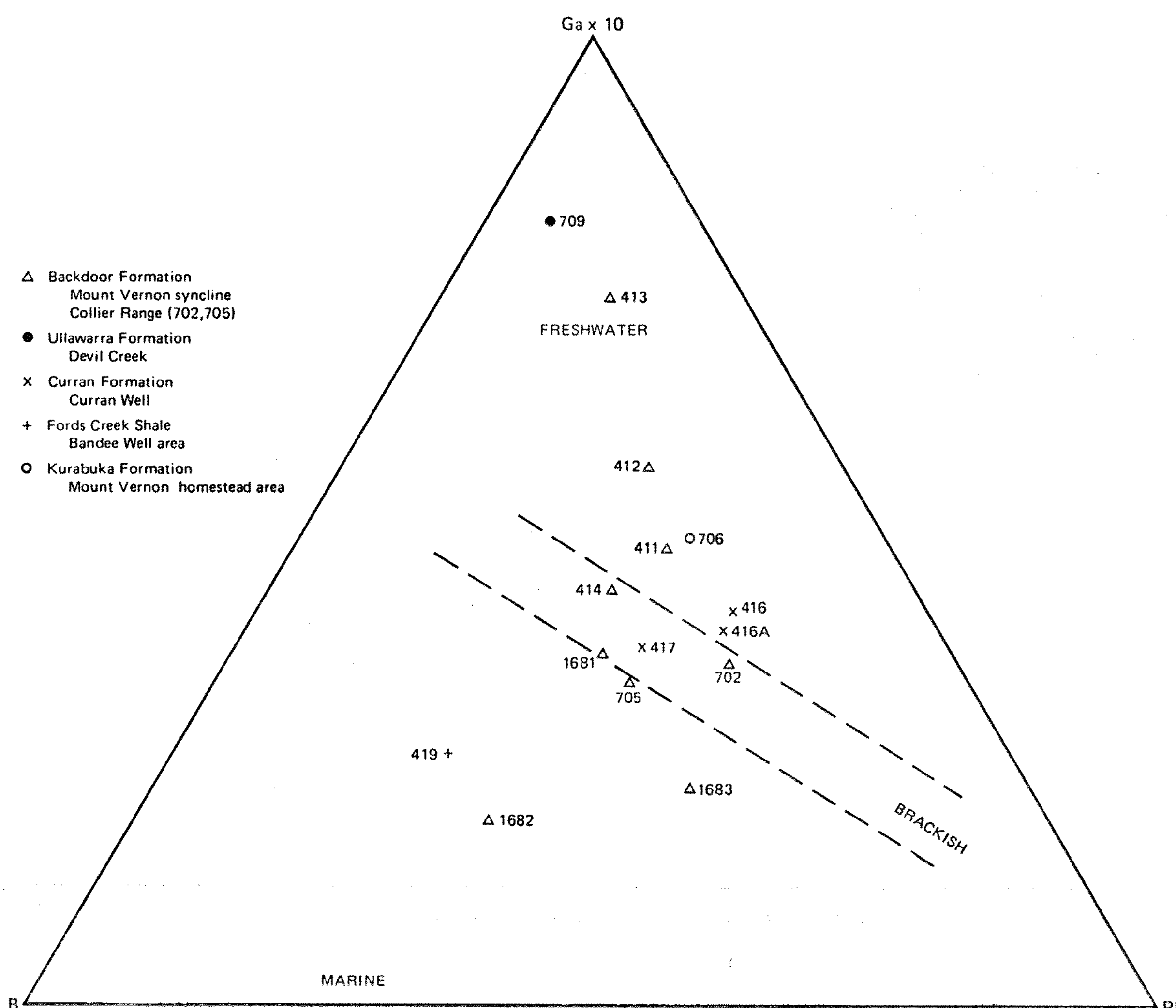

Figure 52 B-Ga-Rb diagram for Bangemall Group rocks

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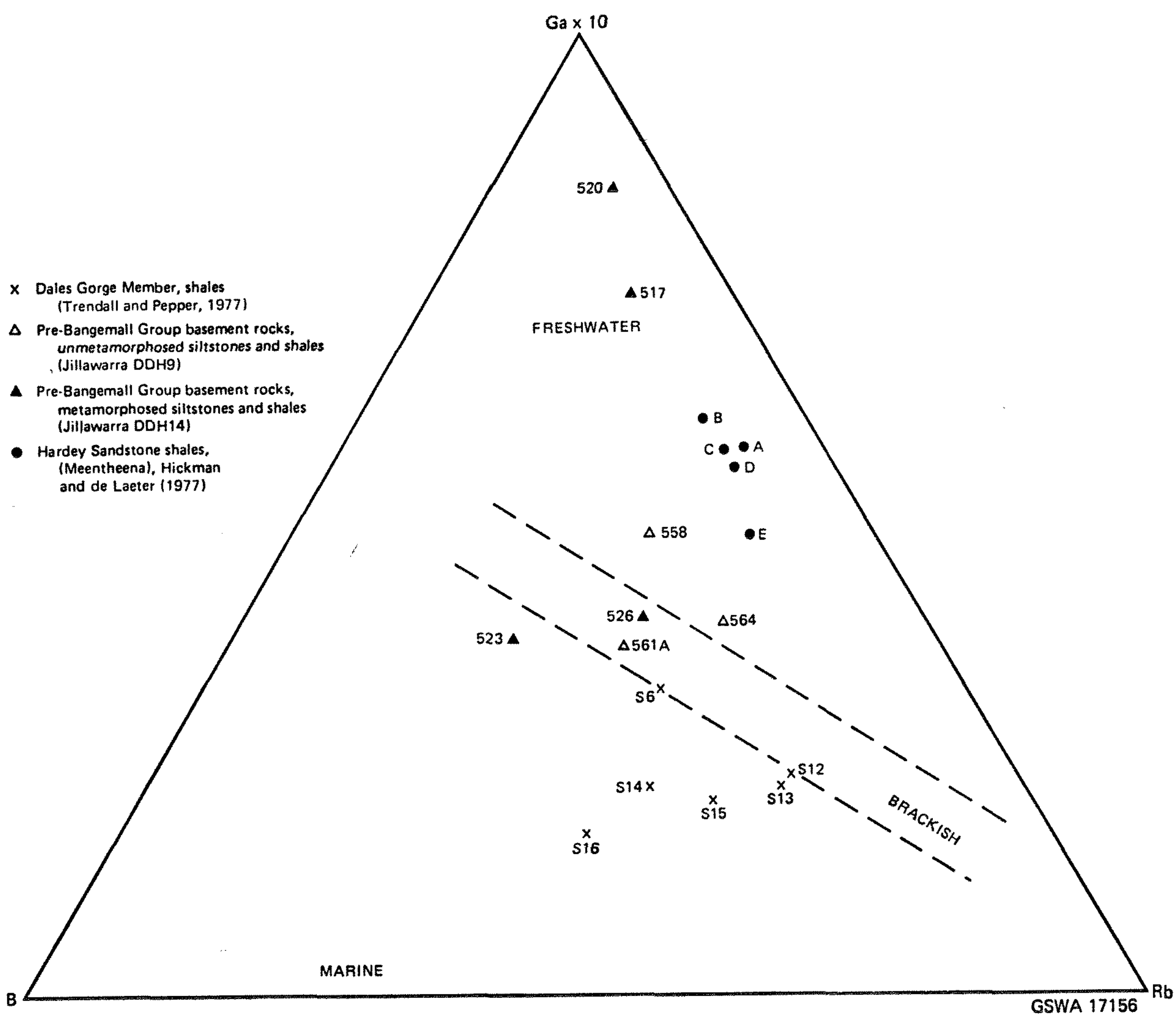

Figure 53 B-Ga-Rb diagram for pre-Bangemall Group and Hamersley Group rocks

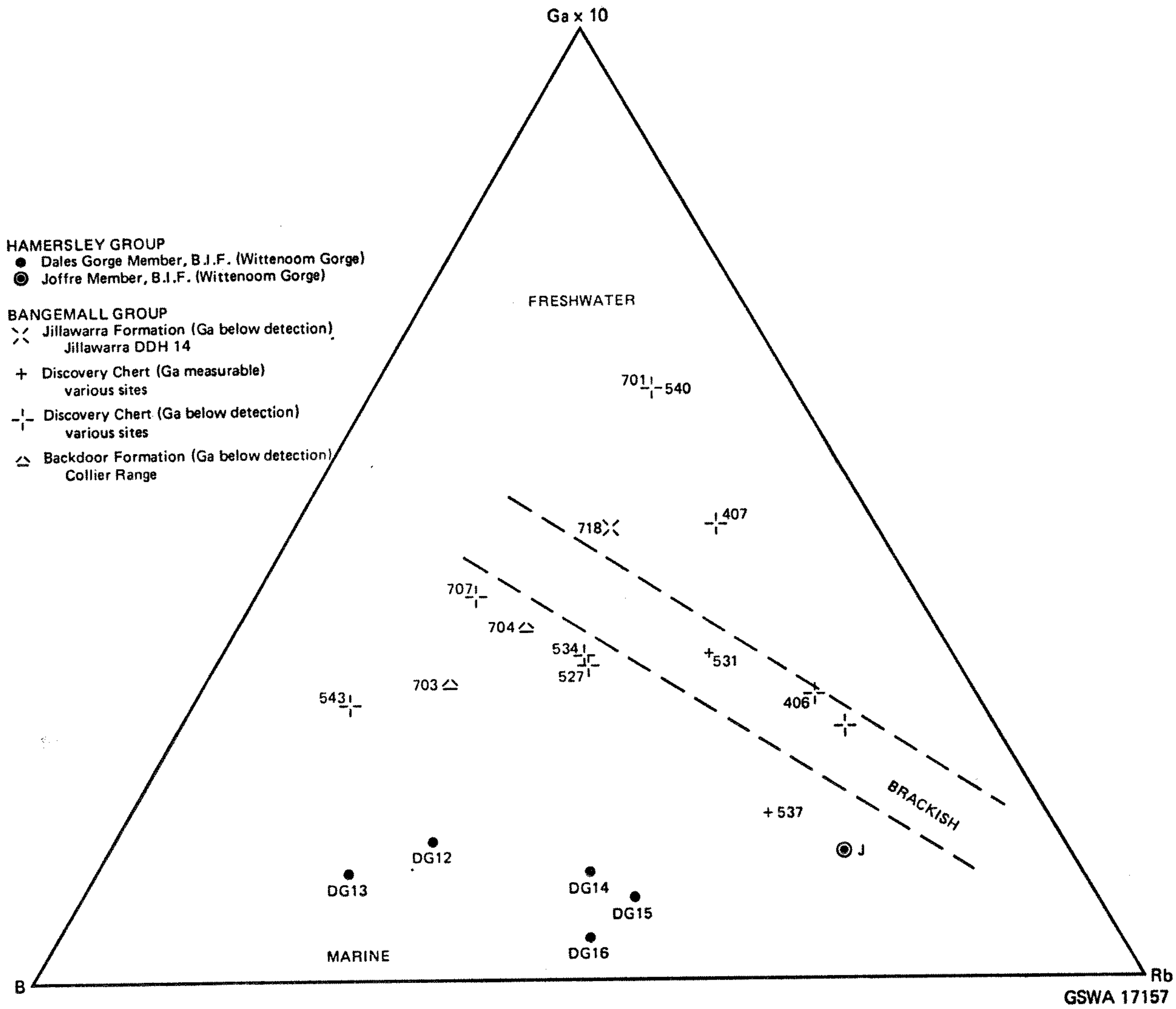

Figure 54 B-Ga-Rb diagram for cherts

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